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Modern and late Holocene foraminiferal record of restricted environmental conditions in the Albufeira Lagoon, SW Portugal

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┤ **A B S T R A C T** ├

Benthic foraminifera from twenty stations sampled twice were analyzed in order to examine the environmental conditions of the Albufeira coastal lagoon. Foraminiferal assemblages show an increase in the abundance, species diversity and allochthonous content seaward. Three zones have been defined: the inner and more restricted area of the lagoon where the main species are the euryhaline *Ammonia tepida* and *Haynesina germanica*; these two species together with *Bulimina gibba* and *Brizalina britannica* dominated the middle area; and, finally, in the mouth and marine- influenced back-barrier area the assemblages are made up of brackish and marine species such as *A. tepida*, *Cribroelphidium williamsoni*, *Cibicides lobatulus* and *H. germanica*. Additionally, samples from three cores were also examined. Sedimentological and micropalaeontological contents represent the last 2500 years of environmental evolution of the lagoon. Foraminiferal assemblages are not very abundant and they are dominated by *H. germanica*, *A. tepida* and *Jadammina macrescens* indicating very restricted conditions through time. In a regional context, and during the Late Holocene, after the development of a detrital barrier *circa* 5.5 cal yr BP, eustasy is considered to be a minor environmental control of the barrier-lagoonal system dynamics. Instead, environmental conditions were forced by local factors, such as frequency and duration of lagoon-ocean water exchanges, induced by both natural and artificial changes in the permeability of the sand-barrier.

KEYWORDS │ Benthic foraminifera. Coastal lagoon. Late Holocene. Environmental evolution. SW Portugal.

INTRODUCTION

Coastal lagoons are part of the marginal marine environments that form the boundary between the land and the sea. Because of postglacial sea-level rise during the Holocene, lagoonal environments are geologically very young. These ecosystems are sensitive to changes (*e.g.*, of sea level, salinity, freshwater runoff, pollution). Due to their accessibility and the low cost of research, these marginal environments (lagoons, estuaries, fjords and deltas) have been investigated more than any other environment (Murray, 2006). Wave-dominated coasts lying obliquely to the crest of the incident waves develop coastal barriers comprising coastal dune, beach and shoreface that are linked by sediment transport feedback and that may separate sheltered lagoons from the open sea.

In general, species diversity is low in these extreme environments but ranges a little higher in normal

marine lagoons. In terms of wall structure, brackish environments have foraminiferal assemblages with a mixture of agglutinated and calcareous hyaline walls. Local species distributions are determined by numerous abiotic and biotic controls and in those studies where authors have used multivariate and statistical measures to determine the relationships between abiotic variables and foraminiferal species there is always a great co-variance and interdependence between variables. Consequently, it is difficult to know exactly which controls are more important (Murray, 2006). By comparison with tidal areas where changes in environmental parameters are continuous, non-tidal environments have a much more stable temperature and salinity structure on timescales ranging from days to weeks. Typical abundance values are generally comprised between 50 to a few hundred individuals per 10cm^{-3}. Although the general controls limiting marginal marine foraminiferal assemblages have been established, there is still much to be investigated about the operation of factors at a local level that can be obtained by field studies targeting specific themes (Murray, 2006).

This study addresses sedimentary materials deposited during the last 2500 years in the Albufeira lagoonal space (SW Portugal). The main objectives are: i) to characterize the modern and past environmental conditions by analyzing the foraminiferal assemblages in surface and buried samples; ii) to evaluate the impact of anthropogenic intervention in the barrier during recent centuries; and iii) to contribute to the interpretation of the Late Holocene evolution of the western Portuguese coast.

Study area

The Albufeira lagoon is located 20km south of Lisbon, in an arcuate high-mesotidal littoral segment, and occupies the terminal area of the Ribeira da Apostiça valley (Fig. 1). This stretch of coast is dominated by a long-period west-northwestern swell and occasionally disturbed by short-lived but violent western or southwestern storms.

The Albufeira lagoon usually presents a flooded surface of 1.3km^2 and a maximum depth, width and length of 15m, 625m and 3.5km, respectively. It has an elongated shape, with its major axis trending northeast-southwest, oblique to the shoreline trend. The lagoon is sheltered from the ocean by a narrow, linear and reflective welded sand barrier. The barrier is 1.2km long and its width is quite variable, averaging 300m. It displays a simple cross-section, composed of a steep beach face with multiple berms. The overwash surface of the higher berm slopes into the lagoon and gradually merges into washovers or relict tidal delta fragments. These deposits overlap, coalesce and interpenetrate to build a shallow sandy platform that occupies the most external rim of the lagoonal body

and extends into deeper waters as a Gilbert-type delta (Friedman and Sanders, 1978), with a submarine slope where sand avalanches during open-inlet periods (Freitas and Andrade, 1994).

The lagoonal body of Albufeira is made up of two basins separated by a narrow and shallow channel. The main body (Lagoa Grande) has an average depth of about 10m, although it may reach 20m due to abundant winter rain. In contrast, the smaller body (Lagoa Pequena) averages 2m in depth (Fig. 1).

Prior to human occupation, the lagoon was an almost permanently closed structure. Only during storm events sporadic and short-lived episodes of barrier breaching and water exchange with the ocean occurred. These events also allowed fresh water accumulated during the rainy season to drain into the sea. However, the occupation of the alluvial plains in the main tributaries for agriculture, the presence of mussel aquaculture and the discharge of urban effluents into the lagoonal space created a permanent need to control the water level and quality, and this need compelled the more frequent artificial breaching of the barrier. The process of artificial barrier breaching is well documented in historical records since the 15th century (Freitas and Andrade, 1994) and at present is done on an annual basis. Once a year, during springtime, a tidal inlet is artificially opened and left free to reach a natural equilibrium. It
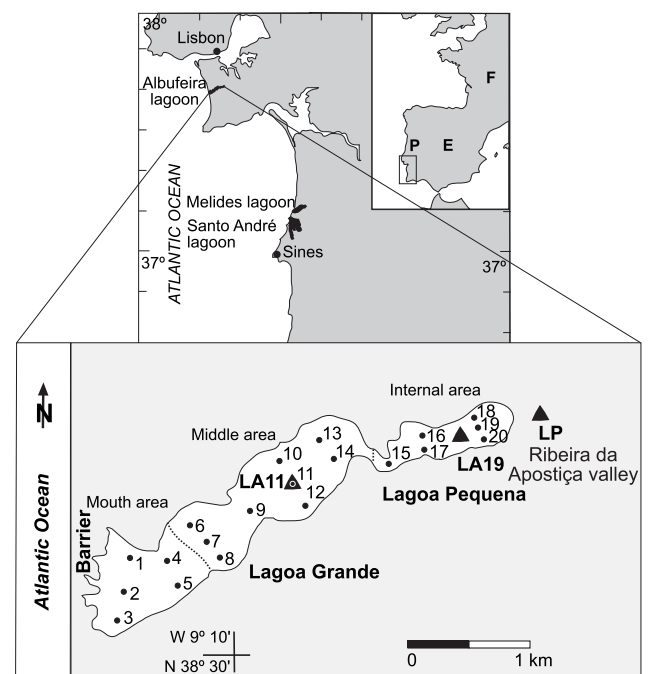
FIGURE 1 | Geographical location of the Albufeira lagoon in SW Portugal, showing the position of surface samples (black dots).

gradually silts up until complete closure that occurs in a period that varies from a fortnight to several months. The morphodynamic changes experienced by the inlet during its lifespan were described by Freitas and Andrade (1994).

