Geologie en Mijnbouw **77:** 311–321, 1999.

A microfaunal and sedimentary record of environmental change within the late Holocene sediments of Boca do Rio (Algarve, Portugal)

R. Hindson[1], C. Andrade[2] & R. Parish[3]

[1]Department of Tropical Environmental Studies and Geography, James Cook University of North Queensland, PO Box 6811, Cairns 4870, Australia; [2]Centro de Geologia e Departamento de Geologia da Faculdade de Ciências de Lisboa. Bloco C2 5 piso, Campo Grande, 1700 Lisboa, Portugal; [3]The Geography Laboratory, Arts Building B, University of Sussex, Falmer, Brighton, BN1 9QN, U.K.

Received October 1996; accepted in revised form 4 March 1999

Key words: climatic change, coastal barrier, palaeoecology, optically stimulated luminescence, seismic subsidence, tsunami sedimentation

Abstract

The foraminifera and ostracods observed in a late Holocene sedimentary sequence within a fluvial valley at Boca do Rio in the coastal zone of the western Algarve, Portugal, reveal a general, though not smooth transition from marine to fluvial conditions. The relative influence of these two environments appears to depend on the degree of permeability of the barrier system at the coast. Optically stimulated luminescence dates and palaeoecological information obtained from the sequence suggest that barrier formation may be related to changes in climate and/or patterns of ocean current circulation. An unusual deposit rich in sand and gravel found within the otherwise mud-dominated sequence has been dated at AD 1801 ± 76 years. This deposit contains foraminifera and ostracods which indicate marine conditions, and which contrast markedly with the brackish-water, estuarine assemblages found in the mud deposits. The rapid transition in the foraminifera and ostracod assemblages indicates a short-lived coastal flooding, which may represent the tsunami associated with the Lisbon earthquake of AD 1755. The variations in the foraminifera and ostracod assemblages also suggest subsidence during the earthquake, with uplift having occurred in the period since then.

Introduction

The Boca do Rio lowland is located in the southern Algarve coast of Portugal (37°04′N, 08°48.5′W) within an otherwise cliff-lined coastal section of predominantly calcareous, Jurassic and Cretaceous sediments (Figure 1). It is separated from the sea by a small gravel-and-sand barrier that prevents wave overtopping during storms. The lowland corresponds to a N-S elongated, flat valley floor that extends inland for about 1 km, slightly above the limit of mean high-water spring tides. Four trenches were excavated within this lowland (Andrade et al. 1994, Dawson et al. 1995) in order to investigate the processes of deposition associated with the tsunami generated by the Lisbon earthquake of 1st November 1755. They revealed a cobble-and-boulder-rich horizon forming the base of the alleged tsunami deposit. The boulders and cobbles are overlain by sand, which was sampled for luminescence dating. The taphonomic and ichnofossil study of cobbles and boulders collected in the trench walls provided the first unquestionable proof of a marine origin for this coarse clastic deposit (Silva et al. 1996). In addition, systematic shallow coring of the site was undertaken in order to provide detailed information on the lithostratigraphy of the Holocene of this lowland area (Figure 2). Cores BDRS2 and BDRS4 were sampled in the laboratory in order to undertake microfossil analysis and further dating.

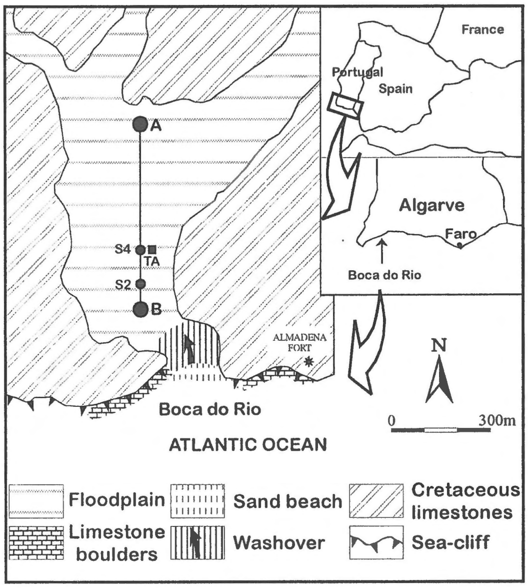


Figure 1. Location map of Boca do Rio area, showing coring sites S2 and S4 and location of trench TA. Line AB indicates cross section shown in Figure 2, constructed with stratigraphic information from 25 boreholes and 4 trenches.

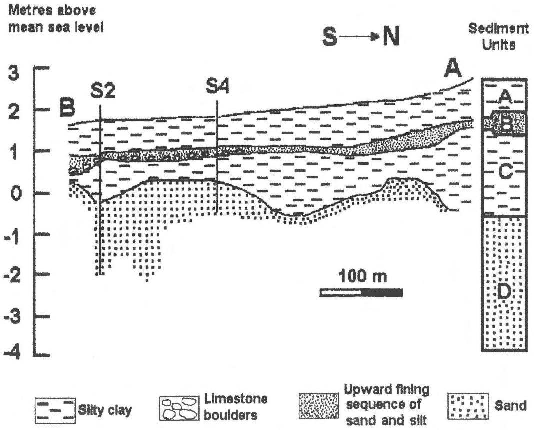


Figure 2. Cross-section showing stratigraphy of the Boca do Rio site. See Figure 1 for location.

Stratigraphy

Figure 2 summarises the main stratigraphic units that form the sediment sequence of the Boca do Rio lowland. Four lithostratigraphic units were recognised.

Unit A – This unit forms the uppermost sediment layer and is activated today by river floods during the rainy season. It consists of a dark-red or brown silty clay with a thickness of 0.8 to 1 m.

