AN UNEXPLORED SEDIMENTARY RECORD FOR THE STUDY OF ENVIRONMENTAL CHANGE IN MEDITERRANEAN COASTAL ENVIRONMENTS: *Posidonia oceanica* (L.) DELILE PEATS

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Abstract. Information on seagrass paleo-ecology is very scarce because detailed seagrass paleo-records are virtually lacking. The endemic Mediterranean seagrass *Posidonia oceanica* conjugates two unusual features that allow the reconstruction of the past history of the plant at two different time scales. On the one hand, the study of the leaf sheaths that remain attached to the rhizomes after leaf abcision (lepidochronology), allows to differentiate up to 30 yearly cycles. On the other hand, radiocarbon dating of peat-like deposits derived from *Posidonia oceanica* rhizomes and roots (‘mattes’), reveals a chronological organic record of the plant spanning several thousands of years. Changes in the isotopic signature ($\delta^{13}C$) of the sheaths along *Posidonia* rhizomes from a meadow off Medes Islands (NW Mediterranean, Spain), were highly correlated with changes in annual leave production and with water transparency. These relationships and the isotopic analysis of sheath debris from several *Posidonia* peats along the Spanish Mediterranean coast are used to make some preliminary inferences about long-term meadow history. Several phenomena potentially difficulting the interpretation of the information contained in *Posidonia* peats are critically discussed. It is concluded that a detailed study of *P. oceanica* peats will open new vistas in Mediterranean paleo-ecological and paleo-environmental research.

1. INTRODUCTION

Our knowledge of terrestrial and aquatic freshwater angiosperm plant communities of the late-Pleistocene and the Holocene ages is considerable due to the wealth of fossil remains preserved in sedimentary deposits [1]. Paleorecords of the only angiosperms that have invaded the submarine realm, seagrasses, are virtually lacking because the appropriate preservation conditions apparently have been very rarely met and because, with a few exceptions, seagrass pollen lacks exine, the outermost coat of the pollen grain. The endemic Mediterranean seagrass *Posidonia oceanica* (L.) Delile, however, conjugates two unusual features that allow investigation of the past history of the plant at different time scales. In many seagrasses it is possible to distinguish yearly cycles through the observation of various characteristics of the sheaths (lepidochronology; [2]) and sheath scars along the rhizome [3]. Several features of the biology of *Posidonia* such as number of leaves, leaf production, plastochron, seasonality, vertical growth, or rhizome production, can be reconstructed for periods spanning up to 3 decades with a seasonal resolution. Moreover and, exceptionally, *Posidonia oceanica* belowground organs accumulate in the sediment forming organic peat-like deposits, so-called ‘mattes’, several meters in thickness. Previous studies using radio-carbon techniques have revealed that these peats, largely sheath- but also root- derived recalcitrant organic matter, constitute an unique organic record spanning several thousands of years, which stratigraphy accurately reflects its chronology of formation [4,5,6]. The *Posidonia* peats thus offer unprecedented possibilities to perform detailed studies of seagrass-dominated paleo-environments.

In this study such possibilities are explored combining lepidochronology and radio-carbon dating with the analysis of stable carbon isotopes in order to obtain clues about the physical surroundings and the growth history of *Posidonia oceanica* meadows along the spanish coast. To this end, the relationships between the number of leaves produced per year, water transparency, and the stable carbon isotope composition of *P. oceanica* have been studied at a decadal scale in recent sheath material using lepidochronology. With this information, a few preliminar inferences about changes in *Posidonia oceanica* biological and environmental features over a time-scale of thousands of years are made using radio-carbon dating and carbon isotopic analysis in *Posidonia* peats.

2. MATERIALS AND METHODS

For the short-term (decadal) approach, 12 vertically growing rhizomes of *P. oceanica* were collected in the Natural Reserve of the Medes Islands, NW-Mediterranean, Spain, over an area of ca. 250 m^2. Sheaths were counted and grouped by years using lepidochronology [2]. The rhizomes were divided in separate segments, each bearing the sheaths formed over one-year periods. In this study we have assumed that the number of sheaths produced per year (which equals the number of leaves produced) is positively related with plant aboveground annual production. The possible use of sheath biomass as a proxy for production was discarded because sheath biomass can be affected by erosion and decay processes.

