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HOLOCENE VARIATIONS OF RADIOCARBON RESERVOIR AGES IN A MEDITERRANEAN LAGOONAL SYSTEM

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ABSTRACT. To obtain a precise radiocarbon Holocene chronology in coastal areas, it is necessary to estimate the modern ^{14}C reservoir age R(t) and its possible variations with time in relation to paleoenvironmental changes. The modern reservoir ^{14}C age was estimated by comparing AMS ^{14}C ages of 2 recent mollusk shells found in sediment cores sampled in the Palavasian lagoonal system (south of France) with ages derived from ^{210}Pb and ^{137}Cs data and historical accounts of identifiable storm events. The calculated modern R(t) value of 943 ± 25 ^{14}C yr is about 600 yr higher than the global mean sea surface reservoir age. This high value, probably due to the relative isolation of the lagoon from marine inputs, is in good agreement with other R(t) estimates in Mediterranean lagoonal systems (Zoppi et al. 2001; Sabatier et al. 2008). ^{14}C ages were also obtained on a series of Holocene mollusk shells sampled at different depths of the ~8-m-long core PB06. Careful examination of the ^{14}C ages versus depth relationships suggests that R(t) in the past was lower and similar to the value presently measured in the Gulf of Lion (618 ± 30 ^{14}C yr, Siani et al. 2000). The change in R(t) from 618 to 943 yr is thought to result from final closure of the coastal lagoon by the sandy barrier, due to the along-shore sediment transfer.

INTRODUCTION

To determine the Holocene timescale, absolute chronology is usually based on radiocarbon measurements of carbonaceous samples, allowing accurate paleoenvironmental and archaeological interpretations. However, when the ^{14}C method is applied to date samples equilibrated in marine or continental bodies of water, it requires a correction, called the reservoir age correction. While the correction for marine reservoir age is well established, many recent studies have focused on climate records in coastal areas, which are strongly influenced by continental river inputs (Spennemann and Head 1998; Oldfield et al. 2003; Dezileau et al. 2005; Sabatier et al. 2008; Sorrel et al. 2009). Indeed, a sample from an estuarine or lagoonal system could be affected by a reservoir age offset (R) due to a mixture between the marine reservoir effect (MRE) and the hardwater effect (HWE) (e.g. Little 1993). The reservoir age of the global mixed marine surface layer is a quantitative measure of the offset between the activities of marine ^{14}C variations in response to atmospheric ^{14}C changes. It is induced by the significant lapse of time required for CO_2 exchange between the atmosphere and the ocean (i.e. to the long residence time of carbon in the ocean, compared to the ^{14}C half-life) (Stuiver et al. 1986; Stuiver and Braziunas 1993). The HWE refers also to the dilution of ^{14}C activity in the marine reservoir by the influx of ^{14}C-free inorganic carbon originating from subaerial dissolution of old carbonate rocks (Spennemann and Head 1998).

The pre-industrial global reservoir age is estimated as 405 ± 22 ^{14}C yr and a time-dependent correction is available by using the Marine04 calibration curve (Hughen et al. 2004). Several studies have suggested the possibility of significant deviations in regional marine reservoir signature from this average value (Goodfriend and Flessa 1997; Ingram and Southon 1997; Siani et al. 2001; Reimer and McCormac 2002; Southon et al. 2002; Fontugne et al. 2004). The reservoir age in coastal areas

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may also vary with time in relation to environmental changes, which would modify the respective proportion of marine and freshwater inputs. These changes include modification of river discharge rates and variation of marine inputs due to the build-up of a delta or due to a change in the sandy barrier morphology. Some examples of lagoonal environments in the Mediterranean area show that R(t) is high and could vary between 600 to 1200 yr (Zoppi et al. 2001; Sabatier et al. 2008). These R(t) values can be estimated by comparing dated pre-industrial marine shells of known age or by comparing the ^{14}C ages of lagoonal mollusks with the ages of sediment derived using ^{210}Pb/^{137}Cs methods or paleostorm events dated from historical accounts. The latter method is applied in this study.

This work is a part of the ECLICA project (Dezileau et al. 2005), one of the aims of which was to estimate the modern R(t) in a coastal lagoon of the northwestern Mediterranean basin and to understand the relation between paleoenvironmental changes and variations in R(t). When appropriate R(t) corrections are applied, a precise and high-resolution chronology of the studied sediment core can be derived. The resulting chronology provides valuable information on the relationship between climate, sediment dynamics, and the implications on human society, in an area inhabited since prehistoric times (Sabatier et al. 2010).

LOCATION OF THE SAMPLING SITE

This study focuses on the Palavasian lagoonal complex located west of the Rhône Delta, in the central part of the Gulf of Lion, 10 km south of Montpellier in southern France (Figure 1). These coastal wetlands are the result of the interaction between a process of shoreline regularization by migration of littoral barriers and the filling of these areas by fluvial and marine particulate inputs (Certain et al. 2004). This area consists of several small, shallow (<1 m) lagoons enclosed by a narrow sandy barrier to the south and to the north by calcareous Mesozoic hills. Most of the sediments supplied to the area are carried during flash-flood events by 2 short coastal rivers (Mosson and Lez). This wetland complex is now crossed by an artificial navigation channel built in the 18th century. In some places, the sandy barrier is less than 60 m wide and 3 m high above the mean sea level. This implies a temporary but strong marine influence during storm events (Dezileau et al. 2005; Sabatier et al. 2008).

