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Com os melhores cumprimentos,
Carlos Marques da Silva

BIOEROSION EVIDENCE OF EXTREME MARINE FLOODING OF ALGARVE REGION (SOUTHERN PORTUGAL) ASSOCIATED WITH THE TSUNAMI OF THE AD 1755 LISBON EARTHQUAKE: TAPHONOMIC AND (PALAEO) ECOLOGICAL ANALYSES

Carlos MARQUES DA SILVA[1], Robert HINDSON[2] & César ANDRADE[3]

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ABSTRACT

The faunal remains and ichnological structures (bioerosion) preserved in boulders collected from a distinct layer of the sediment infill of the Boca do Rio lowland (Algarve, South Portugal) were studied. The results of the taphonomic and (palaeo)ecological analyses indicate that the boulders were originally exposed to a high energy, non-depositional, sand bypassing marine environment that was later replaced by a low energy, fine grained sediment depositional environment. These results are consistent with a hypotheses suggesting that the boulders were lifted from their original location (a shallow open marine environment) and suddenly injected into the middle estuary area of Boca do Rio by a single short lived high magnitude event of marine flooding —the tsunami generated by the Lisbon earthquake of 1st November AD 1755— that disturbed the local low energy lagoonal-estuarine sedimentation pattern.

[1] Departamento de Geologia da Universidade de Lisboa. Rua da Escola Politécnica, 58. P-1294 LISBOA CODEX. PORTUGAL. Centro de Geologia da Universidade de Lisboa. Grupo Paleo. Grupo de Paleontologia do Museu Nacional de História Natural da Universidade de Lisboa.

[2] Division of Geography. Coventry University. Priory St. COVENTRY CV1 5FB. U.K. Centre for Quaternary Studies. School of Natural and Environmental Sciences. Coventry University.

[3] Departamento de Geologia da Universidade de Lisboa. Edifício C2, 5.º Piso. Campo Grande. P-1700 LISBOA. PORTUGAL. Centro de Geologia da Universidade de Lisboa.

INTRODUCTION

The site of Boca do Rio in the western Algarve coast of Portugal, is known to have been extensively affected by the tsunami that accompanied the Lisbon earthquake of 1st November AD 1755. Two types of evidence are available to support this statement: eyewitness records (Pereira de Sousa, 1919, Dawson et al., 1995) and the geological record (Andrade et al., 1994; Dawson et al., 1994, 1995). The latter type of evidence has been the subject of recent research, which has focused on the sedimentology of a particular layer recorded in the stratigraphic column and assumed to represent the positive residue of the flooding of this lowland area by that specific tsunamigenic event.

During the summer of 1994 a trench was excavated at this location, approximately 450 m inland, in order to study the lowland sedimentary sequence. The trench produced abundant pebbles, cobbles and boulders, some of which preserved assemblages of epi- and endolithic organisms as well as their macrobioerosion structures.

These faunal remains and bioerosion structures, their taphonomy and (palaeo)ecology, are analysed in this paper and their significance as evidence of extreme marine flooding of this particular site are discussed.

THE AD 1755 LISBON EARTHQUAKE

The Lisbon earthquake of 1st November 1755 was one of the most destructive seismic events of historical times, with an estimated Richter magnitude of 8.5 (Cabral, 1993). The earthquake had its epicentre approximately 200 km WSW of Cabo São Vicente (Western Algarve) and generated a tsunami that flooded an extensive portion of the Portuguese shore, including the Algarve coast. Near the Almádena fort (located 20 km East of Sagres) there are eyewitness accounts of the sea invading the Boca do Rio lowland to a distance of about 2.5 km inland and having a wave height of 11-13 m. The force of the tsunami inundation is demonstrated in the reference to 50 anchors having been carried over 1 km inland.

THE STUDY SITE

General setting

The site of Boca do Rio is located at approximately 37.° 04' North latitude, 08.° 48.5' West longitude, on the South coast of the Algarve, Portugal (Fig. 1). Boca do Rio is a flat-bottomed fluvial valley, that constitutes a small lowland in the otherwise cliffed coast of the Western Algarve. This lowland area consists of a supralittoral floodplain that is periodically subjected to extensive river flooding. About 1 km inland, at its northern end, it splits into three smaller distinct tributaries (Dawson et al., 1995).

The valley is separated from the sea by a low shingle and sand barrier that together with a rocky spur prevent wave-overtoping during storms. The beach occupies a short and narrow inlet (about 150 m wide), cut in the rocky outcrops of Cretaceous limestones, locally interrupting the cliffed coast line.