The physical-chemical characteristics of the lagoonal water vary with time and are essentially controlled by the exchanges between the lagoon and the sea, and by the amount of fresh water brought into this paralic system by rivers (Freitas *et al.*, 1994). When the inlet is closed, the water body displays stratification, salinity increases with depth and the *hipolimnion* is frequently anoxic. Under open-inlet conditions, the water mass becomes more homogeneous in terms of salinity (similar to marine water) but contrasting levels of dissolved oxygen may persist throughout the water column.

MATERIALS AND METHODS

Twenty surface sediment samples were collected seasonally for micropalaeontological analysis from the lagoon bottom (Fig. 1) in February and June 2003. All samples were collected under closed-inlet conditions. The inlet was artificially opened on 21-22 April 2003 and naturally closed just a few days later. Sediment was collected using a plastic cylindrical, 30mm-diameter sampler (February) or a Van Veen dredge (June), both operated from a boat. Once aboard, 10-15cm³ subsamples from the surface sediment layer (0-1cm) were retrieved and stored. These were wet sieved through 1mm and 63 m sieves to remove large organic fragments and silt and clay, respectively. Samples collected in June were kept in ethanol and their contents were added to an equal volume of rose Bengal and left for one hour following Walton's (1952) method. Rose Bengal stains protoplasm bright red and therefore stained forms, presumed to be alive at the time of collection, could be easily differentiated from unstained empty tests (dead individuals). Samples collected in February were not intended for microfaunal purposes and, consequently, were not preserved in ethanol, so foraminiferal assemblages are total (living plus dead together). Stained samples were sieved and washed again to remove the excess stain and then dried at 50ºC. Foraminifera were concentrated by flotation in trichlorethylene as described by Murray (1979).

Core LP was taken in November 1998 from the eastern shore of Lagoa Pequena (38° 31' 23.96'' N, 9° 8' 40.66'' W), in a distal location relative to the tidal inlet (Fig. 1), using a steel gauge auger and a Dachnowski sampler, to a depth of 7.60m below ground surface. The coring site is located at +3.33m (above mean sea level – MSL). The foraminiferal contents of 46 samples taken at 15cm intervals were studied and 4 samples were dated by standard and AMS ^{14}C

radiometric determination (Bao *et al.*, 1999). Cores LA19 and LA11 were collected in April 2003 from the Lagoa Pequena (38° 31' 19.14'' N, 9° 8' 51.63'' W) at a depth of -1.6m (MSL) and Lagoa Grande (38° 31' 10.47'' N, 9° 9' 43.12'' W) at a depth of -8.9m (MSL) respectively (Fig. 1). A gravity corer was released from a boat and sedimentary columns 0.70m and 0.64m long, respectively, were obtained. In the laboratory each core was cut lengthwise and the halves obtained were then subsampled for sedimentological and micropalaeontological analyses. Sixty-nine samples taken at 1cm intervals (LA19) and 32 samples taken at 2cm intervals (LA11) were collected for foraminiferal study. Each sample consisting of 10cm³ of sediment was wet sieved and washed in the same way as the surface samples (except that they were not stained). When possible, tests were picked until a representative amount of more than 300 individuals per sample was obtained. Otherwise, all the available tests were picked and studied under a stereoscopic binocular microscope using reflected light.

Altogether, more than 9500 foraminifera were examined from surface sediments and almost 10300 tests were analyzed from core samples. All foraminiferal species identified in the samples are listed in Appendix I, and the main species recorded in the material are illustrated in Figure I, available at www.geologica-acta.com. Those species found living today in this and other lagoonal environments of south-western Portugal (Cearreta *et al.*, 2002, 2007) were regarded as autochthonous and those found only as dead tests were considered to be allochthonous forms transported into the lagoon from the adjacent high energy shelf.

In all field campaigns physical-chemical parameters of the water column (salinity, temperature and dissolved oxygen) have been measured along vertical profiles in all stations.

^{210}Pb and ^{137}Cs determinations have also been carried out in core LA19 at the University of Bordeaux 1 to provide a recent chronology. In addition, measurements of the sediment pH along cores LA19 and LA11 were also undertaken by an electrometric method and all sediment samples were processed for grain size using a combination of sieving and a Laser particle analyser.

RESULTS

Surface (modern) samples

The results obtained allowed the definition of three different zones in the Albufeira lagoon: mouth, middle and internal areas, progressively more isolated from the open ocean (Fig. 1). In general, the abundance of foraminifera and open-marine species content are higher

TABLE 1 | Summary of modern environment and microfaunal data. The single value represents the average and those in parentheses give the range

February 2003 (total assemblage)		
Mouth area	Middle area	Internal area
Samples: 1-5	Samples: 6-14	Samples: 15-20
Surface: 0.38km^2	Surface: 0.68km^2	Surface: 0.21km^2
Sediment: sand and sandy mud	Sediment: mud and sandy mud	Sediment: mud and muddy sand
425 (86-937) foram/10cm^3	255 (86-782) foram/10cm^3	208 (86-682) foram/10cm^3
29 (21-35) species	15 (7-25) species	8 (5-12) species
48 (21-63) % allochthonous	30 (0-49) % allochthonous	1 (0-3) % allochthonous
A. tepida 20 (11-45) %	*H. germanica* 28 (5-83) %	*A. tepida* 57 (39-69) %
C. williamsoni 14 (2-36) %	*A. tepida* 20 (11-47) %	*H. germanica* 28 (22-34) %
C. lobatulus 13 (3-28) %	*B. gibba* 13 (3-42) %	*Q. seminula* 7 (2-10) %
G. praegeri 8 (4-11) %	*B. britannica* 10 (0-25) %	
B. britannica 5 (0-12) %	*E. scaber* 5 (0-30) %	
H. germanica 5 (2-8) %		
June 2003 (living assemblage)		
44 (7-100) foram/10cm^3	7 (0-19) foram/10cm^3	11 (1-27) foram/10cm^3
3 (3-4) species	3 (1-6) species	2 (1-2) species
A. tepida		
June 2003 (dead assemblage)		
1186 (291-2363) foram/10cm^3	151 (18-474) foram/10cm^3	479 (7-1652) foram/10cm^3
20 (10-31) species	16 (8-28) species	8 (3-10) species
31 (5-55) % allochthonous	32 (0-57) % allochthonous	3 (1-6) % allochthonous
C. williamsoni 27 (4-28) %	*A. tepida* 22 (10-53) %	*A. tepida* 42 (37-52) %
A. tepida 22 (14-44) %	*H. germanica* 21 (5-63) %	*H. germanica* 27 (12-54) %
H. germanica 10 (6-19) %	*B. gibba* 14 (0-34) %	*Q. seminula* 24 (1-38) %
C. lobatulus 9 (2-16) %	*B. britannica* 11 (9-25) %	
B. britannica 5 (1-13) %	*C. lobatulus* 8 (0-18) %	Total/Dead similarity
	E. scaber 5 (0-20) %	sample 15: 79 %
Total/Dead similarity		sample 16: 83 %
sample 1: 66 %		sample 17: 74 %
sample 2: 68 %	Total/Dead similarity	sample 18: 70 %
sample 3: 40 %	sample 6: 43 %	sample 19: 66 %
sample 4: 77 %	sample 7: 79 %	sample 20: 62 %
sample 5: 82 %	sample 8: 78 %	average internal area: 72 %
average mouth area: 67 %	sample 9: 70 %	
	sample 10: 61 %	
	sample 11: 65 %	
	sample 12: 30 %	
	sample 13: 81 %	
	sample 14: 68 %	
	average middle area: 64 %	