The PB06 core is 7.9 m long and was collected in Pierre Blanche Lagoon (PBL), in the southern part of the Palavasian lagoonal complex (Figure 1), in March 2006 with the Uwitec coring platform (University of Chambéry and Laboratoire des Sciences du Climat et de l'Environnement). Twenty-eight lagoonal shells (*Cerastoderma Glaucum*, *Abra Ovata*, and *Rissoa* sp.) were selected on core PB06 at different depths for ^{14}C age determination. In addition, another shell recovered at 62 cm depth from a nearby core (PRO 15, sampled <100 m away from PB06) was also dated.

ANALYTICAL METHODS

^{14}C analyses were conducted at the Laboratoire de Mesure ^{14}C (LMC14) on the ARTEMIS accelerator mass spectrometer (Accélérateur pour la Recherche en sciences de la Terre, Environnement, Muséologie Installé à Saclay) in the CEA Institute at Saclay (Atomic Energy Commission). These ^{14}C analyses were done with the standard procedures described by Tisnérat-Laborde et al. (2001). ^{14}C ages were converted to calendar years using the CALIB 5.0.2 calibration program (Stuiver and Reimer 1993; Reimer and Reimer 2001). X-ray diffraction (XRD) analyses of shells were performed at the University of Montpellier 2 (Laboratoire de Mesures Physique).

Dating of sedimentary layers was carried out using ^{210}Pb and ^{137}Cs methods on a centennial timescale. Both nuclides together with U, Th, and ^{226}Ra were determined by gamma spectrometry at the

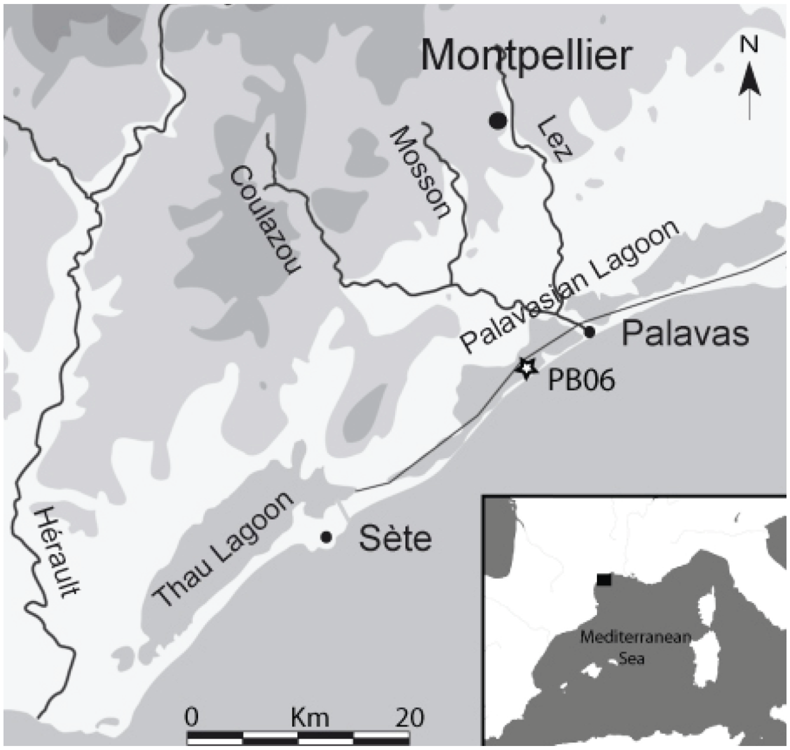

Figure 1 Map of the western Mediterranean Sea and the central part of the Gulf of Lion (south of France) with the location of PB06 core sampled in Pierre Blanche Lagoon (part of the Palavasian lagoonal complex).

Géosciences Montpellier Laboratory (Montpellier, France). The 1-cm-thick sediment layers were washed in deionized water and sieved. The fraction smaller than 1 mm was then finely crushed after drying, and transferred into small gas-tight PETP (polyethylene terephtalate) tubes (internal height and diameter of 38 and 14 mm, respectively), and stored for more than 3 weeks to ensure equilibrium between ^{226}Ra and ^{222}Rn. The activities of the nuclides of interest were determined using a Canberra Ge well detector and compared with the known activities of an in-house standard. Activities of ^{210}Pb were determined by integrating the area of the 46.5-keV photo-peak. ^{226}Ra activities were determined from the average of values derived from the 186.2-keV peak of ^{226}Ra and the peaks of its progeny in secular equilibrium with ^{214}Pb (295 and 352 keV) and ^{214}Bi (609 keV). In each sample, the (^{210}Pb unsupported) excess activities were calculated by subtracting the (^{226}Ra supported) activity from the total (^{210}Pb) activity. (Note that, throughout this paper, parentheses denote activities.) A self-absorption correction based on major element composition and sample density was systematically applied for all photo-peaks, using a modified version of the program written by J Faïn (Pilleyre et al. 2006). The self-absorption corrections were rather small, even for the low-energy peaks (<4%).