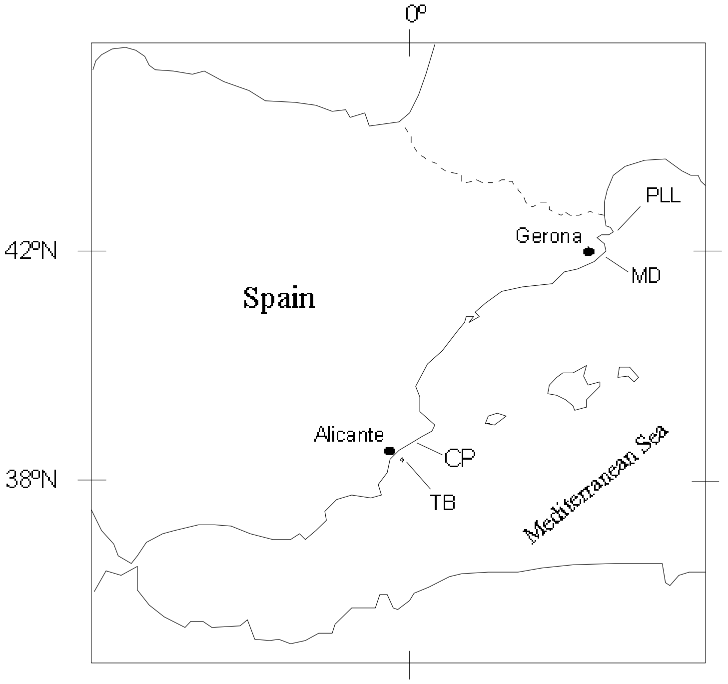

FIG. 1. Geographical location of the sampling sites. Posidonia oceanica peats were sampled at 4 locations: Port lligat (PLL), Medes Islands (MD), El Campello (CP), and Tabarca Island (TB). Additionally, Posidonia rhizomes were collected in Medes Islands.

Table I. Main features of the various *P. oceanica* peats studied

Site	Age range (years B.P.)			Thickness sampled (cm)	δ ^{13}C (‰)	SEM	*N*	Max. (‰)	Min. (‰)	Range (‰)
PLL	710	-	1600	123	-12.7	0.41	5	-11.3	-13.8	2.5
MD	1310	-	3330	200	-13.7	0.69	10	-13.2	-14.2	1.0
CP-A	670	-	1490	200	-15.5	0.77	5	-14.1	-17.4	3.3
CP-B	540	-	1340	200	-14.7	0.45	5	-13.0	-15.5	2.5
CP-C	530	-	1240	200	-14.6	0.39	5	-13.6	-15.8	2.2
TB-A	210	-	1330	170	-13.8	1.22	5	-12.4	-15.1	2.7
TB-B	210	-	1020	140	-16.1	0.28	4	-15.3	-16.6	1.3
TB-C	310	-	1060	140	-16.3	0.20	4	-15.7	-16.6	0.9

SEM: Standard error of the mean
Adapted from [6]

Table II. Average accretion rates and δ^{13}C values for the various *P. oceanica* peats studied

Site	Accretion rates (cm year^{-1})	δ^{13}C (‰)	SEM	*N*
PLL	0.088	-12.7	0.41	5
MD	0.079	-13.7	0.69	10
CP	0.203	-14.8	0.31	15
TB	0.114	-15.4	0.34	13

SEM: Standard error of the mean
Adapted from [6]

For the pluri-millenarian approach, *Posidonia oceanica* peats were sampled in 4 locations along the Spanish Mediterranean coast (Figure 1; Tables I and II). In Port Lligat, a peat core was obtained by means of a floating drilling platform that combined pneumatic percussion and rotation. A jagged drilling head was specially dessigned to adequately penetrate into the fibery peat minimizing material compaction. Only the first section (123 cm length) of the ca. 5 m core obtained, was sectioned into 1 cm slices. Five of these slices were selected for radio-carbon dating and isotopic analysis (see further). Data from the rest of the core will not be reported in this work. From each of the selected 1 cm slices, the organic fraction retained by a >1mm mesh sieve (that consisted in 100% *P. oceanica* detritus) was separated and fractionated again into sheath-, root-, and rhizome-derived material. The rest of the peats were sampled by horizontally coring naturally-cut faces of *P. oceanica* peat using a corer operated by SCUBA divers. Details on the sampling sites and sampling procedures are described elsewhere [6]. Only sheath material was selected off the samples for analytical procedures.