in the mouth area than in the middle and internal areas. Total assemblages of the February samples show that in the internal area the abundance is moderate and the species richness shows the minimum values. The assemblage is dominated by *Ammonia tepida* and *Haynesina germanica* with minor *Quinqueloculina seminula* (Table 1; Fig. 2). The middle area is characterized by a similar test abundance and higher species richness. Here, the main species are *H. germanica* and *A. tepida* together with marine and restricted species such as *Bulimmina gibba*, *Brizalina britannica* and *Eggerelloides scaber*. Allochthonous foraminifera represent one third of the assemblage. Finally, the mouth area exhibits the highest abundance and species richness. The allochthonous content reaches almost half

of the assemblage and the main species are *A. tepida*, *Cribroelphidium williamsoni* and *Cibicides lobatulus* with *Gavelinopsis praegeri*, *B. britannica* and *H. germanica* as secondary species.

In the June samples, living assemblages show an extremely low abundance and only sample 1 contained enough foraminifera for statistical studies. In this case the assemblage is almost exclusively composed of *A. tepida*. Other species present in the lagoon as living individuals are *H. germanica*, *C. williamsoni*, *B. britannica* and *B. gibba* (Table 1, Fig. 3). On the other hand, dead assemblages are more abundant and, in general, exhibit an increase in species richness and
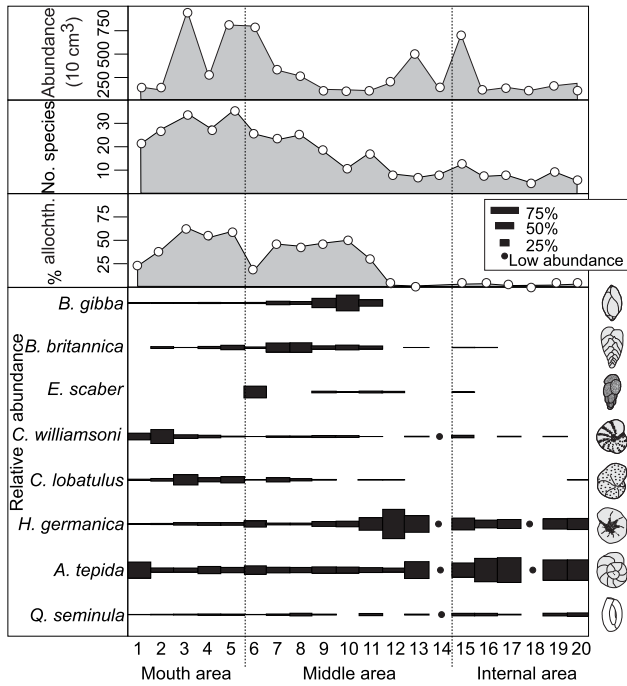
FIGURE 2 | Absolute abundance of foraminiferal tests (10cm³), number of species, allochthonous content and distribution and relative abundance of the main foraminiferal species in the February samples of the Albufeira lagoon (total assemblage).
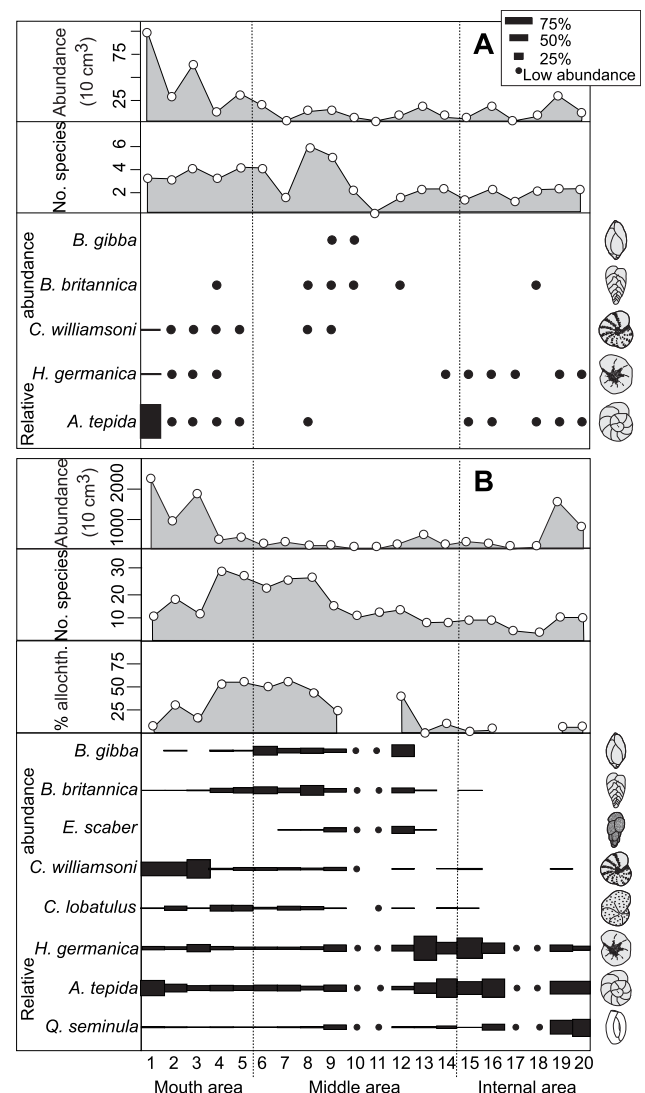
allochthonous content mouthward. The assemblages of the lagoonal inner area have moderate abundance and low species diversity with dominant *A. tepida*, *H. germanica* and *Q. seminula*. The middle area is characterized by the lowest abundance values but the species richness increases. The foraminiferal assemblage is made up of a mixture of marine and restricted species such as *A. tepida*, *H. germanica*, *B. gibba* and *B. britannica* with *C. lobatulus* and *E. scaber* as minor species. The allochthonous, open-marine species, reach here their maximum presence. Finally, the foraminiferal assemblage in the mouth area shows the highest abundance and species richness with an allochthonous content similar to the previous area (average 31%). *Cribroelphidium williamsoni*, *A. tepida*, *H. germanica* and *C. lobatulus* are the main species.