Immediately to the East and West of the Boca do Rio beach the meso- and upper infralittoral zones are extensively occupied by Cretaceous limestone boulders —covering a sublittoral shore platform—, resulting from cliff erosion, some of them bearing present-day macrobioerosion structures similar to those studied in this paper.

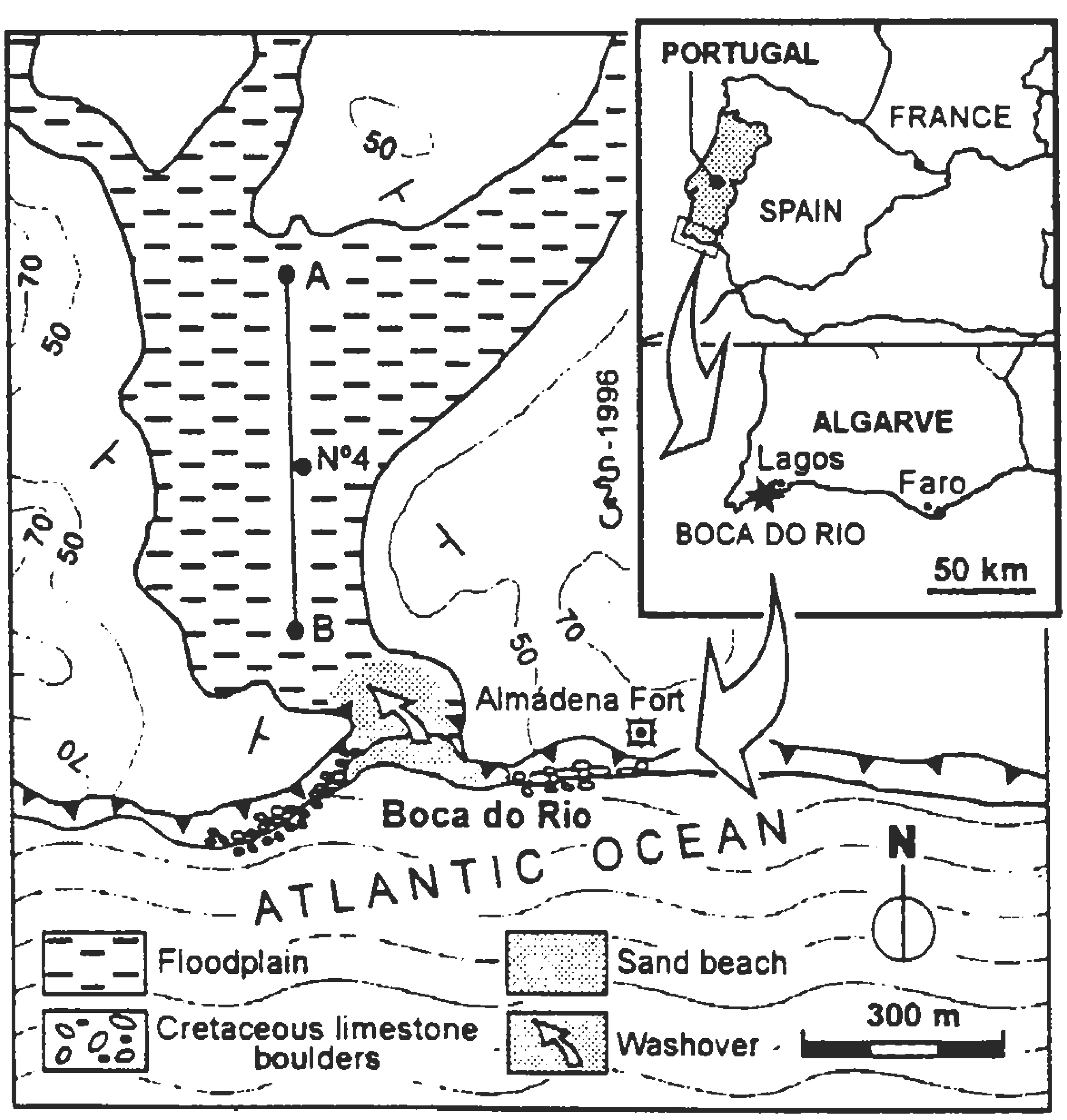

Figure 1. Location map and study area. Line A-B indicates cross section shown in Figure 2.

STRATIGRAPHY

The stratigraphy of this site is summarised in Figure 2. The Late Holocene valley infilling consists of four distinct sedimentary units which are referred to as Units A, B, C and D.

Unit A

This unit comprises the uppermost layer of the sedimentary sequence and is activated today by flooding episodes during the rainy season. It consists of dark red/brown silty clay with a thickness of 0.8-1 m that thins out and disappears towards the overwash fan.