Root-derived organic material was discarded because downwards growth of the roots may lead to incoherences between radio-carbon age and stratigraphic position in the peat. All *P. oceanica* samples (recent and old material) were oven-dried at 70 °C until constant weight and ground to a fine powder in a glass morter prior to elemental and isotopic analysis.

2.1. Isotopic analysis

The carbon stable isotope ratios were determined by mass spectrometry (Finnigan Delta S Isotope RMS – Conflo II interface; total analytical error was 0.13 ‰). Isotopic ratios are expressed in the common notation:

$$\delta^{13}C\left({}^{o}/_{oo}\right)=\frac{R_{sa} - R_{std}}{R_{std}}\cdot 1000$$

where R is the isotopic ratio $^{13}C/^{12}C$ of the sample (*sa*) or of the standard (*std*) VPDB.

2.2. Age determination

The age of the millenary samples was established by determining the ^{14}C content of the samples using high-precision accelerator mass spectrometry (National Ocean Sciences AMS Facility, Woods Hole Oceanographic Institution). For each of the 5 samples dated, the carbon dioxide from the combustion of ca. 1 mg of powdered *P. oceanica* sheath material was reacted to graphite using a Fe/H_2 catalytic-reduction. Graphite was analyzed on the accelerator along with the NBS Oxalic Acid I (NIST-SRM-4990) standard and with a process blank sample (graphite powder, Johnson-Mathey 99.9999%). Ages are calculated using the internationally accepted modern value of $1.176 \pm 0.010 \times 10^{-12}$ [7] and a final ^{13}C-correction was made to normalize to a $\delta^{13}C_{VPDB}$ value of -25 ‰. Ages are reported as radio-carbon ages (years before present; 1950) following the convention outlined in [8, 9].

2.3. Water transparency data series

Annual mean water transparency (Secchi depth) was calculated by averaging daily measurements available for the same period in the proximity of Medes Islands (J. Pascual, unpublished data).

2.4. Numerical procedures

Relationships between the studies variables were explored using simple regression procedures [10] and time series analysis (STATISTICA Kernel release 5.5, '99 Edition, STATSOFT, Inc, OK, USA).

3. RESULTS AND DISCUSSION

3.1. Recent archives

Lepidochronological dating of the *Posidonia oceanica* vertical rhizomes allowed the identification of 14 complete years (from 1979 to 1992). The effect of light intensity on the stable carbon isotope composition of seagrasses has been repeatedly demonstrated either by field sampling along a bathymetrical gradient [11], in situ shading experiments [12], or mesocosms experiments [13, 14]. The pattern found in the mentioned experiments (i.e. lower $\delta^{13}C$ values at lower irradiances) is corroborated in the present study by the good correlation between the annual average carbon isotopic composition of the sheaths and the corresponding average Secchi depths ($\delta^{13}C = -17.40 + 0.24 \times$ Secchi; , $R = 0.78$, $P = 0.003$, $N = 14$; Fig. 2). This pattern is a consequence of a differential enzymatic discrimination against ^{13}C during photosynthesis of the individuals growing at different light intensities (lower discrimination at higher irradiances; see review by [15]. Coherently, a good correlation between $\delta^{13}C$ values and the annual leaf production of the plant was found (number of leaves = $-16.44 + 0.40 \times \delta^{13}C$, $R = 0.75$, $P = 0.002$, $N = 14$; Fig. 3).