RESULTS

Since Goldberg (1963) first established a method based on ^{210}Pb chronology, this procedure has provided a very useful tool for dating recent sediments. Several ^{210}Pb models were later proposed, allowing a precise calculation of sedimentation rates (e.g. Appleby and Oldfield 1978, 1992). In the simplest model, the initial $(^{210}Pb)_{ex}$ is assumed constant and thus $(^{210}Pb)_{ex}$ at any time is given by the radioactive decay law. In the CFCS ("constant flux, constant sedimentation rate") model (Goldberg 1963; Krishnaswamy et al. 1971), the ^{210}Pb flux and sedimentation rate are assumed to be constant. The sedimentation rate in Pierre Blanche Lagoon is clearly variable due to the near-instantaneous sedimentation of sandy storm deposits; however, the CFCS model can be applied when typical lagoonal conditions prevail (Sabatier et al. 2008). Using the CFCS model, the ^{210}Pb data indicate a sedimentation rate of 2.65 ± 0.2 mm/yr (Figure 2, Table 1).

The most common dating method based on ^{137}Cs data (Robbins and Edgington 1975) assumes that the depth of maximum ^{137}Cs activity in the sediment corresponds to the maximum atmospheric production in 1963. On the other hand, the 1986 Chernobyl fallout is used to date the most recent part of cores (Appleby 1991). A property of Cs is its high mobility in marine sediments, with a preferential downward diffusive transport in porewater (Radakovitch et al. 1999). Despite the potential Cs mobility by diffusive transport, leading to the spreading of the Cs peak, we can see in Figure 2 that the ^{137}Cs profile shows a clear maximum corresponding to 1963. The ^{137}Cs activity depth profile thus gives accumulation rates of 2.6 and 3 mm/yr, respectively, for the 1963 and 1986 depths (Figure 2, Table 1). These rates are in good agreement with ^{210}Pb data.

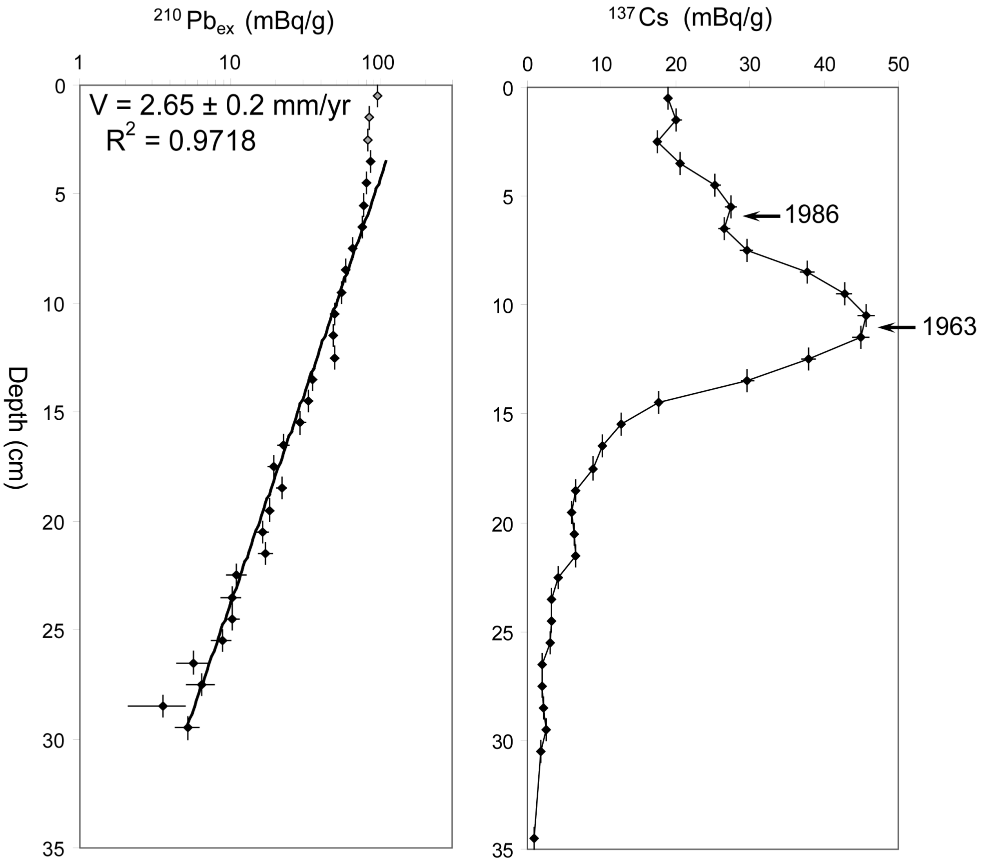

Figure 2 $^{210}Pb_{ex}$ and ^{137}Cs activity depth profiles in core PB06 from Pierre Blanche Lagoon. ^{210}Pb excess disappears at around 30 cm. Using the CFCS model, the ^{210}Pb data indicate a sedimentation rate of 2.65 ± 0.2 mm/yr. The ^{137}Cs activity depth profile displays 2 peaks at 6 and 11 cm, resulting in accumulation rates of 2.6 and 3 mm/yr, respectively, for the 1963 and 1986 depths.

Table 1 Activities of radionuclides in core PB06.