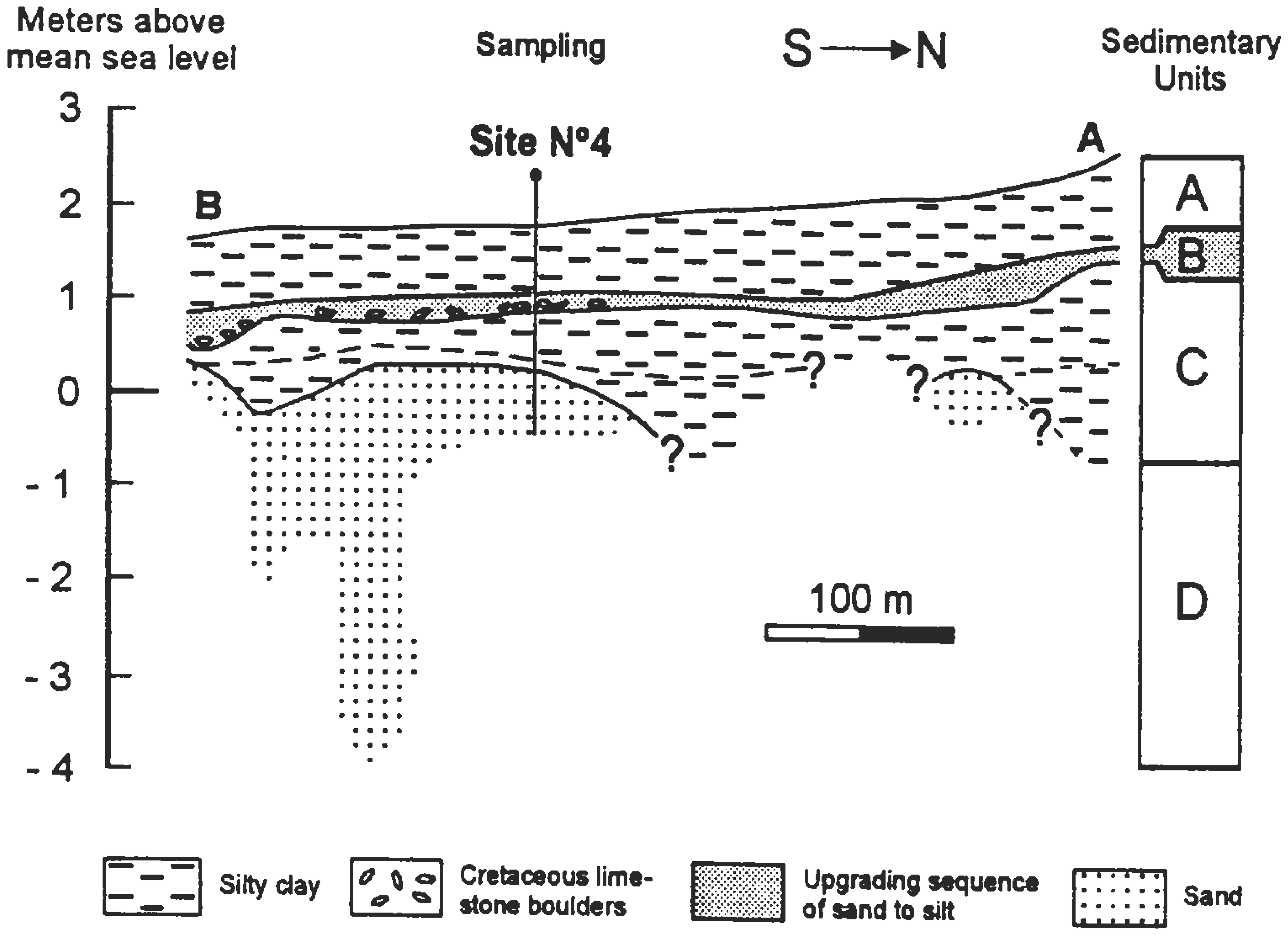

Figure 2. Summary stratigraphy of the Boca do Rio Lowland (see text for explanation). Trench opened at coring site N.° 4.