Comparison of the June dead assemblages with the total assemblages found in February for the same sampling location on a species by species basis, using the similarity index defined by Rogers (1976), indicates a very high degree of similarity due to the presence of very scarce living assemblages in the Albufeira lagoon that make total and dead foraminiferal assemblages highly similar (Table 1). In fact, only samples 3, 6 and 12 show <61% similarity whereas all the others are on average 72% similar.

Core (Late Holocene) samples

Core LP shows a very low content of foraminifera. Only 4 samples located in the top core section yielded enough foraminifera for statistical studies. Based on foraminiferal presence, abundance and species richness, together with sedimentological criteria, the core has been divided into four different zones and two subzones (Fig. 4).

Foraminiferal Zone 1 consists of organic mud and is barren of foraminifera. Foraminiferal Zone 2 is a very narrow interval of mud associated to a bioclastic sandy lens which contains a very low-abundance (average 30 tests/10cm³) and species-rich (average 2 species/sample) foraminiferal assemblage. The few tests present belong to
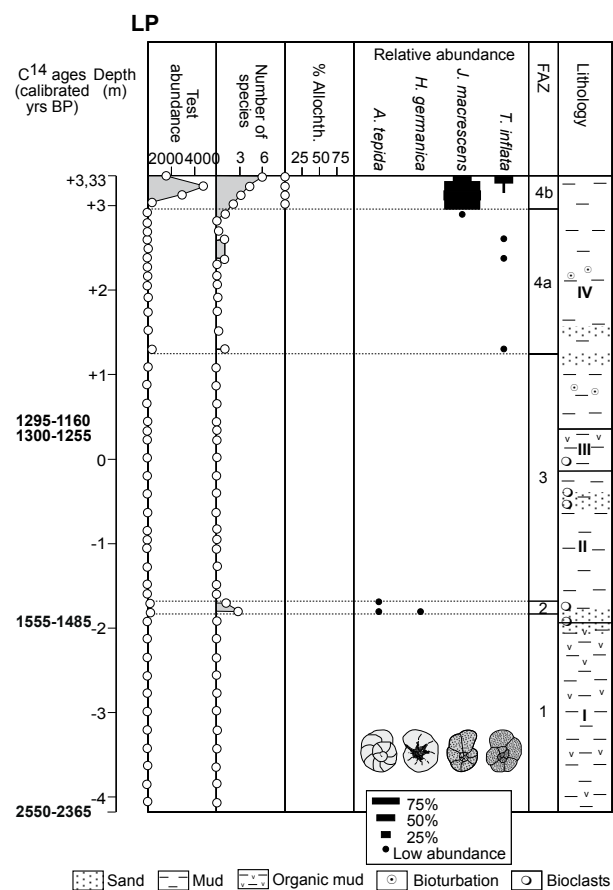

FIGURE 3 | Absolute abundance of foraminiferal tests (10cm³), number of species, allochthonous content and distribution and relative abundance of the main foraminiferal species in the June samples of the Albufeira lagoon (A: living assemblage; B: dead assemblage).

the euryhaline, calcareous species *A. tepida*, *H. germanica* and *Cribroelphidium oceanensis*. Foraminiferal Zone 3 consists of sandy mud barren of foraminifera. Finally, Foraminiferal Zone 4 consists of 2.5m of mud that can be subdivided, based on its microfossil abundance, into two different subzones. Subzone 4a represents the lowermost 2.1m and is characterized by a very scarce content in agglutinated foraminifera (average 1 tests/10cm^3). Subzone 4b comprises the overlying 0.4m and contains a very abundant (average 2322 tests/10cm^3) but a low species richness (average 4 species/sample) assemblage, which is highly dominated by the agglutinated *Jadammina macrescens* (average 84%) and *Trochammina inflata* (average 12%).

On the other hand, Core LA19 exhibits a moderately abundant foraminiferal assemblage. The core is very homogenous sedimentologically and it consists of mud with very low sand content. The measurements of ^{210}Pb and ^{137}Cs (first published in Freitas *et al.*, 2010) yielded a sedimentation rate ranging between 0.48 and 0.59cm/yr

for the Lagoa Pequena, this core representing the sediment accumulation since the first half of the 19th century. Only one foraminiferal assemblage has been found throughout the core and this has been subdivided into 5 subzones (a-e) based on test abundance, separating microfossil-rich and poor intervals (Fig. 5). The main species along the sequence are the euryhaline *H. germanica* (average 54%) and *A. tepida* (average 40%). Other secondary species are *Q. seminula* and *C. oceanensis*. Although some sediment samples show both low pH values and low abundance of foraminifera, in general vertical variation in pH throughout the core does not correspond to a similar variation in test abundance of calcareous-foraminifera, suggesting that the scarce number of foraminifera in certain subzones is not directly related to *post-mortem* dissolution of tests, but is probably due to *in-situ* low production and transport of tests from other lagoonal areas related to the artificial breaching of the detrital barrier.

Finally, Core LA11 shows a very low content of foraminifera (Fig. 6). Only 3 samples along the core yielded enough foraminifera for statistical study. These samples exhibit a low abundance (average 1 tests/10cm^3) and low-medium species richness (average 7 species/sample). The more important species are the euryhaline *H. germanica* (average 50%) and *A. tepida* (average 40%). Less important forms are *C. williamsoni*, *E. scaber* and *B. gibba*. The characteristics of low abundance and low-medium species richness in foraminifera found along core LA11 are shared with the surface sample collected at the coring location (site 11) (Figs. 2, 3).