Depth (cm)	^{210}Pb (mBq/g)	^{226}Ra (mBq/g)	^{210}Pb$_{ex}$ (mBq/g)	^{137}Cs (mBq/g)
0.5	113.49 ± 2.47	19.12 ± 0.32	94.38 ± 2.49	18.89 ± 0.53
1.5	102.50 ± 2.93	19.47 ± 0.43	83.03 ± 2.97	20.09 ± 0.68
2.5	101.23 ± 2.22	19.73 ± 0.20	81.50 ± 2.23	17.54 ± 0.45
3.5	104.61 ± 2.59	18.94 ± 0.26	85.67 ± 2.60	20.60 ± 0.56
4.5	99.11 ± 2.66	19.05 ± 0.23	80.06 ± 2.67	25.36 ± 0.64
5.5	99.47 ± 2.50	21.78 ± 0.25	77.68 ± 2.51	27.40 ± 0.70
6.5	97.17 ± 2.16	21.97 ± 0.23	75.20 ± 2.18	26.55 ± 0.67
7.5	83.06 ± 2.10	17.61 ± 0.23	65.45 ± 2.12	29.53 ± 0.75
8.5	76.28 ± 1.93	18.18 ± 0.22	58.10 ± 1.95	37.78 ± 0.93
9.5	72.25 ± 1.97	17.77 ± 0.22	54.48 ± 1.98	42.73 ± 1.04
10.5	66.90 ± 2.03	17.03 ± 0.22	49.87 ± 2.04	45.63 ± 1.11
11.5	65.30 ± 1.91	17.18 ± 0.21	48.12 ± 1.92	44.91 ± 1.09
12.5	65.68 ± 2.01	16.48 ± 0.22	49.20 ± 2.03	37.94 ± 0.93
13.5	55.60 ± 2.02	20.13 ± 0.42	35.47 ± 2.06	29.69 ± 0.82
14.5	49.23 ± 1.54	16.04 ± 0.19	33.20 ± 1.55	17.67 ± 0.46
15.5	48.99 ± 1.65	19.70 ± 0.22	29.28 ± 1.66	12.71 ± 0.36
16.5	41.71 ± 1.13	19.10 ± 0.21	22.61 ± 1.15	10.13 ± 0.27
17.5	39.20 ± 1.33	19.75 ± 0.28	19.45 ± 1.36	8.89 ± 0.31
18.5	39.27 ± 1.73	17.18 ± 0.24	22.09 ± 1.75	6.58 ± 0.24
19.5	35.32 ± 1.57	17.17 ± 0.33	18.15 ± 1.60	5.98 ± 0.32
20.5	36.13 ± 1.53	19.65 ± 0.32	16.48 ± 1.57	6.39 ± 0.32
21.5	35.16 ± 0.95	18.04 ± 0.18	17.13 ± 0.97	6.45 ± 0.19
22.5	31.08 ± 1.33	20.03 ± 0.30	11.05 ± 1.37	4.16 ± 0.23
23.5	29.00 ± 1.27	18.78 ± 0.28	10.22 ± 1.30	3.29 ± 0.21
24.5	28.83 ± 1.32	18.48 ± 0.32	10.35 ± 1.35	3.26 ± 0.24
25.5	28.18 ± 1.43	19.40 ± 0.33	8.78 ± 1.47	3.06 ± 0.24
26.5	22.58 ± 0.93	16.92 ± 0.20	5.67 ± 0.95	1.98 ± 0.11
27.5	22.22 ± 0.83	15.77 ± 0.20	6.45 ± 0.85	1.96 ± 0.11
28.5	24.57 ± 1.05	20.98 ± 0.23	3.58 ± 1.08	2.14 ± 0.16
29.5	26.08 ± 1.15	20.85 ± 0.23	5.23 ± 1.17	2.48 ± 0.20
30.5	21.84 ± 1.21	21.60 ± 0.30	0.24 ± 1.25	1.83 ± 0.18
34.5	20.88 ± 1.13	21.23 ± 0.28	–0.35 ± 1.16	0.94 ± 0.14

Conventional ^{14}C measurements performed on shells from core PB06 result in model ages covering a time interval between 7600 to 1050 BP. The ^{14}C ages are expressed in Table 2 as BP following Stuiver and Polach (1977). The XRD analysis of the shells shows a >99% aragonite composition, excluding any recrystallization process. These conventional ages display 2-σ inversions between 139 and 173 cm and between 567 and 610 cm, respectively. Moreover, a large age plateau is observed between 264 and 289 cm. The dated mollusks live within the first 5 cm of sediment. Therefore, bioturbation or mollusk habitat depth cannot explain these inversions. This uncalibrated ^{14}C chronology adopted for core PB06 allows us to estimate important reservoir age fluctuations since the modern period, and/or variations in the sedimentation rate.

Table 2 ^{14}C data for mollusk shells from cores POR 15 (1 sample) and PB06. ^{14}C ages are calibrated in the last 2 columns using the Marine04 calibration curve with different values of the reservoir age ΔR. Age models 1 and 2 correspond to Figure 4b and 4c, respectively. Age model 1 uses a constant ΔR of 605 ± 30 yr, while Age model 2 dates are calibrated with a ΔR of 605 ± 30 yr for the upper 5 samples and with ΔR of 245 ± 30 yr (see text for details).