Table 1. OSL dates of samples from trench TA, Boca do Rio. Surface elevation is 1.9 m above mean sea-level

Sample	Unit	Depth below surface (cm)	ED (Gy)	OSL age before 1995 (years)
BDR-A	A	70–85	2.44 ± 0.14	587 ± 38
BDR-B	B	95–130	0.29 ± 0.12	194 ± 76
BDR-C1	C	135–150	4.76 ± 2.1	1236 ± 540
BDR-C2	C	173–197	5.97 ± 1.83	1363 ± 420
BDR-D1	D	212–226	3.39 ± 0.23	1815 ± 411
BDR-D2	D	289–301	3.04 ± 0.42	1944 ± 280
BDR-D3	D	368–384	4.54 ± 0.67	2320 ± 617

Unit B – This unit is extremely variable in terms of both its thickness and sedimentary characteristics. It reaches a maximum thickness of 0.45 m though it is generally thinner and sometimes absent. Unit B is sedimentologically complex but for the sake of simplicity it may be divided in two distinct horizons which are generally present. A basal horizon, which lies unconformably over Unit C and consists of a chaotic and structureless matrix-supported muddy conglomerate or coarse muddy sand including abundant carbonate boulders or cobbles and large shell fragments. The upper horizon, which is spatially more continuous, is essentially represented by an upward fining sequence of medium sand to silt, occasionally containing mudballs, small pebbles or shell fragments.

Unit C – Unit C is quite similar in texture and mineralogical composition to Unit A but shows some enrichment in fermented plant debris and charcoal. At some sites it grades downwards into a black organic mud with distinct *in situ* plant remains. The total thickness of Unit C varies between 0.5 and 1 m.

Unit D – This unit forms the base of the cored sequence. It consists mainly of coarse, grey marine sands with shells, both broken and whole. Some gravelly horizons were found, particularly towards the top of the unit. It was cored to a depth of 5 m below ground surface (2 m below mean sea-level) without reaching its base.

Dating

Methods

Seven samples from Boca do Rio, taken from trench TA (Figure 1), opened close to coring site S4, were dated using optically stimulated luminescence (OSL; Table 1). The lack of substantial quantities of organic matter within this sedimentary sequence precluded the use of radiocarbon dating methods. OSL dating of waterlaid sediments has been successfully carried out in previous studies (Parish 1992, Dawson et al. 1995). For Units A and C the 4–11 μm fraction was used and for Units B and D the 180–225 μm fraction. The silt-rich samples were deflocculated with Calgon, before treatment with 1 mol. HCl to remove carbonates. They were then washed thoroughly in distilled water, wet-sieved through a 63 μm mesh, washed in acetone and left to dry. The 4–11 μm fraction was separated by settling for 2 and 20 minutes. The sand samples were washed in 1 mol. HCl to remove carbonates, air-dried and sieved to extract the 180–225 μm fraction. The quartz-rich material from this fraction was isolated by heavy-liquid separation (sodium polytungstate). These grains were etched in 40% HF for 40 minutes to remove the outer layer affected by external alpha radiation. The aliquots from sand samples were mounted with silicone spray on 10-mm aluminium disks whilst the fine-grained samples were settled onto similar disks from suspension in acetone. All samples were normalised by a 0.5 second exposure prior to measurement. Bleaching was undertaken under a 300 W Wotan sunlamp, filtered through clear glass to reduce the UV component, and irradiation was done with a ^{90}Sr beta source delivering 14.3 Gy/minute. Measurements were made in a Riso automated reader using a 60 seconds exposure from a halogen light source filtered through three GG420 filters, with detection filtered through two U340 filters (270–380 nm).

Age determination was achieved by the additive-dose method. Dosimetry was achieved by on-site gamma spectrometry and by thick source beta counting. Cosmic doses were taken from the values given by Prescott & Hutton (1988).

Uncertainties in the annual dose rate as a result of fluctuations of the water table comprise a significant component of the error inherent with this dating method. An estimate of 5% was used for the water content in this study, although this may be somewhat conservative for this environment.

Results

The OSL date for sample BDR-B agrees within error limits with the thermoluminescence age of AD 1734 ± 60 previously referred to by Dawson et al. (1995). The three dates from Unit D are in stratigraphic order (Table 1). The dates for the fine-grained samples are more problematic than those for the coarse-grained ones. Unit A appears not to have been bleached at deposition. The low error on the equivalent dose (ED) would indicate that this is not a case of mixed bleached and unbleached material. The errors associated with samples C1 and C2 are very high, primarily due to the uncertainty in ED determination. For these samples the ED was determined from four sets of 24 aliquots. The signal intensities were lowest for sample BDR-A at 1784 counts in the first second of the natural signal after background subtraction. The lower intensity for BDR-A may be attributed not only to its young age, but also to its mineralogical composition: fine-grained samples may contain significant quantities of material that is not luminescent. Bleaching of the samples for 4 hours under the lamp resulted in negligible levels of OSL signals. No recuperation of the signal was apparent.

Foraminifera and ostracods

Foraminifera and ostracod assemblages within the sediment sequence were utilised in order to attempt to reconstruct the history of environmental change at Boca do Rio. Both microfossil groups are sensitive environmental indicators, and have been widely used in the reconstruction of palaeoenvironmental change within Holocene sedimentary sequences in the coastal zone (Kilkenyi 1969, Murray & Hawkins 1976, Whitaker 1981, Whatley 1983, Penney 1987, Cearreta 1994, Williams 1995). Salinity plays a key role in controlling the colonisation of a particular coastal environment by benthic foraminifera and ostracods (Murray 1973, 1991, Whitaker 1981). It is also a crucial factor in determining the diversity of species (Cearreta 1989, Whatley 1983). Species diversity in both microfossil groups is high in fully marine conditions, falling rapidly in brackish water (Murray 1991, Kilkenyi 1969). Ostracods, unlike foraminifera, can tolerate freshwater conditions, and distinct assemblages occur in this environment (Whitaker 1981). Within the estuarine environment foraminifera and ostracods display faunal associations which have a close