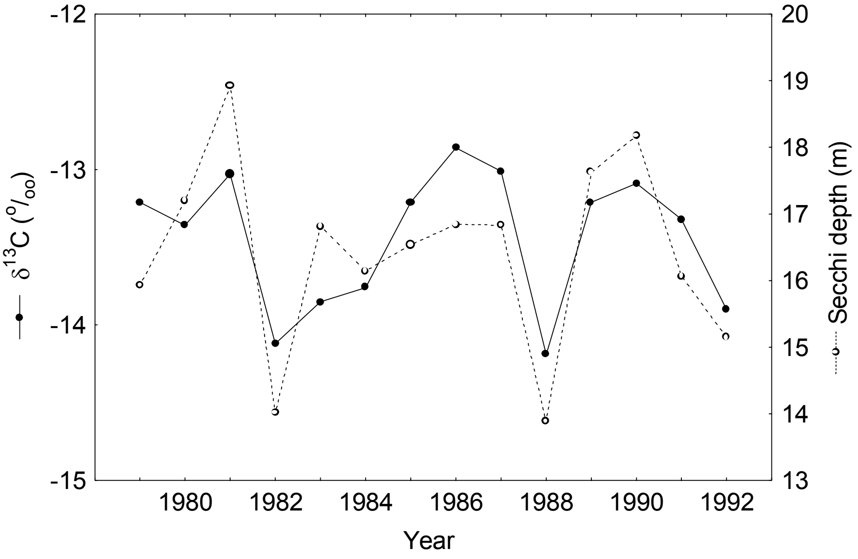

FIG. 2. Relationship between annual average water transparency (Secchi depth) and the carbon stable isotope composition of *__Posidonia__* *__oceanica__* *sheaths. Sheat age was determined using lepidochronology.*

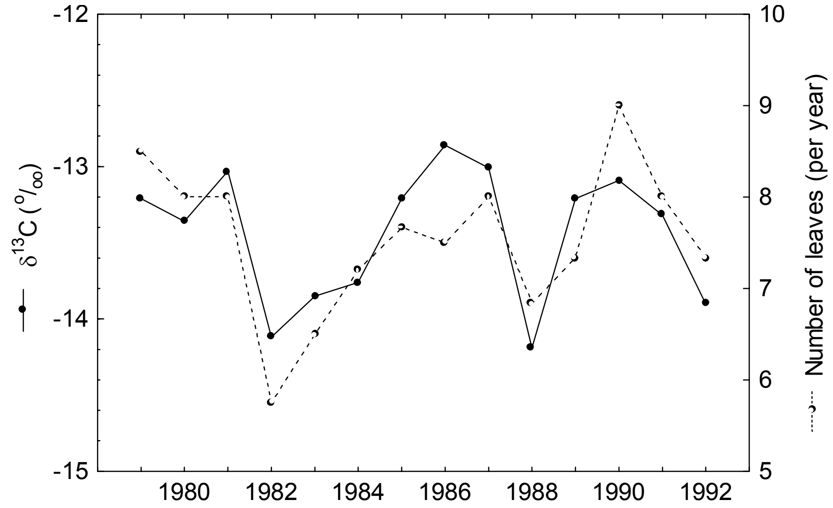

FIG. 3. Relationship between annual average leaf production (number of sheaths) and the carbon stable isotope composition of *__Posidonia__* *__oceanica__* *sheaths. Sheat age was determined using lepidochronology.*

3.2. Millenary archives

A departure point for determining the potential of *P. oceanica* for paleo-reconstruction purposes, is the assessment of the maximum period of time that can be expected to be spanned by continuous *Posidonia* peats. In this study the oldest sample was that in the base of a 2 m-thick peat wall in Medes Islands, revealing a ca. 3400 yr BP organic record (Table I).

That peat wall in Medes Islands continued 2 more meters downwards, potentially duplicating the actual age observed. Direct observations reported in early works on *Posidonia* meadows describe natural cut faces of *Posidonia* peats as thick as 6 m, probably continuing deeper down the sediment [16]. Assuming a constant accretion rate of the organic material, a 6 m-thick peat could be as old as 10 000 years. Accretion rates, however, have been found to be highly variable within the same peat wall (A, B, C, replicates where separated only 50 cm from each other) or between peat walls of different sampling sites ([6] and present work, Table II, Fig. 4). It has been suggested that the most ancient *Posidonia* continuous peats cannot be older than ca. 11 000 yr BP [17]. In that time, the last glacio-eustatic regression of the Mediterranean Sea took place, hypothetically enabling the present *Posidonia oceanica* meadows to initiate the last colonization and, therefore, the buildup of the peats.