Lab code	Depth (cm)	Species	Conventional age BP	Marine04 (cal BP, 2 σ)	Age model 1 (cal BP, 2 σ)	Age model 2 (cal BP, 2 σ)
SacA 6253	20	*Cerastoderma g.*	1055 ± 30	551–673	0–149	0–149
SacA 6254	83	*Cerastoderma g.*	1285 ± 30	745–907	255–430	255–430
SacA-10833	127	*Cerastoderma g.*	1780 ± 30	1264–1389	644–818	644–818
SacA 6160	131	*Cerastoderma g.*	1955 ± 30	1404–1597	776–989	776–989
SacA 10720	139	*Cerastoderma g.*	2090 ± 30	1562–1771	929–1143	929–1143
SacA 6161	173	*Cerastoderma g.*	1645 ± 30	1133–1277	531–674	842–1054
SacA 10834	199	*Cerastoderma g.*	1820 ± 30	1283–1447	670–871	1029–1249
SacA 6162	225	*Cerastoderma g.*	2100 ± 30	1578–1787	940–1157	1301–1505
SacA 10835	255	*Cerastoderma g.*	2615 ± 30	2169–2365	1455–1696	1881–2113
SacA 6163	264	*Cerastoderma g.*	3090 ± 35	2757–2959	2012–2290	2447–2726
SacA 10722	267	*Cerastoderma g.*	2950 ± 30	2771–2794	1858–2094	2300–2572
SacA 10725	267	*Abra ovata*	3045 ± 30	2737–2895	1955–2243	2385–2691
SacA 6164	278	*Cerastoderma g.*	3050 ± 30	2741–2903	1966–2253	2390–2695
SacA 10723	278	*Cerastoderma g.*	3230 ± 30	2935–3165	2163–2429	2687–2855
SacA 10724	289	*Cerastoderma g.*	3065 ± 30	2749–2920	1986–2268	2417–2708
SacA 6255	311	*Cerastoderma g.*	3145 ± 30	2831–3045	2101–2319	2515–2760
SacA 6165	354	*Rissoa*	3360 ± 30	3131–3331	2340–2618	2768–3021
SacA 6166	398	*Cerastoderma g.*	3805 ± 30	3647–3846	2867–3150	3347–3562
SacA 6256	451	*Cerastoderma g.*	4105 ± 30	4053–4279	3266–3493	3689–3949
SacA 6257	498	*Cerastoderma g.*	4400 ± 30	4432–4678	3616–3861	4091–4373
SacA 6167	531	*Cerastoderma g.*	5050 ± 30	5300–5484	4497–4786	4944–5258
SacA 6168	567	*Cerastoderma g.*	4965 ± 35	5236–5434	4377–4653	4825–5123
SacA 6169	610	*Cerastoderma g.*	5440 ± 35	5719–5901	4976–5275	5452–5648
SacA 6258	635	*Abra ovata*	5645 ± 30	5946–6159	5288–5509	5658–5883
SacA 6170	657	*Cerastoderma g.*	5855 ± 35	6189–6360	5507–5721	5900–6148
SacA 6171	684	*Cerastoderma g.*	2120 ± 60	1548–1852	926–1220	1282–1567
SacA 6260	710	*Abra ovata*	6220 ± 30	6568–6754	5906–6146	6286–6484
SacA 6259	744	*Abra ovata*	7175 ± 30	7569–7708	6966–7209	7354–7540
SacA 6261	758	*Abra ovata*	7600 ± 30	7976–8149	7417–7565	7711–7923

DISCUSSION

Modern Reservoir Age Estimation

Compared to the average modern ^{14}C marine reservoir age (R(t)) = 405 ± 22 ^{14}C yr), the Mediterranean Sea ^{14}C reservoir age displays higher R(t) values, with a deviance from the global mean sea surface reservoir age (ΔR) of 58 ± 85 yr. Its western part presents a ΔR of 40 ± 15 yr (Siani et al. 2000; Reimer and McCormac 2002). For the central part of the Gulf of Lion, Siani et al. (2000) found a higher ΔR estimated at 245 ± 30 yr (R(t) = 618 ± 30 ^{14}C yr), which is the average of 3 samples collected at Sète and Banyuls and recalculated by using the calibration model of Hughen et al. (2004). This offset from the Marine04 model has been explained as a result of biological processes or hardwater effects due to the discharge of coastal rivers after dissolution of limestone via several brackish lagoons, before reaching this part of the Mediterranean Sea.

Here, we estimate the modern ^{14}C reservoir age in Pierre Blanche Lagoon by comparing ^{14}C values with both historical events and ^{210}Pb and ^{137}Cs chronologies. Sabatier et al. (2008) recognized, in several cores, 3 main storm events related to events recorded in historical accounts in AD 1742, 1848, and 1893. In core PRO15, collected <100 m away from core PB06, 1 shell (SacA 6270) was recovered at 62 cm depth, just above the AD 1848 event. This shell dated to 1095 ± 30 ^{14}C yr (Table 3). On the other hand, the youngest age on PB06 at 20.5 cm depth is 1055 ± 30 ^{14}C yr. This age corresponds to a date of AD 1930 ± 5 yr, derived from the ^{210}Pb CFCS model ages and the ^{137}Cs chronology (average sedimentation rate of 2.65 ± 0.2 mm/yr).