DISCUSSION

In general, foraminiferal assemblages from the Albufeira lagoon show an increase in species diversity and content in allochthonous forms towards the mouth area, although *A. tepida* is the dominant species in all areas. The sediments also show a pronounced longitudinal gradient in texture: in the mouth area the sand content reaches 99% and it decreases inwards with increasing depth and lower tidal influence (Freitas and Andrade, 1994). Abundance of the living assemblages was extremely small, so the total and dead assemblages have been used to define the modern conditions in the lagoon (Fig. 7). In the inner area, the foraminiferal assemblage exhibits a moderate abundance and low species diversity with *A. tepida*, *H. germanica* and *Q. seminula* as the main species, suggesting a restricted and brackish environment, hardly reached by marine waters from the open sea. In the central area, the abundance shows similar values, but the species diversity increases. *Ammonia tepida* and *H. germanica* are the dominant species together with *B. gibba*, *B. britannica* and *E. scaber*. *Bulimina* and *Brizalina* are small and fragile

FIGURE 4 | Absolute abundance of foraminiferal tests (10cm^3), number of species, allochthonous content, distribution and relative abundance of the main foraminiferal species, foraminiferal assemblages (FAZ) and lithological units in the Core LP. The calibrated radiocarbon dates are also indicated.

forms that characterize deep, muddy and low-oxygenated coastal environments worldwide. Their elongated test is considered an adaptation to hypoxia (Sen Gupta and Machain-Castillo, 1993; Martins and Gomes, 2004). The maximum depth in this area exceeds 15m and the average dissolved oxygen content is 0.44mg/l (range 0.3-0.6mg/l) (Silva, 2003). Finally, in the mouth area both the test abundance and species diversity reach the maximum values, probably due to the transport promoted by wave and tidal-driven currents that introduce allochthonous species from the shelf into the lagoon and rapidly lose transport potential away from the inlet's constricted area. Consequently, marine-allochthonous species (such as *C. lobatulus* and *G. praegeri*) reach on average 48% of the assemblage, although indigenous *A. tepida*, *C. williamsoni* and *H. germanica* are still the main species. The absolute abundance in the June samples (average 508 test/10cm³) is higher than in the previous February samples (average 283 test/10cm³) and we interpret this contrast as due to the breaching of the barrier between these two dates.

Cearreta *et al.* (2002, 2007) studied the modern foraminiferal assemblages and their seasonal changes in bottom sediments from other lagoonal environments of the SW Portuguese coast (Melides and Santo André) (Fig. 1). Extremely low abundance and species diversity of foraminifera are characteristic of living assemblages in the Melides lagoon. The euryhaline *H. germanica* and *A. tepida* are practically the only species present in the area. Due to artificial breaching of the inlet, foraminiferal dead tests are more abundant and diverse, particularly in the middle area of that lagoon. However, dead assemblages are also highly dominated by these two species (average 95%) suggesting a persistent, restricted paralic environment (Cearreta *et al.*, 2007). At the Santo André lagoon, a high abundance of individuals has been found after the (annual) artificial breaching of the sand barrier, whereas low abundance of foraminifera is characteristic of closed-inlet conditions. Assemblages are permanently dominated by euryhaline *A. tepida*, *H. germanica* and *C. oceanensis*, plus *Q. seminula* following the entrance of open ocean water into the lagoon. Rapid and intense environmental changes that range from low-salinity and low-oxygen near-bottom water under closed-inlet conditions to brackish and well-oxygenated under open-inlet conditions seem to be responsible for foraminiferal assemblages characterized by extremely low species diversity, high species dominances, seasonal variable abundances and common deformed tests.

Numerous studies on the European Atlantic coast have shown that certain species of benthic foraminifera characterize particular environments (*cf.*, Murray, 2006, for a summary). Some authors use the living assemblage for environmental interpretations and consider the total assemblages as a less adequate proxy (Jorissen

et al., 1995; Alve and Murray, 2001). On the contrary, others consider the total association (living plus dead assemblage) as representing a more complete picture of the original biocoenoses, thus preserving more of the palaeoenvironmental constraints (de Rijk and Troelstra, 1997; Serandrei-Barbero *et al.*, 1999; Patterson *et al.*, 2000). Moreover, in the lagoonal environments under low energy conditions, such as the Albufeira lagoon, the post-mortem transport of foraminiferal test is presumed to be negligible (Cearreta *et al.*, 2002).

The foraminiferal microfaunas of the Atlantic seaboards of Europe and North America are remarkably similar although this is not always immediately obvious because of different usage of species names. However, several species have not been recorded from lagoons in one or other area (*e.g.*, *E. scaber* has not been recorded from the Atlantic seaboard of North America) or *Cribroelphidium* species are variable in morphology and consequently difficult to identify, so the differences between the two areas may be apparent rather than real. There are major differences in
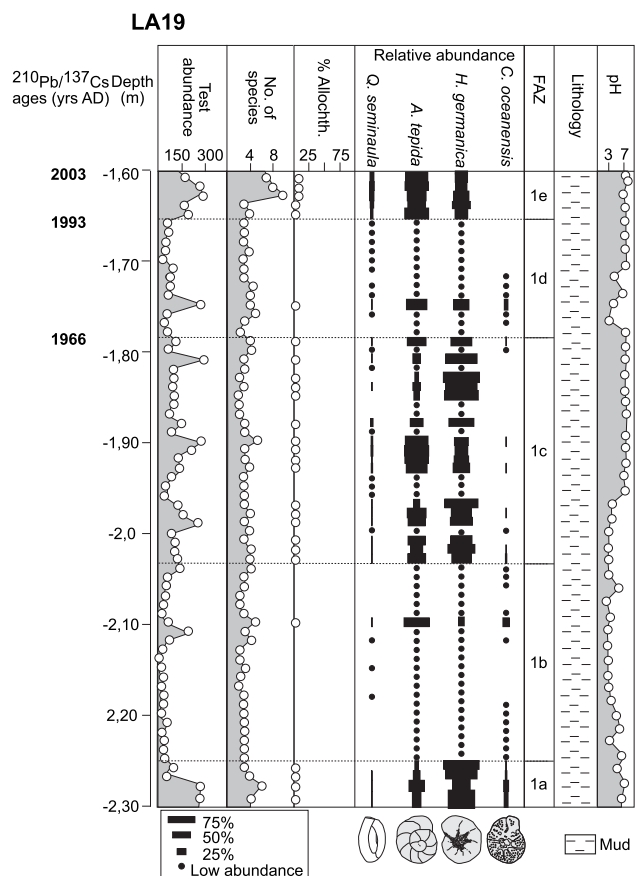
FIGURE 5 | Absolute abundance of foraminiferal tests (10cm³), number of species, allochthonous content, distribution and relative abundance of the main foraminiferal species, foraminiferal assemblages (FAZ) and lithological units in the Core LA19. The ²¹⁰Pb and ¹³⁷Cs estimated ages and pH values are also indicated.

the latitudinal positions of the northern limits of certain taxa. Both *Ammonia* group and *H. germanica* have their northern limit in Europe in southern Scandinavia (latitude 60°N) whereas in North America the limit is located in Nova Scotia (latitude 45°N). This reflects the influence of the North Atlantic Drift on European climate (Murray, 2006).