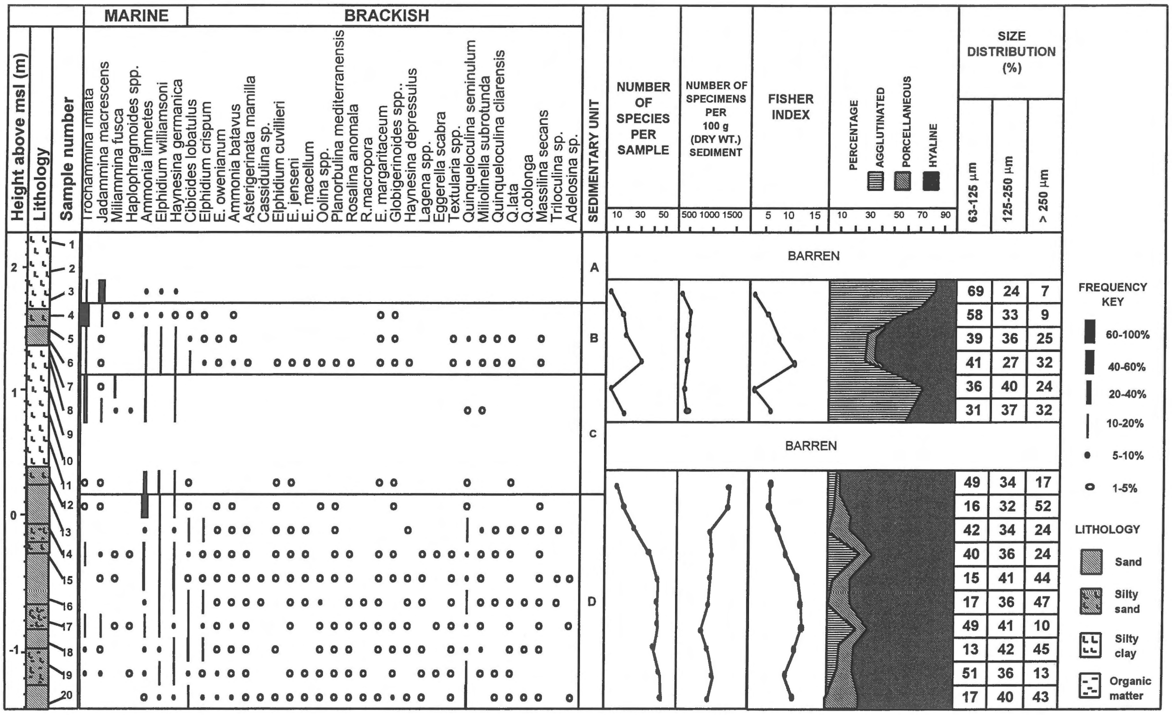


Figure 3. Distribution of foraminifera in Boca do Rio core S2. The Fisher Index illustrates the degree of diversity in the microfossil assemblage.

relationship with both sedimentary environment and tidal level (Haynes & Dobson 1969, Kilkenyi 1969, Scott & Medioli 1986, Penney 1987). Variations in these faunal associations within a sediment sequence can reveal changes in the degree of marine, brackish or freshwater influence within a coastal system over a period of time. These trends may be in turn related to either changes in the coastal configuration due to normal coastal processes or to changes in relative sea level (Murray & Hawkins 1976, Penney 1987, Cearreta 1994).

Microfossil analysis

Methods

The samples utilised in this study were dried in an oven at approximately 20°C, and 100 g of the dried sample were taken for further analysis. Samples were sieved into the following size fractions: 63–125 μm, 125–250 μm, and > 250 μm. Each of these size intervals was then treated with 1:1:1 trichloroethane in order to float off and separate the microfauna from the sediment particles. The entire sample was then counted using a binocular microscope. In cases where there were exceptionally large numbers of individuals, a fraction of the sample was counted, and the numbers counted multiplied in order to give a figure for the number of individuals per 100 g of sediment.

The identification of the foraminifera was based on Haynes (1973), Murray (1971, 1979) and Galhano (1963). The ostracods were identified according to Athersuch et al. (1989) and Bonaduce et al. (1975). For each sample the data gained was analysed and compared using a number of different indices and parameters: relative abundance of each species, state of preservation, size distribution, and in the case of the foraminifera the composition of the test (agglutinated, hyaline or porcellaneous).

Results

Foraminifera and ostracods were analysed from core sites BDRS2 and BDRS4 (Figures 3–6). The results obtained from these two sites are considered to be representative of the sequence as a whole. A number of different assemblages were identified, which

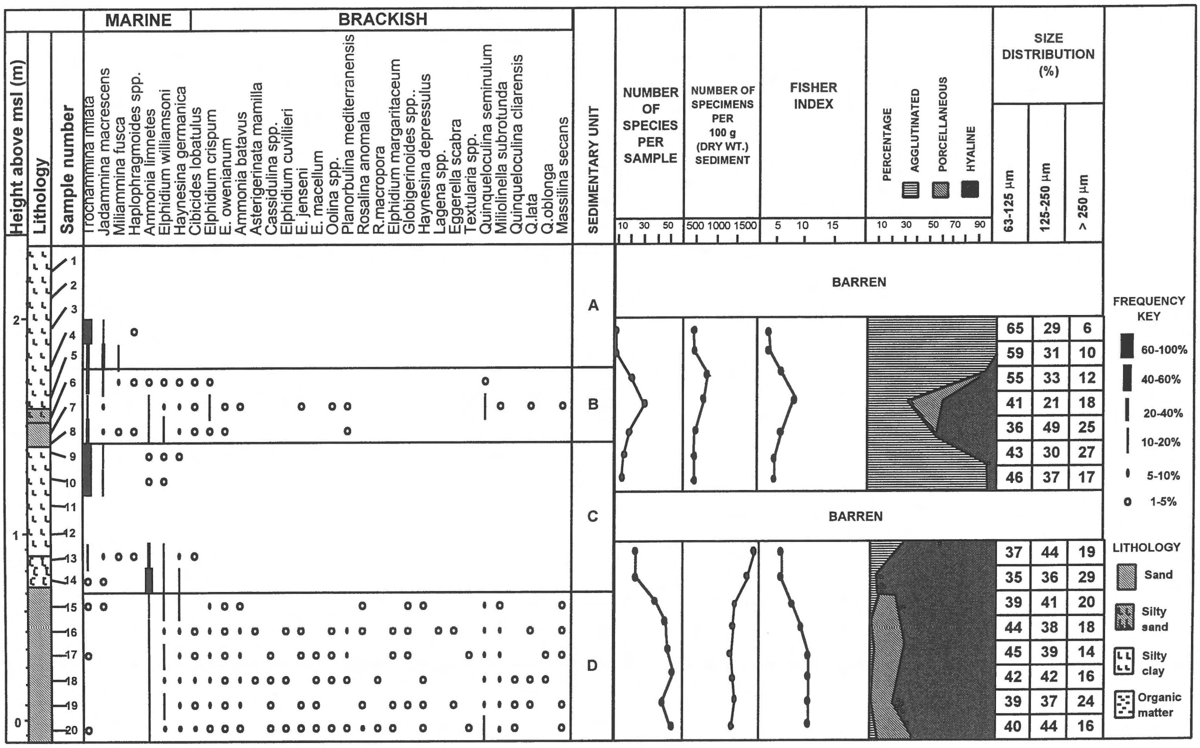


Figure 4. Distribution of foraminifera in Boca do Rio core S4.

can be related to different sedimentary environments. Studies on contemporary estuarine and lagoonal systems have been considered in order to interpret the palaeoenvironmental conditions indicated by the foraminifera and ostracods (Haynes & Dobson 1969, Kilkenyi 1969, Murray 1973, Murray & Hawkins 1976, Whitaker 1981, Cearreta 1989, Murray 1991).