Sea surface reservoir ^{14}C ages R(t) for the first modern shell (SacA 6270) on core PRO15 were calculated by subtracting the atmospheric ^{14}C value estimated for the historical date AD 1848 (113 ± 9 ^{14}C yr, Reimer et al. 2004) from the measured apparent ^{14}C ages of the mollusks (1095 ± 30 ^{14}C yr, Table 3, Figure 3). This gives a R(t) value of 982 yr. The deviance from the global mean reservoir age (ΔR) is then obtained by subtracting the marine model age value estimated for AD 1848 (485 ± 24 ^{14}C yr, Hughen et al. 2004) from the measured apparent ^{14}C age of the shell (1095 ± 30 ^{14}C yr, Table 3, Figure 3). The ΔR value is thus estimated as 610 ± 40 yr (Figure 3). By adopting a similar approach for shell (SacA 6253) on core PB06 dated to AD 1930 by ^{210}Pb and ^{137}Cs chronologies (Table 3), we obtain R(t) = 903 ^{14}C yr (ΔR = 600 yr). These 2 dated shells suggest that in Pierre Blanche Lagoon, the average reservoir age R(t) is 943 ± 25 ^{14}C yr (ΔR = 605 ± 30 yr). This high R(t) value compared to the Mediterranean Sea in the studied area (R(t) = 618 ± 30 ^{14}C yr, Siani et al. 2000) can be explained either by variable discharge of coastal rivers, after draining a watershed mostly composed of limestone, and/or by the non-permanent marine influence in relation to the lagoonal system.

Table 3 ^{14}C dates of modern pre-bomb shell samples in PBL and their reservoir ages.

Lab code	Sample	Age of shells (yr AD)	^{14}C age (BP)	Tree-ring ^{14}C age (BP) IntCal04	Reservoir age R(t) (yr)	Model age Marine04	ΔR (yr)
SacA 6270	PRO15-60	1848	1095 ± 30	113 ± 9	982	485 ± 24	610
SacA 6253	PB06-20	1930	1055 ± 30	152 ± 7	903	454 ± 23	601

Reservoir Age Correction During the Holocene

In order to apply an accurate ΔR correction for ^{14}C dating of marine shells, it is necessary to estimate past R(t) fluctuations (Goodfriend and Flessa 1997; Ingram and Southon 1997; Siani et al. 2001; Reimer and McCormac 2002; Southon et al. 2002; Fontugne et al. 2004). The same precaution has to be taken in coastal areas especially when high R(t) variability may occur.

From a sedimentological point of view, core PB06 (Figure 4) displays a relatively homogenous lagoonal deposit characterized by gray clays and silts with some sand layers (corresponding to paleostorm events). However, the high-resolution stratigraphy of fauna indicates a clear shift in mollusk population between 190 and 170 cm (Sabatier et al. 2010) with an increase of lagoonal species (*Hydrobia acuta*), whereas the number of marine species (*Bittium recticulatum*) decreases (Figure 4a). These data suggest a variation in environmental conditions (salinity, temperature, nutriments, oxygen content). This change is interpreted as the result of the final closure of the coastal lagoon by a sandy barrier due to sediment transfer along the littoral. In this area, sandy barriers build up as a result of along-shore progradation of sand spits from inherited topographic highs, by east-west coastal drift carrying sand material from the Rhône River (Raynal et al. 2009). Therefore, the fauna content clearly shows a shift from a protected lagoon (with permanent inlet) to an isolated lagoon environment at around 170-cm core depth.