Core LP records the palaeoenvironmental history of the most internal area of the lagoon during the last 2500 years. Given its distal location in relation to the sea and proximal position in relation to the lagoon-terrestrial boundary, any environmental signal of possible changes in the long-term averaged permeability of the sandy barrier must be quite dimmed. This fact can also explain the few foraminiferal tests collected in this core since these organisms live under marine and brackish conditions (Sen Gupta, 1999). Only foraminiferal zones (FAZs) 2 and 4 contained a few foraminifera tests suggesting slightly brackish water conditions during their deposition. However, whereas FAZ2 contains very scarce calcareous tests deposited inside the inner lagoonal water body, FAZ4 is made of abundant agglutinated foraminifera characteristic of

an inter-supratidal salt marsh environment worldwide (Murray, 2006) suggesting the development of this type of marginal marine environment in the area during recent years, followed by reedswamp facies. On the contrary, FAZs 1 and 3 are barren of foraminifera and indicate dominant fresh-water conditions, in complete agreement with results from Bao *et al.* (1999) that studied the diatom and sedimentological characteristics of this core. In fact, FAZ2 coincides with diatom zone D of these authors, the only zone in the whole core representing a brief episode of pronounced brackish conditions (salinity of at least 17‰) and clearly showing temporary influence of oceanic water. This brackish episode, occurred *circa* 1500 cal BP, it must have corresponded to an exceptional breaching of the barrier (in intensity or duration), allowing the deposition of sediment rich in shell debris (whole shells and shell fragments of bivalves, dominated by *Cerastoderma edule* and rare gastropods), otherwise uncommon along the rest of the column.

On the other hand, Core LA19 represents the sediment accumulated during the 19th and 20th centuries in the internal lagoonal area (Lagoa Pequena), a time interval characterized by annual artificial re-opening of the detrital barrier (Freitas and Andrade, 1994). No correspondence has been found between low pH values and low abundant foraminiferal assemblages discounting post-mortem dissolution of tests as the cause for the foraminiferal abundance variations. Consequently, it seems that during certain time intervals, characterized by abundant foraminifera, penetration of open-ocean water has been more effective in reaching the most internal areas of the lagoon (for instance, the period between *Anno Domini* 1993 and 2003), whereas during other periods with a very scarce foraminiferal record (for instance, between *Anno Domini* 1966 and 1993), the prevailing environmental conditions have been even more restrictive (Fig. 5). Species diversity is extremely low and the main species are always *H. germanica*, *A. tepida*, *Q. seminula* and *C. oceanensis*.

Finally, Core LA11 has a very short and homogeneous muddy sedimentary record characterized by a unique foraminiferal assemblage composed of an extremely low number of foraminifera that represents very recent sediment deposition in the middle area of the lagoon. These low abundance and species diversity agree with results from the surface samples studied that suggest a restricted lagoonal enviroment.

The palaeoenvironmental evolution of the Albufeira lagoon during the last 7000 years has been previously reconstructed from the study of several proxies in cored sediments (Queiroz and Mateus, 1994; Freitas and Andrade, 1994). In agreement with the environmental evolution model proposed for this coastal region,
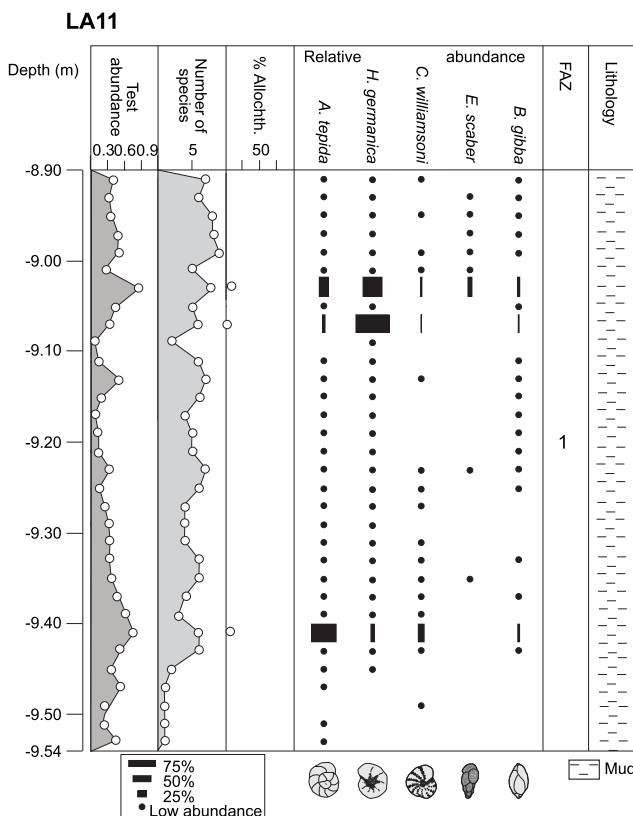
FIGURE 6 | Absolute abundance of foraminiferal tests (10cm³), allochthonous content, number of species, distribution and relative abundance of the main foraminiferal species, foraminiferal assemblages (FAZ) and lithological units in the Core LA11.
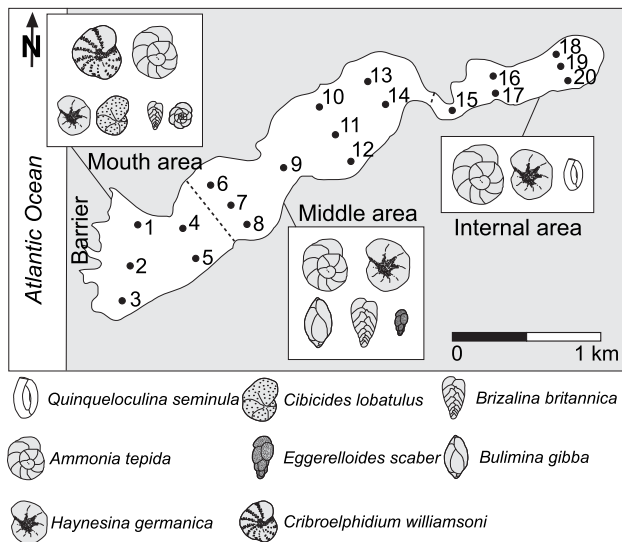
FIGURE 7 | Summary of the modern foraminiferal assemblages distribution in the Albufeira lagoon. Size of the species represents its relative abundance and black dots indicate surface samples.

the sea-level rise before 5ka promoted flooding of this low-lying area and Albufeira became a brackish estuary. Around 5ka, the sea-level rise rate decreased and a detrital barrier developed regionally isolating the lowland basin from the open ocean and developing a lagoon with alternating fresh-water and brackish-water conditions as a consequence of natural changes in the effectiveness of the barrier. Since then, and in the same way as other nearby lagoonal areas (Cearreta *et al.*, 2007), more restricted, fresh-water periods are represented by lagoonal sediment barren of foraminifera whereas brackish conditions within the lagoon were characterized by dominant *A. tepida* and *H. germanica*. During the last 2.5ka, freshwater conditions prevailed at Lagoa Pequena, with the exception of a single short-lived episode around 1500 cal yr BP, where brackish conditions have been registered associated to coarser sedimentation, indicating more marine influence, probably due to an important though ephemeral event of barrier breaching. Changes in environmental conditions throughout the last 600 years have been controlled by the human influence on the area with the annual artificial opening of the barrier and reclamation for agricultural purposes (Freitas and Andrade, 1994). The contemporaneous assemblages are mainly composed by *J. macrescens* and *T. inflata* in the vegetated marginal salt marsh areas and by *A. tepida* and *H. germanica* in the deeper zones of the lagoon.