The isotopic composition in the different peats studied showed a considerable geographical variability, the average value being -14.2 ‰ and the range 6.1 ‰, (Tab. I). Significant differences between the sites located around the parallel 42.5ºN (PLL and MD) and those around the parallel 38.5ºN (CP and TB) were found (-13.2 ‰ and -15.1 ‰, respectively; $P<0.01$). A significant latitudinal gradient has been observed in the isotopic composition of seagrasses [15]. However, the pattern observed here, i.e. higher isotopic discrimination in the sothernmost sites, is in contradiction with that latitudinal gradient and with most of studies relating latitude, irradiance, and $\delta^{13}C$ ([15] and references therein). Local variability is likely to account for this contradiction. This hypothesis is supported by the lack of correlation found accross the studied sites for peat accretion rate, suggesting that within certain geographical limits, the effects of local factors on seagrass biology can override those of environmental changes at a larger geographical scale [6].

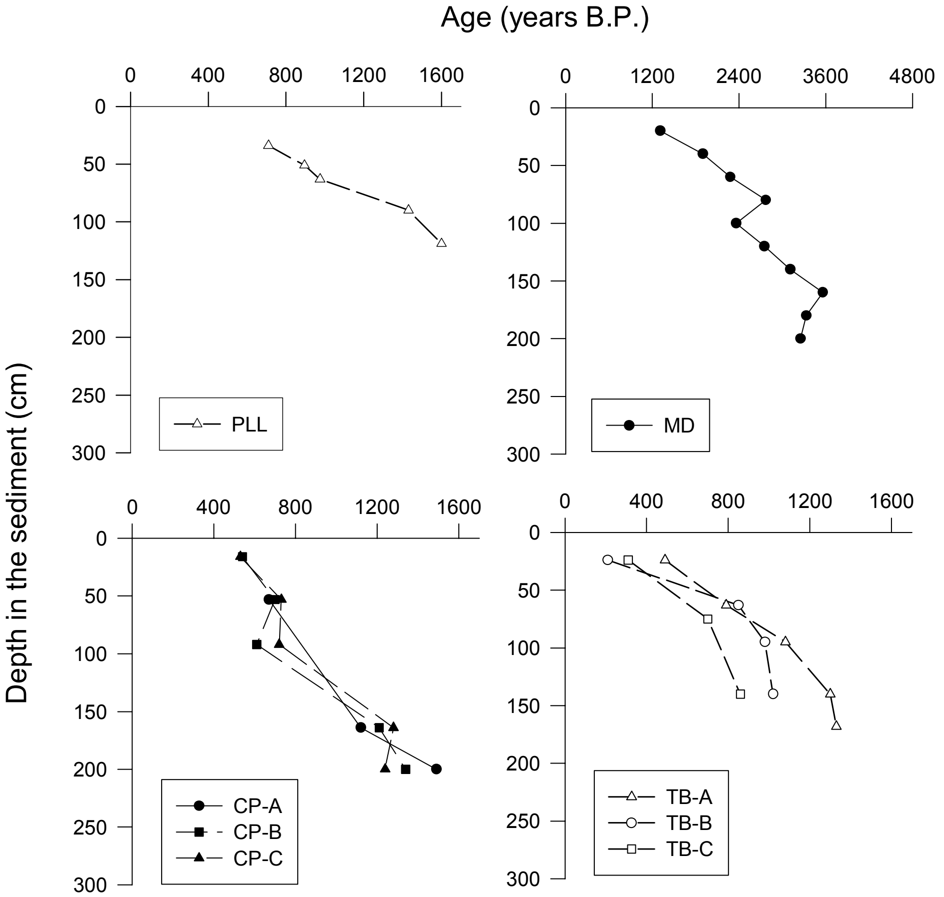

FIG. 4. Radiocarbon-age distribution along the various Posidonia oceanica peats studied. A, B, and C are replicates separated ca. 50 cm from each other. Present time is referred to 1950.

One typically local factor that is critical for seagrass growth is water transparency [18]. Taking into account the relationship found between *Posidonia* sheaths $\delta^{13}C$ and Secchi depths (Fig. 2), the present carbon isotopic compositons of the studied peats suggest that water transparency has been, in the average, higher in the northern areas than in the southern areas of the Spanish Mediterranean coast (3 or more meters clearer). *Posidonia oceanica* reacts to decreasing water transparency (and/or to incresing sedimentation) by increasing the vertical elongation rates of its rhizomes [18, 19, 20].