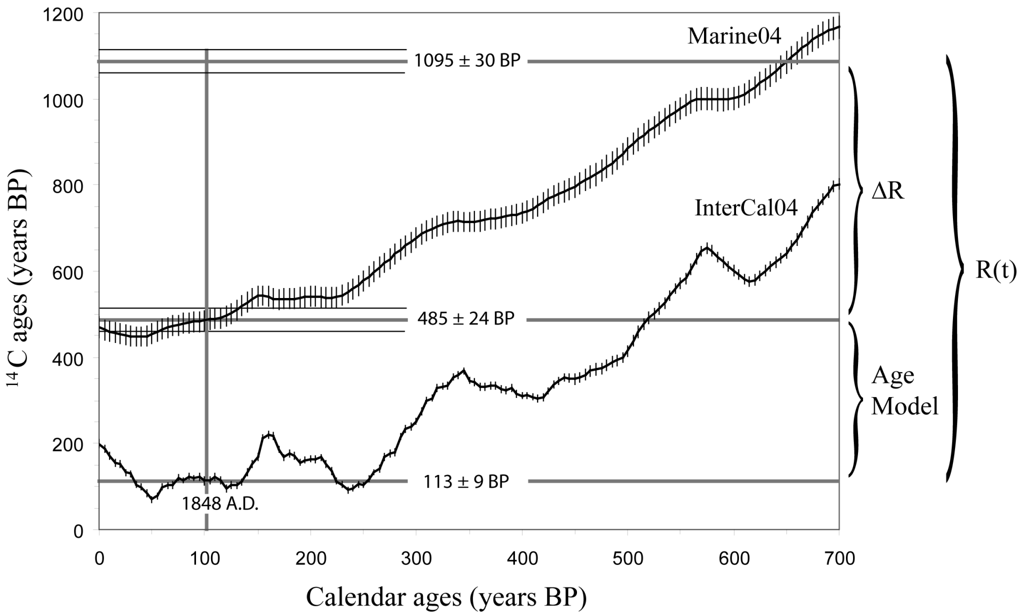

Figure 3 Conversion of ^{14}C conventional ages into calendar ages for subaerial samples equilibrated with atmosphere (lower curve) and marine samples (upper curve). The age difference between the 2 curves for a given calendar date corresponds to the marine reservoir age R(t). Dating of the AD 1848 mollusk shell SacA 6270 found in core PRO 15 gives a conventional ^{14}C age of 1095 yr and thus a reservoir age of 1095–113 = 982 yr. Deviance from the global mean reservoir age (ΔR) for this same mollusk shell is obtained by subtracting the marine model age value estimated at the historical date from the measured apparent ^{14}C age, giving 1095–485 = 610 yr.

Correction of the reservoir age, as calculated above (ΔR = 605 ± 30 yr), was first applied to the whole ^{14}C data set in core PB06 (Table 2), defined as Age model 1 (Figure 4b). The results indicated the persistence of significant ^{14}C age inversions occurring between 130 and 200 cm along the core. By taking into account the mollusk fauna record, we can assume that apparent ^{14}C age inversions could be related to a change in R(t) between the 2 lagoonal paleoenvironments (one open to the sea, the other closed). Therefore, we suggest correcting ^{14}C ages using (1) ΔR = 245 ± 30 yr due to the local marine reservoir age during a protected lagoon environment (similar to the value of 618 yr found for the Gulf of Lion by Siani et al. [2000]), and (2) ΔR = 605 ± 30 yr when isolated lagoonal conditions prevailed. Therefore, Age model 2 (Figure 4c) was calculated using ΔR = 245 ± 30 yr for 173–758 cm depth and ΔR = 605 ± 30 yr for 0–139 cm depth. The very slight ^{14}C inversion (Figure 4c) between 139 cm (i.e. 1036 ± 107 yr cal BP) and 173 cm (i.e. 948 ± 106 yr cal BP) is within the uncertainties.

The ^{14}C chronology presented in Figure 4c between 250 and 300 cm displays the same ^{14}C age (between 2500 and 2600 yr cal BP). This apparent strong increase of sedimentation rate around 270 cm is probably the result of a ^{14}C age plateau. Indeed, between 2350 and 2700 yr cal BP the calibration curve presents a ^{14}C age plateau caused by a strong increase of ^{14}C production in the atmosphere at 2750 yr cal BP (Reimer et al. 2004), known as the “Hallstatt disaster.” Another age inversion occurred at around 550 cm, between 4875 and 5275 yr cal BP, and is probably also due to the increase of ^{14}C production in the atmosphere around 5300 yr cal BP, likely a similar scenario previously observed during the “Hallstatt disaster.”