CONCLUSIONS

In general, foraminiferal assemblages from bottom sediments of the Albufeira lagoon show an increase in

species diversity and allochthonous-test content towards the mouth area. In the inner and more restricted region, the foraminiferal assemblages exhibit a moderate abundance and low species diversity with *A. tepida, H. germanica* and *Q. seminula* as the main species. In the central area, abundance shows similar values but the species diversity increases. Small and fragile forms, such as *B. gibba, B. britannica* and *E. scaber*, show here their maximum values and characterize a deep, muddy and low-oxygenated environment. The main species are *H. germanica* and *A. tepida*. Finally, abundance and species diversity reach their maxima in the mouth area, in relation with facility of water input and renewal from the open ocean. The assemblage here is made up of a mixture of brackish and marine species such as *A. tepida, C. williamsoni, C. lobatulus* and *H. germanica*, with *B. britannica* and *G. praegeri* as minor species.

The palaeoenvironmental conditions of the lagoon during the last 2500 years have been controlled by changes in the effectiveness of the sandy barrier in controlling water exchange with the ocean and this is recorded by a number of foraminiferal zones indicating alternating fresh- and brackish-water conditions. Longer or prevailing periods of intense restricted conditions result as barren of foraminifera in the sedimentary record whereas short-lived brackish conditions (as the one at 1500 BP) are characterized by dominant *A. tepida* and *H. germanica*, just as in the sedimentary record of the nearby Melides and Santo André coastal lagoons.

The palaeoenvironmental signature of the last century in the geological record has been controlled by the human influence on the area with the annual artificial opening of the barrier that modulated the abundance of foraminiferal assemblages in the inner area of the lagoon.

REFERENCES

Alve, E., Murray, J.W., 2001. Temporal variability in vertical distributions of live (stained) intertidal foraminifera, southern England. Journal of Foraminiferal Research, 31, 12-24.

Bao, R., Freitas, M.C., Andrade, C., 1999. Separating eustatic from local environmental effects: a late-Holocene record of coastal change in Albufeira Lagoon, Portugal. The Holocene, 9, 341-352.

Cearreta, A., Alday, M., Freitas, M.C., Andrade, C., Cruces, A., 2002. Modern foraminiferal record of alternating open and restricted environmental conditions in the Santo André lagoon, SW Portugal. Hydrobiologia, 475-476, 21-27.

Cearreta, A., Alday, M., Freitas, M.C., Andrade, C., 2007. Postglacial foraminiferal record and palaeoenvironmental evolution of the Melides lagoon (SW Portugal): towards a regional model following eustatic sea-level rise and sandy barrier formation. Journal of Foraminiferal Research, 37, 125-135.

de Rijk, S., Troelstra, S.R., 1997. Salt marsh foraminifera from the Great Marshes, Massachusetts: environmental controls. Palaeogeography, Palaeoclimatology, Palaeoecology, 130, 81-112.

Freitas, M.C., Andrade, C., 1994. Tidal inlet evolution and hydraulic characteristics at Albufeira lagoon. In: Soares de Carvalho, G., Veloso Gomes, F. (eds.). Proceedings of Littoral '94. Lisbon, EUROCOAST Portugal, 1, 257-271.

Freitas, M.C., Andrade, C., Cruces, A., 2010. Heavy metals in sediments of lagoonal systems from the southwestern coast of mainland Portugal. In: Neiva, J.M., Ribeiro, A., Mendes Victor, L., Noronha, F., Ramalho, M. (eds.). Ciências Geológicas – Ensino e Investigação e sua História. Geologia e Ambiente. Publicação Comemorativa do "Ano Internacional do Planeta Terra", Associação Portuguesa de Geólogos-Sociedade Geológica de Portugal, 2(II), 207-218.

Freitas, M.C., Cachão, M., Fonseca, L.C., Caroça, C., Carvalho, A.M.G., 1994. Unusual co-occurrence of Serpulids and Bryozoa in a lagoonal system (Albufeira coastal lagoon - Portugal). Gaia, 8, 39-46.

Friedman, G.M., Sanders, J.E., 1978. Principles of Sedimentology. New York, John Wiley & Sons, 792pp.

Jorissen, F.J., de Stigter, H.C., Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabits. Marine Micropaleontology, 26, 3-15.

Martins, M.V.A., Gomes, V.R.D., 2004. Foraminíferos da margem continental NW ibérica: sistemática, ecologia e distribuição. Aveiro, Celso Gomes, 377pp.

Murray, J.W., 1979. British Nearshore Foraminiferids. Synopsis of the British Fauna (New Series) 16. London, Academic Press, 68pp.

Murray, J.W., 2006. Ecology and Applications of Benthic Foraminifera. Cambridge, Cambridge University Press, 440pp.

Patterson, R.T., Hutchinson, I., Guilbault, J.-P., Clague, J.J., 2000. A comparison of the vertical zonation of diatom, foraminifera and macrophyte assemblages in a coastal marsh: implications for greater paleo-sea level resolution. Micropaleontology, 46, 229-244.

Queiroz, P.F., Mateus, J.E., 1994. Preliminary palynological investigation on the Holocene deposits of Lagoa de Albufeira and Lagoa de Melides, Alentejo (Portugal). Revista de Biologia, 15, 15-27.

Rogers, M.J., 1976. An evaluation of an index of affinity for comparing assemblages, in particular of foraminifera. Palaeontology, 19, 503-515.

Sen Gupta, B.K., 1999. Introduction to modern foraminifera. In: Sen Gupta, B.K. (ed.). Modern Foraminifera. Kluwer Academic Publisher, 3-7.

Sen Gupta, B.K., Machain-Castillo, M.L., 1993. Benthic foraminifera in oxygen-poor habitats. Marine Micropaleontology, 20, 183-201.

Serandrei-Barbero, R., Carbognin, L., Taroni, G., Cova, E., 1999. Distribution of recent benthic foraminifera in the southern basin of the Venice lagoon (Italy): statistical evaluation of taxa significance. Micropaleontology, 45, 99-111.

Silva, E., 2003. Dissolved oxygen content in the central area of the Albufeira lagoon (SW Portugal). Personal communication.

Walton, W.R., 1952. Techniques for recognition of living foraminifera. Contributions from the Cushman Foundation for Foraminiferal Research, 3, 56-60.