The sands and muddy sands of the lower part of Unit D contain a diverse assemblage and relatively large numbers of individuals of both foraminifera and ostracods. The most abundant foraminifera species throughout Unit D include the euryhaline, hyaline species *Ammonia limnetes*, *Elphidium williamsoni* and *Haynesina germanica*. These species are typically found in marginal marine environments where salinity is variable. In addition, a number of stenohaline species are present including *Cibicides lobatulus*, *Elphidium* spp. and several porcellaneous miliolid species, most notably *Quinqueloculina seminulum*. These species vary from being well preserved to badly abraded and broken, and it appears that they have undergone extensive transportation, and are exotic to the environment in which they have been deposited. The agglutinated species *Trochammina inflata* and *Jadammina macrescens* tend to be better preserved, and form a significant proportion of the assemblage only in the organic-rich muddy-sand sections of the unit.

Within the lower part of Unit D the most common ostracod species consist of a mixture of open-marine, stenohaline forms such as *Urocythereis distinguida*, *Loxoconcha rhomboidea*, *Aurila convexa* and *Heterocythereis albomaculata* and euryhaline, brackish-water forms including *Loxoconcha elliptica, Cyprideis torosa* and *Cytherois fischeri*. In addition, several species of the genus *Leptocythere*, which are characteristic of both these ecological classes, are also present. The mud-rich horizons are dominated by the brackish-water species, consisting of large numbers of *Loxoconcha elliptica*, and smaller numbers of *Cyprideis torosa, Cytherois fischeri* and *Leptocythere* spp. A large number of the individuals observed in these horizons are juvenile forms, which are absent from the sand-dominated samples. The ostracod population in the mud-free sand is skewed towards larger, fully marine species like *Aurila convexa* and *Urocythereis distinguida*, many of which show signs of abrasion.

Both the foraminifera and ostracods display a decrease in species diversity and an increase in number