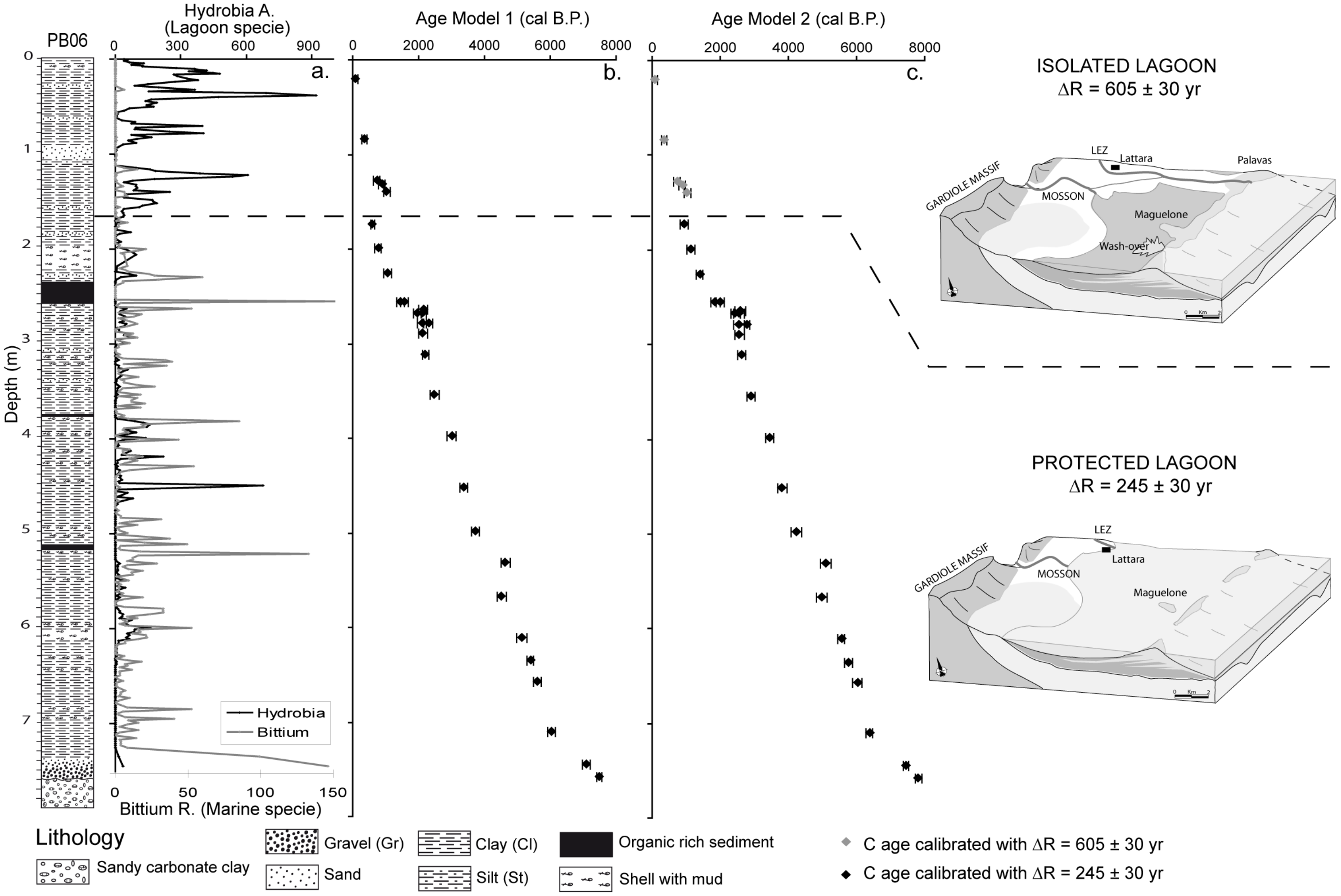

Figure 4 Age models for core PB06. Lithologic description and (a) faunal depth distribution of *Bittium recticulatum* (marine species) and *Hydrobia acuta* (lagoonal species); (b) Age model 1 obtained on lagoonal mollusk shells (Table 2) with a ΔR of 605 ± 30 yr; (c) Age model 2 calculated with a ΔR of 605 ± 30 yr for the isolated lagoonal environment (since about AD 950) and a ΔR of 245 ± 30 yr for the more open lagoonal environment (before AD 950). PLC paleoenvironmental evolution before and after the closure of the sandy barrier around 1000 yr cal BP.

In Pierre Blanche Lagoon, the final model (Age model 2) for PB06 core (Figure 4c) suggest a low sedimentation rate of 0.3 mm/yr at the base of the core. This rate increases from 1 mm/yr from 6385 to 948 ^{14}C yr to 1.5 mm/yr over the last millennium. For the modern part of the core, the accumulation rate is the same as that estimated at 2.65 mm/yr using the ^{210}Pb and ^{137}Cs chronologies.

R(t) Comparison with Other Mediterranean Lagoons

In the northern part of the Lagoon of Venice, Zoppi et al. (2001) estimated a high R(t) value of ~1200 yr by comparing benthic foraminifera and continental leaves at 1900 cal BP. This area seems to be more isolated from the sea than Pierre Blanche Lagoon, with a strong input of freshwater that explains the larger R(t) values. On the other hand, in the Thau Lagoon (Figure 1), 2 ^{14}C dates were obtained on continental seed (2935 ± 35 BP) found at an archaeological site and on a lagoonal shell (3535 ± 35 BP, *Cerastoderma glaucum*). Calculating the R(t) gives a value of about 600 ± 50 ^{14}C yr (M Court-Picon, unpublished data). Such an R(t) value is similar to that obtained by Siani et al. (2000) at Sète for the same species but for the modern period (AD 1907–1892: R(t) = 618 ± 30 ^{14}C yr). This value, smaller than the modern value in Pierre Blanche Lagoon, is probably due to a strong marine water input through the large permanent inlet. These R(t) discrepancies between different Mediterranean lagoonal environments seem to be in good agreement when the lagoons are isolated systems, resulting in an increase in R(t) when the lagoonal environment is less open to the sea and more influenced by riverine inputs.

CONCLUSION

The modern ^{14}C reservoir age in Pierre Blanche Lagoon was estimated by comparing ^{14}C ages of 2 mollusk shells with the ages of sediment layers derived from historical storm events and from ^{210}Pb and ^{137}Cs chronologies. The high value found (943 ± 25 ^{14}C yr) compared to the average marine reservoir age results from a hardwater effect caused by the discharge of coastal rivers and/or by the relative isolation of the lagoon from the sea. This interpretation is in good agreement with data reporting high R(t) values for different Mediterranean lagoons in variable isolation states (Venice, Thau). Our data further suggest that R(t) has probably changed with time, with an increase of >350 yr between the mid and late Holocene. This change most likely results from the final closure of the coastal lagoon with the growth of the sandy barrier. The age model of core PB06 indicates a low sedimentation rate of 0.3 mm/yr between 7817 and 6385 ^{14}C yr, corresponding to the last stand of postglacial sea-level rise. The sedimentation rate is then relatively constant at 1 mm/yr over a period of protected lagoonal environment (from 6385 to 948 ^{14}C yr), then increasing to 1.5 mm/yr during isolated lagoonal conditions (last millennium). This latter rate is in good agreement with the rate derived from ^{210}Pb and ^{137}Cs chronologies. This study confirms that a careful estimation of R(t) is necessary when accurate ^{14}C ages are to be derived in high-resolution studies of coastal areas. This would avoid misinterpretation of archaeological or paleoenvironmental data.

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