This results in potentially higher peat accretion rates. This fact can be one of the reasons explaining the higher peat accretion rates observed in the peats from the south (CP, TB) respect to those in the peats from the north (PLL, MD). Also, as derived from the positive relationship between sheaths carbon isotopic composition and annual leaf production, it can be hypothesized that such an effort in increasing the vertical elongation of the rhizomes, may lead to a reduction in the investment in total leaf productivity as reported elsewhere.

The robustness of the inferences made in paleo-reconstruction studies using *P. oceanica* peats, can be compromised by various phenomena. Below, we critically consider the several phenomena potentially hindering a correct interpretation of the $\delta^{13}C$ profiles along the peat wall.

3.2.1. Changes in the carbon isotope signature of the carbon source

Seagrass meadows grow in shallow coastal areas. The input of terrestrially-derived debris into the meadows can be highly variable depending on the local meteorological and hydrological characteristics (e.g. precipitation and sea current pattern). The CO_2 released during the decomposition of terrestrial organic matter is relatively depleted in ^{13}C respect to the marine autochthonous CO_2. This is due to a higher discrimination against ^{13}C during photosynthesis of most terrestrial (C_3) vegetation. It follows that terrestrial organic inputs may lead to changes in the isotopic signature of the carbon source for seagrass photosynthesis. This may be regarded as an advantage when the aim pursued is the reconstruction of the periodicity in terrestrial runoff. To discriminate between changes in this isotopic 'background level' and the changes accounted for by plant physiological processes, the isotopic signature of the dissolved inorganic carbon (DIC), needs to be known. This can be done with the aid of the carbonate parts of e.g. calcareous benthic algae, foraminifera, sponges, bryozoans, bivalves or gastropodes associated with seagrass meadows. Although isotopic disequilibrium exists during carbonate precipitation from the surrounding DIC, $\delta^{13}C$ values of organogenic carbonates serve to extract accurate information on DIC-$\delta^{13}C$ values at the time deposition took place [21].

3.2.2. Erosion and redeposition

Alterations of the accretion or depositional chronology of *Posidonia oceanica* peats by erosion and redeposition of peat layers or by changes in the sedimentary regime of the area, may result in abrupt or incoherent changes in sample ages and isotopic values, hampering reconstruction tasks.

3.2.3. Diagenetic effects

To which extent the carbon isotopic signature of *P. oceanica* tissues remains constant long after plant death, is another major question to be addressed. Diagenetic processes possibily may produce changes in detrital $^{13}C/^{12}C$ ratios. During the early stages of the decomposition process, the relative proportion of the various carbon compounds of the plant debris changes due to differences in decomposition susceptibility. In *spartina alterniflora* a slight $\delta^{13}C$ decrease in bulk plant material has been observed as a consequence of the preferential loss of isotopically heavier polysaccharides remaining the relatively ^{13}C-depleted lignin-derived carbon [22, 23]. In the case of decomposing seagrass detritus, however, no significant changes were observed [24]. Studies on long-term diagenetic effects conclude that in typical marine sediments, a diagenetic ^{13}C-depletion in organic matter up to 2.8 ‰ may take place [25, 26]. Other workers, however, consider that diagenesis effect on $\delta^{13}C$ values of organic matter below the bioturbation zone may be negligible [27, 28]. In general, none of the works cited above have observed any systematic difference between the isotopic composition of the sedimentary organic matter and its natural precursor (phytoplankton). Moreover, a diagenetic effect would be expected to result in an gradual change of the isotopic signature, and, so far, this has not been observed neither in those works or in the present one. A possible solution to overcome potential problems derived from diagenetic effects, could be the use of seagrass-specific recalcitrant compounds for isotopic analyses (e.g. seagrass sheaths lignin; [29, 30]). This will minimize early diagenetic effects and avoid 'isotopic noise' from non-seagrass material (e.g. micro-decomposers associated with seagrass detritus).

3.2.4. Paleo-meadow depth

The depth limit for seagrass distribution strongly depends on the light arriving to the canopy. *Posidonia oceanica* meadows extend from nearly the water surface to depths of 35-40 meters, where the photosynthetic compensation point is attained. As discussed before, the most obvious cause of changes in light availability (at least in the Medes Islands) is the change in the turbidity of the water surrounding the meadow. Such changes would result in cyclic or random changes in plant productivity.