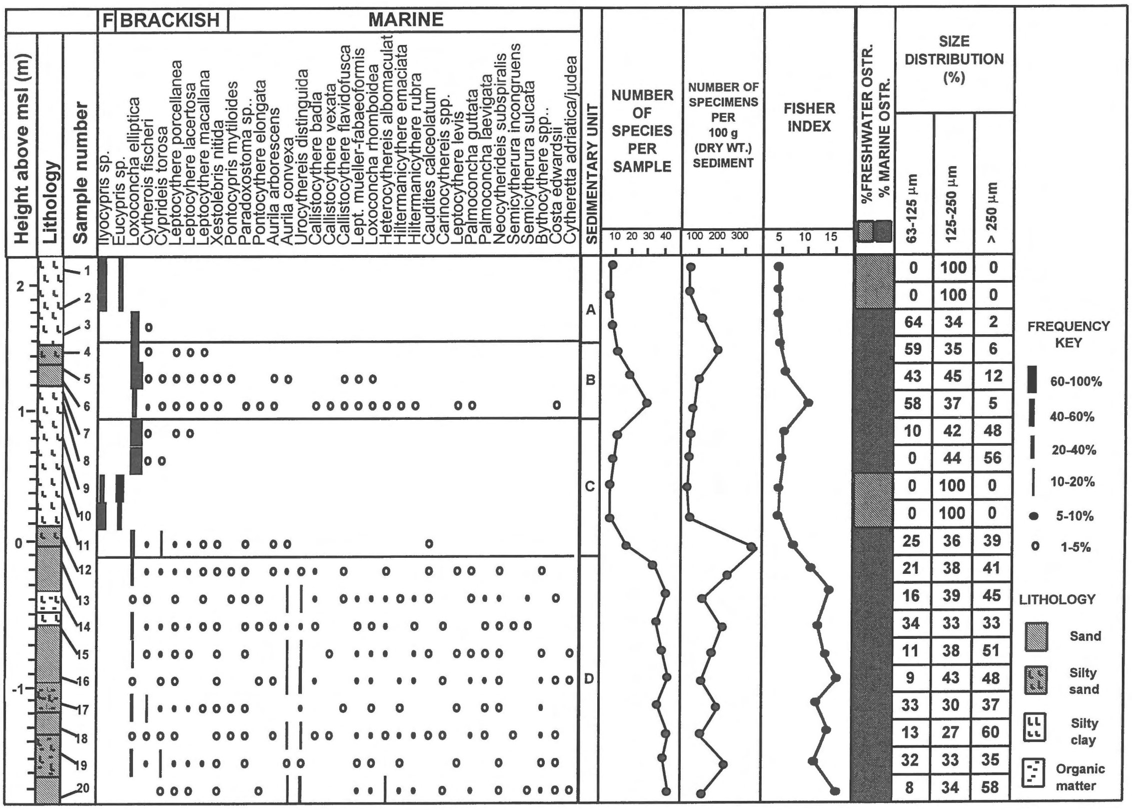


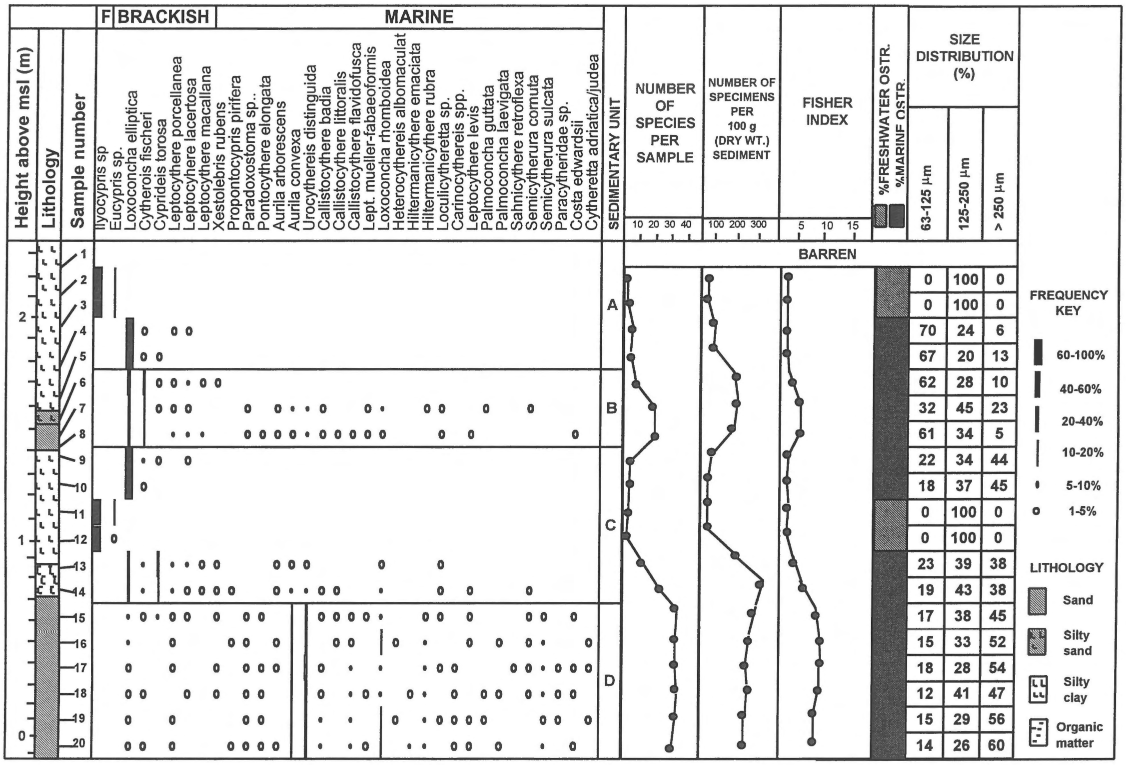
Figure 5. Distribution of ostracods in Boca do Rio core S2. F – Freshwater species.

of individuals towards the top of Unit D, and into the basal section of Unit C. The upper section of Unit D and the lower section of Unit C are dominated by the foraminifera species *Ammonia limnetes*, *Elphidium williamsoni* and *Haynesina germanica*, with very few agglutinated or porcellaneous species being recorded. The boundary of Units D and C is marked by the increasing dominance of brackish-water ostracods such as *Loxoconcha elliptica*, along with less numerous brackish-water species including *Cytherois fischeri, Cyprideis torosa* and *Leptocythere* spp. Above the basal section of Unit C no foraminifera are present, and only small numbers of the freshwater ostracod genera *Ilyocypris* and *Eucypris* occur.

Small numbers of foraminifera and ostracods are present in the organic-rich, upper section of Unit C. The foraminifera assemblage is dominated by the agglutinated forms *Trochammina inflata*, *Jadammina macrescens*, *Miliammina fusca* and *Haplophragmoides* sp. and the hyaline forms *Elphidium williamsoni*, *Haynesina germanica* and *Ammonia limnetes*. The ostracod assemblage is almost completely dominated by *Loxoconcha elliptica*, with *Cyprideis torosa, Cytherois fischeri, Leptocythere lacertosa, Leptocythere macallana* and *Leptocythere porcellanea* being present as secondary species.

A marked increase in diversity is observed in Unit B. This is especially apparent in the sand-rich section where the foraminifera are dominated by *Ammonia limnetes*, *Elphidium williamsoni*, *Haynesina germanica*, *Cibicides lobatulus* and *Quinqueloculina seminulum,* and the ostracods by *Loxoconcha elliptica* and *Cytherois fischeri*. The overall assemblage of both microfossil groups is similar to that noted in the mud-free sands of Unit D, but its numbers of individuals present are much lower. The tests tend to be poorly preserved, and many are broken or show strong signs of abrasion. There are also a large number of individuals which display a red-coloured coating of iron oxide. The boundary separating Units C and B is sharp, both sedimentologically and micropalaeontologically.

The upper mud-rich section of Unit B contains a less diverse foraminifera assemblage which is dominated by *J. macrescens* and *T. inflata*, with *Haplophrag-*



Sample	63-125 µm	125-250 µm	> 250 µm
2	0	100	0
3	0	100	0
4	70	24	6
5	67	20	13
6	62	28	10
7	32	45	23
8	61	34	5
9	22	34	44
10	18	37	45
11	0	100	0
12	0	100	0
13	23	39	38
14	19	43	38
15	17	38	45
16	15	33	52
17	18	28	54
18	12	41	47
19	15	29	56
20	14	26	60

Figure 6. Distribution of ostracods in Boca do Rio core S4. F – Freshwater species.

moides sp., *A. limnetes* and *E. williamsoni* present as secondary species. *Loxoconcha elliptica* continues to dominate the ostracods. A marked decrease in the size of the individual tests is noted from the base to the top of Unit B, with the largest numbers of individuals being found increasingly in the 63–125 μm fraction.

The base of Unit A contains a similar assemblage of both foraminifera and ostracods to that observed in the mud-rich upper section of Unit B, and there is a continued bias towards smaller individuals. The overall assemblage at the base of Unit A is also similar to that found in the top part of Unit C. However, in contrast, the size distribution of the population is strongly skewed towards juveniles.

The uppermost section of Unit A is barren of foraminifera, but there are small numbers of the freshwater ostracods *Ilyocypris* sp. and *Eucypris* sp.

Palaeoenvironmental interpretation

The foraminifera assemblage within Unit D is similar to that described for subtidal channels of the Dovey estuary of Wales (Haynes & Dobson 1969) and the subtidal zone of the ria of San Vicente de la Barquera in northern Spain (Cearreta 1989). The well-preserved, hyaline, euryhaline foraminifera species along with the agglutinating forms are indigenous to the estuarine environment, with the abraded, open-marine forms having been transported in from offshore (Murray & Hawkins 1976). The ostracods show characteristics similar to those noted by Whitaker (1981) in Christchurch Harbour, southern England, being typical of the zone of mixing between brackish and marine waters.