ELECTRONIC APPENDIX

Foraminiferal reference list. S: surface samples; C: core samples

Autochthonous species

Ammonia tepida (Cushman) = *Rotalia tepida* (Linné) var. *tepida* Cushman, 1926: S, C

Amphycorina scalaris (Batsch) = *Nautilus scalaris* Batsch, 1791: S

Bolivina pseudoplicata Heron-Allen and Earland, 1930: S

Brizalina britannica (Macfadyen) = *Textularia variabilis* Williamson var. *laevigata* Williamson, 1858: S, C

Cribroelphidium oceanensis (d'Orbigny) = *Polystomella oceanensis* d'Orbigny, 1826: S, C

Cribroelphidium williamsoni (Haynes) = *Elphidium williamsoni* Haynes, 1973: S, C

Cribostomoides jeffreysii (Williamson) = *Nonionina jeffreysii* Williamson, 1858: C

Eggerelloides scaber (Williamson) = *Bulimina scabra* Williamson, 1858: S, C

Elphidium magellanicum Heron-Allen and Earland, 1932: S

Fissurina lucida (Williamson) = *Entosolenia marginata* (Montagu) var. *lucida* Williamson, 1848: S

Haynesina germanica (Ehrenberg) = *Nonium germanicum* Ehrenberg, 1840: S, C

Jadammina macrescens (Brady) = *Trochammina inflata* (Montagu) var. *macrescens* Brady, 1870: S, C

Lagena clavata (d'Orbigny) = *Oolina clavata* d'Orbigny, 1846: S

Lagena sulcata (Walker and Jacob) = *Serpula (Lagena) sulcata* Walker and Jacob, 1798: S

Lagena tenuis (Bornemann) = *Ovulina tenuis* Bornemann, 1855: S

Lagena sp: S

Lenticulina inortatus (d'Orbigny) = *Robulina inortata* d'Orbigny, 1846: C

Miliammina fusca (Brady) = *Quinqueloculina fusca* Brady, 1870: S, C

Quinqueloculina dimidiata Terquem, 1876: S

Quinqueloculina seminula (Linné) = *Serpula seminulum* Linné, 1758: S, C

Textularia bocki Höglund, 1947: S

Trochammina inflata (Montagu) = *Nautilus inflatus* Montagu, 1808: S, C

Allochthonous species

Acervulina inhaerens Schultze, 1854: S

Adelosina cliarensis (Heron-Allen and Earland) = *Miliolina cliarensis* Heron-Allen and Earland, 1930: S

Astacolus crepidulus (Fichtel and Moll) = *Nautilus crepidula* Fichtel and Moll, 1798: S

Asterigerinata mamilla (Williamson) = *Rotalia mamilla* Williamson, 1858: S, C

Brizalina difformis (Williamson) = *Textularia variabilis* Williamson var. *difformis* Williamson, 1858: S

Brizalina spathulata (Williamson) = *Textularia variabilis* Williamson var. *spathulata* Williamson, 1858: S

Brizalina variabilis (Williamson) = *Textularia variabilis* Williamson, 1858: S

Bulimina elongata d'Orbigny, 1846: S

Bulimina gibba Fornasini, 1902: S

Bulimina marginata d'Orbigny, 1826: S

Cassidulina carinata (Silvestri) = *Cassidulina laevigata* d'Orbigny var. *carinata* Silvestri, 1896: S

Cassidulina obtusa Williamson, 1858: S

Cibicides lobatulus (Walker and Jacob) = *Nautilus lobatulus* Walker and Jacob, 1798: S

Cribroelphidium gerthi (Van Voorthuysen) = *Elphidium gerthi* Van Voorthuysen, 1975: S

Elphidium crispum (Linné) = *Nautilus crispus* Linné, 1758: S

Elphidium macellum (Fichtel and Moll) = *Nautilus macellum* Fichtel and Moll, 1798: S

Elphidium margaritaceum Cushman, 1930: S, C

Fissurina marginata (Montagu) = *Vermiculum marginatum* Montagu, 1803: S, C

Fissurina orbignyana Seguenza, 1862: S

Stainforthia fusiformis (Williamson) = *Bulimina pupoides* d'Orbigny var. *fusiformis* Williamson, 1858: S, C

Gavelinopsis praegeri (Heron-Allen and Earland) = *Discorbina praegeri* Heron-Allen and Earland, 1913: S

Haynesina depressula (Walker and Jacob) = *Nautilus depressulus* Walker and Jacob, 1798: S, C

Miliolinela circularis (Bornemann) = *Triloculina circularis* Bornemann, 1855: S

Miliolinella subrotunda (Montagu) = *Vermiculum subrotundum* Montagu, 1803: S

Nonionella atlantica Cushman, 1947: S

Oolina hexagona (Williamson) = *Entosolenia squamosa* (Montagu) var. *hexagona* Williamson, 1858: S

Oolina melo d'Orbigny, 1839: C

Oolina sp: S

Patellina corrugata Williamson, 1858: S

Pateoris hauerinoides (Rhumbler) = *Quinqueloculina subrotunda* (Montagu) forma *hauerinoides* Rhumbler, 1936: S

Planorbulina mediterranensis d'Orbigny, 1826: S

Pyrgo depressa (d'Orbigny) = *Biloculina depressa* d'Orbigny, 1826: S

Pyrgo sp: S

Quinqueloculina bicornis (Walker and Jacob) = *Serpula bicornis* Walker and Jacob, 1798: S, C

Quinqueloculina lata Terquem, 1876: S, C

Quinqueloculina oblonga (Montagu) = *Vermiculum oblongum* Montagu, 1803: S

Quinqueloculina quadrata Nörvang, 1945: S

Rosalina anomala Terquem, 1875: S

Rosalina irregularis (Rhumbler) = *Discorbina irregularis* Rhumbler, 1906: S

Spirillina sp: S

Spiroloculina excavata d'Orbigny, 1846: S

Spirorutilis wrightii (Silvestri) = *Spiroplecta wrightii* Silvestri, 1903: S

Trifarina angulosa (Williamson) = *Uvigerina angulosa* Williamson, 1858: S

Triloculina bermudezi Acosta, 1940: S

Triloculina trigonula (Lamarck) = *Miliolites trigonula* Lamarck, 1804: S

Uvigerina peregrina Cushman, 1923: S

FIGURE I | Main foraminiferal species found in surface samples and cores of the Albufeira lagoon. Scale bar indicates 0.1mm. 1) Quinqueloculina seminula (Linné, 1758), core LA19-FAZ1e; 2) Ammonia tepida (Cushman, 1926), core LA19-FAZ1c; 3) Haynesina germanica (Ehrenberg, 1840), sample 17-June 2003; 4) Cibicides lobatulus (Walker and Jacob, 1798), sample 3-February 2003; 5) Cribroelphidium williamsoni (Haynes, 1973), sample 1-February 2003; 6) Eggerelloides scaber (Williamson, 1858), sample 6-February 2003; 7) Brizalina britannica (Macfadyen, 1942), sample 10-June 2003; 8) Bulimina gibba Fornasini 1902, sample 7-February 2003; 9) Jadammina macrescens (Brady, 1870), core LP-FAZ4b: 10) Trochammina inflata (Montagu, 1808), core LP-FAZ4b; 11) Cribroelphidium oceanensis (d'Orbigny, 1826), sample 12-June 2003.