Changes in paleo-meadow relative depth due to eustatic sea level changes, however, would lead to recognizable trends in light availability, as a consequence of changes in the length of the water column acting on light extinction. Several phenomena may account for long-term changes in meadow depth, mainly: (1) organic accretion, (2) compaction, (3) subsidence, and (4) sea-level changes. (1) The growth of *P. oceanica* results in the elevation of the meadow bottom as the organic material derived from rhizomes and roots accumulates together with sediment. The elevation rate has been estimated to be around 0.1 cm yr^{-1} (0.061-0.414 cm yr^{-1}; [4, 5, 6, 31]). This estimate is substantially lower than very early ones suggesting a rate of 1 meter per century [16]. The latter estimate may be closer to the potential elevation rate of the peat, as it does not consider long-term perturbations affecting meadow growth or survival. (2) The compaction of the peat, as expected from all sedimentary formations, may be enhanced by decay of the organic matter in the peat. It has been shown that the organic material of the peats undergoes a very slowly decay process (decay rate from 0.00008 to 0.00036 yr^{-1}; [6]). In time, the lower layers may gradually collapse as a consequence of the weakening of the structure and of the weight of the overlying layers, concurring with typical compaction. Such a process has been described for peats [32]. Although in the seagrass peat the proportion of sediment is much higher, a certain degree of compaction can be expected. This would be evidenced by a negative exponential relationship between strata age and relative position within the peat. Such a relationship is not found, however, in the various peats studied. The high proportion of sediment forming the matrix of the peat, the hard nature of the organic material and the low susceptibility to be affected by gravity forces, will probably keep compaction in *Posidonia oceanica* peats at an almost negligible level. (3) Subsidence is a relatively local phenomenom resulting from the interplay of a complex set of geological processes. A local geological study would be required to assess the magnitude of these processes in the study site. (4) Since the end of the last glacioeustatic sea level rise (ca. 5000 yr BP), the level of the Mediterranean Sea seems to have experienced only very small fluctuations, in the order of a few centimeters [33, 34]. Depth gradients of 40 m have been shown to be needed to result in a ca. 5 ‰ change in the seagrass isotopic signature [11]. So the relative depth changes associated to sea level fluctuations are not likely to have been be a potential source of changes in production or in $\delta^{13}C$ values for the tiem period considered.

3.2.5. Sampling procedures

Using the corer diameter (15 cm) and the accretion rates estimated for the sampled peats (0.079-0.414 cm yr-1; [6]), it can be roughly calculated that every sample was pooling the material of ca. 35-190 years. The result is the smoothing of changes in the isotopic signal preventing the identification of phenomena occurring with a frequency higher than 35-190 years. That was the case for the present peats estudied except for the case of PLL, where a drilling platform was used.

4. CONCLUDING REMARKS

In conclusion, as is true for other palaeo-reconstruction studies based on the analyses of chronologically-deposited materials, the interpretation of the information recorded in *Posidonia oceanica* peats must be tackled with caution. *Posidonia oceanica* peats, however, have a clear advantage to pure sediment cores. Bioturbation, erosion and re-deposition phenomena, are unlikely to have serious effect on the chronology of the strata due to the firm nature of these peats. In addition, its abundant presence along the Mediterranean sea offers the possibility of making comprehensive and comparative studies on Mediterranean coastal environments. Much longer *Posidonia oceanica* organic records may be obtained by means of vertical deep vibro-coring as has been done for mangrove millenary deposits [35]. The detailed analysis of the *Posidonia* cores may provide the necessary chronological resolution to study local and global changes in key environmental and biological variables during the Holocene. Moreover, it will give the unprecedented opportunity to assess the persistence of seagrass-dominated communities during several thousands of years. We conclude that the combined analyses of various isotopic signatures of the plant material (e.g. $\delta^{13}C$, $\delta^{18}O$ and $\delta^{15}N$) and associated fossil fauna (e.g. foraminiferans, ostracods, and molluscs) in *Posidonia oceanica* peats, will open new vistas in Mediterranean paleo-ecological and paleo-environmental research.

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