The sedimentary evidence suggests that Unit D represents a dominantly marine environment, with active wave reworking of the bottom sediments. Taken together, the sedimentological and micropalaeontological results indicate that the depositional environment was a shallow estuary, open to waves and tidal currents. The concentration of agglutinated forms in the samples dominated by muddy sand suggests the proximity of a more sheltered environment such as intertidal mudflats or marshes (Murray 1991). An environment similar to the present-day open ria systems of NW Spain is suggested for this unit.

The change in ostracod assemblage from the top part of Unit D into the basal part of Unit C suggests a transition to brackish-water conditions (Athersuch et al. 1989) that occurred simultaneously with a marked change of the provenance and nature of sedimentation. The foraminifera are typical of lower intertidal conditions (Haynes & Dobson 1969) suggesting that the sedimentary environment was becoming less influenced by open-marine conditions. The change in the microfossil assemblages indicates that the basin was silting up, with deposition occurring in a progressively shallower sedimentary environment.

The freshwater ostracods within the middle section of Unit C indicate that the estuary was completely isolated from marine influence for a period of time, being replaced by a fluvial or lagoonal basin. The silting up of the ria system with muddy sediments and the restriction in open-marine influence leading to the establishment of a lagoonal environment may have occurred as a result of barrier formation. The initial change from marine to brackish water conditions may indicate the formation of a barrier with an inlet, which allowed access to tidal waters. This would have led to the establishment of a sheltered, mud-dominated, inter-tidal environment free from the activity of waves. The brackish character of the microfossil assemblages indicates an increasing freshwater influence. The transition to freshwater ostracods in the middle section of Unit C suggests that the inlet was temporarily closed, resulting in the barrier becoming impermeable to tidal waters.

The small numbers of foraminifera and ostracods in the top part of Unit C may be due to chemical dissolution of the tests. This commonly occurs during the transition between the upper tidal flat and the saltmarsh due to organic acids produced during the breakdown of plant matter (Murray 1973). Alternatively this characteristic may be due to the creation of an unstable environment in which occasional breaching of the barrier occurred allowing the brackish-water foraminifera and ostracods to become established for only short periods of time.

The assemblage found within Unit B represents a mixture of open-marine and estuarine forms. The high degree of abrasion of these forms suggests high-energy deposition, and the iron-oxide staining in some individuals may have been caused during a period of sub-aerial exposure in a back-beach or foredune environment. The upward fining of the test size mirrors that seen in the modal particle size of Unit B sediments (Dawson et al. 1995), and suggests that the upper section of this unit has been deposited slowly from suspension.

It is unclear whether the basal part of Unit A represents an environment similar to that which existed during the deposition of the top part of Unit C or whether the foraminifera and ostracods in this basal part have been reworked from the upper section of Unit B by fluvial activity. The presence of freshwater ostracods in the upper part of Unit A suggests the onset of freshwater conditions most likely similar to the present-day fluvial system.

Discussion

The major change in the foraminifera and ostracod assemblages, as well as in the sediments which occurs at the base of Unit C may be interpreted as the moment at which a coastal barrier became established as a permanent and efficient hydrodynamic filter, providing shelter to the estuarine lowland and allowing fluvial sedimentation to become progressively established in this lowland. The OSL dates suggest that barrier establishment occurred between 1800 and 1300 years ago. If this is the case then it appears that the barrier has not formed in response to a slowing in the rate of sea-level rise. Evidence from other sites in this region suggests that sea-level rise began to slow down in the period between 6000 and 3300 BP (Bettencourt 1994, Pereira & Soares 1994). Barrier formation may have been caused by local factors, probably related to sudden changes in the sediment budget related to climate change. Both the sedimentological boundary and the changes in the composition of the foraminifera and ostracod assemblages suggest that the process of barrier formation was comparatively rapid, indicating that some kind of major alteration occurred. Examples of rapid changes in the pattern of coastal sedimentation have been described by Dabrio et al. (1996), Lario et al. (1995), Goy et al. (1995) and Zazo et al. (1994) from coastal locations around the south of the Iberian Peninsula, and appear to indicate a major change in the wind circulation regime around 2300 BP. In addition, work by Soares (1993a, b) on the Portuguese coast and by Dabrio et al. (1996 and this issue) on the southern coast of Spain suggests that another significant modification in the wind regime and in the associated coastal upwelling occurred between 1300 and 1100 BP, causing adjustments to the sedimentary budget of the littoral zone. The period in which barrier establishment occurred (1800–1300 BP) lies temporally between these events (2300 BP and 1300–1100 BP). The large error associated with the OSL dates means that the exact date of barrier formation is still unclear, and it is therefore very difficult to associate this event with any of the two major fluctuations in the climatic record investigated by other authors in the littoral zone of Iberia.

The second major environmental change indicated by the microfossil and sedimentary evidence is associated with Unit B. This unit appears to have been deposited by a sudden input of high-energy water from the open sea. This input does not appear to correspond with a storm overwash, because Unit B is found over 1000 m inland, compared with a maximum penetration of around 300 m for the modern storm-overwash fan. In addition, Unit B contains cobbles and boulders transported around 500 m inland, much further than any storm-surge-generated boulder transportation which has occurred in modern times. Coarse-grained material of this type is generally confined to the highest backbeach storm ridge or found dispersed within the sand-rich overwash fan up to 100 m inland.

The foraminifera and ostracod assemblages suggest that Unit B sediment was eroded from the shallow offshore, beach and dune environments. It was then transported onshore where it became mixed with low-energy estuarine inter-tidal muds before being deposited. Two luminescence dates obtained from the upper sand layer of Unit B indicate AD 1734 ± 60 years (Dawson et al. 1995) and AD 1801 ± 76 years (Table 1). These dates strongly suggest that the tsunami generated by the Lisbon earthquake of AD 1755 is the most likely mechanism for the deposition of Unit B. The marine origin already established for the boulder and cobble horizon within Unit B, therefore confirms the interpretation derived from the study of the foraminifera and ostracod assemblages.

The base of Unit A marks a return to marginal marine conditions (inter-tidal mud flats or salt-marsh) for a short period of time after the tsunami occurred. One explanation is that the tsunami flooding allowed a large amount of marine water containing living foraminifera and ostracods to become ponded in the estuary, and that barrier breaching by subsequent overwash events allowed the return of tidal influence for a short while. A similar episode occurred in a coastal lake in Texas where a hurricane overwash was distinguished on the basis of the foraminiferal record (Williams 1995).

It must be noted that the pre-tsunami assemblage was already typical of a high-marsh environment, occupying the highest part of the inter-tidal zone. The deposition of Unit B rapidly raised the surface by on average 40 cm. If the surface of the lowland was raised this should have resulted in the inhibited flow of tidal waters to this area. The continued tidal influence in this area can be explained by a second hypothesis, which speculates that coseismic subsidence may have occurred along the Algarve coast during the 1755 earthquake. If the earthquake was accompanied by subsidence along this coast it would allow tidal waters to continue to enter the lowland area in spite of the raised high-marsh surface. Continued tidal influence would also account for the continued colonisation of the lowland by brackish-water foraminifera and ostracods after the tsunami. In the period since 1755, uplift has occurred as a result of tension accumulating along the active seismic fault zone due to the collision of the African and Eurasian plates (Buforn et al. 1988, Cabral 1993, Ribeiro 1994). As a result of this uplift, tidal waters would no longer have reached the lowland area and fluvial conditions would have begun to dominate the environment, resulting in the extinction of this fauna. Geomorphological observations by Andrade (1992) of the backbarrier deposits of Tavira island, located in the eastern section of the Algarve coast, and also interpreted as being due to the 1755 tsunami, suggest that there was coseismic subsidence of the coastal zone following the earthquake. This author also concludes that there was slow uplift along the coast of the central and eastern Algarve during the following decades. This uplift resulted in tidal delta structures, which formed in the inter-tidal zone, being raised to a level slightly above spring water flood tide level, and implies an uplift of about 1 m above the altitude at which they were deposited.

In the western Algarve coseismic subsidence caused by the 1755 earthquake would have maintained intertidal conditions in the estuarine lowland of the Boca do Rio during the post-tsunami period. The historically recorded destruction of the barrier and associated foredune by the tsunami would also have made this lowland more accessible to tidal waters. As the barrier reformed and crustal uplift occurred, fluvial sedimentation would begin to dominate the lowland.

Conclusions

Major environmental changes are recorded by the foraminifera and ostracod assemblages preserved in the late Holocene sediments of the Boca do Rio lowland in the southern Algarve coast of Portugal, and these environmental changes can be dated using the

OSL method. The number of individual microfossils occurring in each of the four sediment units comprising the sediment infill of this lowland as well as the composition and size of the tests, preservation and faunal diversity, allow the distinction of two major environmental changes.

The first is characterised by a transition from sand to mud-dominated sedimentation in association with a change from marine to brackish-water foraminifera and ostracod assemblages, and can be linked to the moment when the beach barrier became established as an efficient hydrodynamic filter, providing shelter to the estuarine lowland and allowing freshwater sedimentation to gradually take over. The OSL dates suggest that this episode took place between 1800 and 1300 years ago, a time interval that may be related to large-scale changes in the sediment budgets of other Atlantic coastal locations of the Iberian Peninsula. The process of barrier formation seems to have been relatively rapid, causing a pronounced alteration in the local pattern of sedimentation, and was apparently related to climate change rather than to a slowing down in the rate of sea-level rise, which is known to have occurred well before this time.

The second change is well defined by both the foraminiferal and ostracod assemblages as well as by sedimentological criteria, and relates to the massive coastal flooding generated by the 1755 Lisbon earthquake. Stress release associated with the earthquake may have resulted in co-seismic subsidence of the land surface, allowing tidal influence to return for a short period of time. In the period since 1755, uplift caused by tectonic stress as a result of the collision of the African and Eurasian plates, together with vertical accretion of the barrier and lowland appears to have inhibited tidal waters from reaching the lowland, giving rise to the present-day fluvial environment.

Acknowledgements

This work was funded by the Commission of the European Communities, Directorate General for Science, Research and Development (DG XII), Environment Programme, as part of the projects ‘Climate Change and Coastal Evolution in Europe’ (EV5V-CT94-0445) and ‘Genesis and Impacts of Tsunamis on the European Coast-GITEC’ (EV5V-CT92-0175).

References

Andrade, C. 1992 Tsunami generated forms on Algarve barrier islands – Science of Tsunami Hazards 10: 21–34

Andrade, C., R. Hindson, C. Freitas & A. Dawson 1994 Sedimentary evidence of tsunami flooding in Algarve coastal lowlands. In: Carvalho, G. & F. Gomes (eds) Littoral ’94, Proc. 2nd Internat. Sympos. Eurocoast, Lisboa: 1035–1036

Athersuch, J., D. Horne & J. Whitaker 1989 Marine and brackish water Ostracods – Synopsis of the British Fauna (New Series) 43, Brill, Leiden, 343 pp

Bonaduce, G., G. Ciampo & M. Masoli 1975 Distribution of Ostracods in the Adriatic Sea – Pubblicazione staz. zool. Napoli 40, Suppl. 1, 315 pp

Bettencourt, P. 1994 Les environnements sédimentaires de la Côte Sotavento (Algarve, Sud Portugal) et leur évolution Holocène et actuelle – PhD Thesis, University of Bordeaux, 112 pp

Buforn, E., A. Udias & M. Colombas 1988 Seismicity source of the mechanics of the Azores – Gibraltar plate boundary – Tectonophysics 152: 89–118

Cabral, J. 1993 Neotectonica de Portugal continental – PhD Thesis, University of Lisbon, 435 pp

Cearreta, A. 1989 Foraminiferal assemblages in the ria of San Vicente de la Barquera – Rev. Española Micropalaeontol. 21: 67–80

Cearreta, A. 1994 Análisis micropalaeontológica y interpretación palaeoecológica del relleno sedimentario Holocénico en el estuario del Bidasoa (Golfo de Biskaia) – Geobios 27: 271–283

Dabrio, C., M. Polo, C. Zazo, M. Hoyos, J. Lario, J. Goy, F. Sierro, J. Flores, A. Gonzalez, T. Bardaji & F. Borja 1996 Late Holocene sequence of sea level oscillations in the southwestern Spanish Atlantic coast. Recent climatic changes and forecast for future coastal changes and hazards – Unpublished Report, Project Climate Change and Coastal Evolution in Europe, contract EV-0445, Universidad Complutense de Madrid. In: De Groot, T.A.M. (ed.) Climate Change and Coastal Evolution in Europe, Final Report. Rijks Geol. Dienst, Haarlem, 3: 11-1–11-30

Dabrio, C.J., C. Zazo, J. Lario, J.L. Goy, F.J. Sierro, F. Borja, J.A. Gonzàlez & J.A. Flores (this issue) Sequence stratigraphy of Holocene incised-valley fills and coastal evolution in the Gulf of Cadiz (southern Spain).

Dawson, A., R. Hindson, C. Andrade, C. Freitas, R. Parish & M. Bateman 1995 Tsunami sedimentation associated with the Lisbon earthquake of 1 November AD 1755: Boca do Rio, Algarve, Portugal – The Holocene 5: 209–215

Galhano, M. 1963 Foraminiferos da costa de Portugal (Algarve) – Publ. Inst. Zool. Dr Augusto Nobre 89, Fac. Ciências do Porto, 104 pp

Goy, J., C. Zazo, C. Dabrio, J. Lario & F. Borja 1995 Global and regional factors controlling changes of coastlines in southern Iberia during the Holocene – Abstr. Intern. Geolog. Correl. Project (IGCP) 367, 2nd Annual Meeting, Antofagasta, Chile: 37

Haynes, J. 1973 Cardigan Bay Recent Foraminifera (Cruises of the R.V. Antur, 1962–1964) – Bull. British Museum (Natural History), Zool. Suppl. 4, 245 pp

Haynes, J. & M. Dobson 1969 Physiography, foraminifera and sedimentation in the Dovey estuary (Wales) – Geol. J. 6: 217–256

Kilkenyi, T.I. 1969 The problems of ostracod ecology in the Thames estuary – In: Neale, J.W. (ed.) The Taxonomy, Morphology and Ecology of Recent Ostracods. Oliver & Boyd, Edinburgh: 268–298

Lario, J., C. Zazo, C. Dabrio, L. Somoza, J. Goy, T. Bardaji & P. Silva 1995 Record of recent Holocene sediment input on spit bars and deltas of south Spain – J. Coastal Research Spec. issue 17, Holocene Cycles: Climate, Sea Levels and Sedimentation: 241–245

Murray, J. 1971 An Atlas of British Recent Foraminiferids. Heinemann Educational Books, London, 244 pp

Murray, J. 1973 Distribution and Ecology of Living Benthic Foraminiferids. Heinemann Educational Books, London, 274 pp

Murray, J. 1979 British nearshore Foraminiferids – In: Kermack, D.M. & R.S.K. Barnes (eds) Synopsis of the British fauna (New Series) 16. Academic Press, London, 68 pp

Murray, J. 1991 Ecology and Palaeoecology of Benthic Foraminifera. Wiley, New York, 397 pp

Murray, J. & A. Hawkins 1976 Sediment transport in the Severn Estuary during the past 8,000–9,000 years – J. Geol. Soc. London 132: 385–398

Parish, R. 1992 The application of sedimentological analysis and luminescence dating to waterlain sediments from archaeological sites – PhD Thesis, University of Durham, UK, 183 pp

Penney, D.N. 1987 Application of Ostracoda to sea-level studies – Boreas 16: 237–247

Pereira, A. & A. Soares 1994 A estabilização holocénica do nível do mar. Vestígios no litoral de Armação de Pera – Gaia 9: 91–94

Prescott, J. & J. Hutton 1988 Cosmic ray and gamma ray dosimetry for TL and ESR – Nuclear tracks and radiation measurements 14: 223–227

Ribeiro, A. 1994 Deformable plate tectonics of the Azores-Gibraltar boundary: where the next 1755 earthquake will strike again? – Gaia 9: 109–113

Scott, D. & F. Medioli 1986 Foraminifera as sea level indicators – In: Van de Plassche, O. (ed.) Sea level research: a manual for the collection and evaluation of data – Geo. Books, Norwich: 435–456

Silva, C., R. Hindson & C. Andrade 1996 Bioerosion evidence of extreme marine flooding of Algarve region (southern Portugal) associated with the tsunami of the AD 1755 Lisbon earthquake: taphonomic and palaeoecological analysis – Actas, II Reunion de Tafonomia y Fosilizacion, Zaragoza: 371–378

Soares, A. 1993a O teor em 14C das conchas marinhas: evidências da variabilidade do 'upwelling' costeiro em Portugal durante o Holocénico – Actas, 3ª Reunion del Quatern. Iberico, Coimbra: 105–115

Soares, A. 1993b The 14C content of marine shells: evidence for variability in coastal upwelling off Portugal during the Holocene. Proc. Internat. Sympos. Applications of Isotope Techniques in the Study of Past and Current Environmental Changes in the Hydrosphere and the Atmosphere, Vienna: 471–485

Whatley, R.C. 1983 The application of Ostracods to palaeoenvironmental analysis – In: Maddocks, R.F. (ed.) Applications of Ostracods. Geoscience University of Houston: 51–77

Whitaker, J.E. 1981 The living Ostracods of Christchurch harbour, Dorset. In: Neale, J.W. & M.D. Brasier (eds) Microfossils from Recent and Fossil Shelf Sea. Ellis Horwood, Chichester: 293–303

Williams, H. 1995 Foraminiferal record of recent environmental change: Mad Island Lake, Texas – J. Foraminif. Research 25: 167–179

Zazo, C., J. Lario, J. Goy, A. Lezine, H. Faure, C. Dabrio, L. Somoza & F. Borja 1994 Late Pleistocene and recent Holocene rapid coastal changes in south Iberia – Abstr. 1st Int. Meeting Intern. Geolog. Correl. Project (IGCP) 367 'Late Quaternary Coastal Records of Rapid Change' Scotland, UK: 56