Unit B

This unit is laterally variable in terms of both its thickness and its sedimentary characteristics. It reaches a maximum thickness of 0.45 m, although locally it may be absent. Unit B is sedimentologically very complex, and the simplest way of describing it is to consider a further subdivision into two distinctive subunits, that are generally present. Basal subunit - This subunit is referred to as the «chaotic layer». Its lower contact is erosional and its upper contact highly irregular. It consists of a massive, structureless matrix-supported mass of sediment ranging from a muddy/sandy conglomerate to a coarse muddy sand. Most of the coarser fraction is represented by carbonate lithoclasts (limestones and dolomitic limestones) which are poorly sorted and range from several millimetres up to 40 cm in diameter. Some of the larger boulders display abundant borings of marine endolithobionts and the attached shells of epilithic organisms. Shell fragments are also quite abundant in the matrix (up to several centimetres long) showing angular edges and associated with muddy (sometimes sand-armoured) balls apparently eroded from the underlying sediments. Upper subunit - The upper subunit generally consists of an upgrading sequence of sand to silt. The sand is medium grained, clean, yellowish and contains shell fragments and rare small pebbles or mudballs. Previous work on this sediment revealed landward fining and a similarity with recent marine sands, suggesting that deposition of this unit had taken place as a result of a marine flooding event. Dating of this sand using thermoluminescence (TL) procedures indicated a maximum age of 260 ± 60 years —AD 1734 (Dawson *et al.*, 1995).

Unit C

The upper section of this unit is indistinguishable from Unit A, consisting of the same brown mud with occasional plant matter and charcoal. At some sites, the brown mud grades down into a black organic mud with distinct in situ rootlets and plant remains. The total thickness of Unit C varies between 0.5 and 1 m.

Unit D

This unit forms the base of the known sequence of the Boca do Rio site, consisting of marine grey sands with shells. Unit D was cored down to a maximum extent of approximately 5 m below ground surface, without encountering a basal contact.

THE STUDY OF THE BIOEROSION STRUCTURES

FAUNAL AND ICHNOLOGICAL CONTENTS OF THE BOULDERS

The ten largest boulders incorporated in the «chaotic layer» (Unit B, basal subunit) collected from site N.°4 (Fig. 2) were washed and analysed for their faunal and ichnological contents. Three of them (boulders N.°1, 2 and 9) display a heavily biogenic bored surface and the abundant skeletal remains of endo- and epilithic organisms. The studied boulders are similar, both in lithology and macrobioerosion sculpture, to many of those presently found in the neighbouring meso- and upper infralittoral zone of the Boca do Rio beach.

Boulder N.°1 (Figs. 3.1-3.3). Dimensions (cm): 22.0x13.0x10.5. Epilithobionts: Bryozoa (rare, unidentified colonies); Polychaeta (rare, unidentified tubes). Endolithobionts: Mollusca, Bivalvia, nearly thirty specimens of *Petricola lithophaga* (Retzius) and one fragmented specimen of *Lithophaga cf. lithophaga* (Linnaeus) inside their borings (in situ). Bioerosion structures: Several dozens of tightly packed ichnospecimens of *Gastrochaenolites* Leymerie (*Gastrochaenolites ichnosp.* and, at least, one of *G. torpedo Kelly* & Bromley, produced by the bivalve *L. lithophaga*) covering one side of the boulder almost completely; abundant ichnospecimens of *Entobia* Bronn (sponge structures) covering almost all the boulder's surface; 3-5 ichnospecimens of *Caulostrepsis* Clarke (polychaete annelid structures) and several «*Tripanites*-like» structures - simple cylindrical, more or less meandering borings, with a single aperture.

Boulder N.°2 (Fig. 3.4). Dimensions (cm): 15.4x12.3x8.5. Epilithobionts: Not found. Endolithobionts: Mollusca, Bivalvia, nearly ten specimens of *P. lithophaga* inside their borings (*in situ*). Bioerosion structures: Fifteen ichnospecimens of *Gastrochaenolites* ichnosp. structures produced by the bivalve *P. lithophaga*; nearly thirty ichnospecimens of *Caulostrepsis ichnosp.*, some of them of very small dimensions (max. diameter of the dumb-bell-shaped aperture: 1-3 mm) and one ichnospecimen of *Entobia ichnosp.*

Boulder N.° 9 (Figs. 3.5-3.6). Dimensions (cm): 18.0x14.8x11.5. Epilithobionts: Bryozoa (rare, unidentified colonies); Polychaeta (rare, unidentified tubes); Arthropoda, Crustacea, Cirripedia, Balanomorpha (remains of nearly one dozen heavily perforated unidentified barnacle tests). Endolithobionts: Mollusca, Bivalvia, nearly ten specimens of *P. lithophaga* still inside their borings (*in situ*). Bioerosion structures: Several dozen tightly packed ichnospecimens of *Gastrochaenolites ichnosp.* structures; abundant specimens of *Entobia ichnosp.* covering almost all the boulder's surface and rare (2-3) specimens of *Caulostrepsis ichnosp.*

TAPHONOMY

The taphonomic analysis of the faunal remains and the bioerosion structures preserved in the boulders from the «chaotic layer» has shown that the *post mortem* infilling of the shells of *P. lithophaga* and/or the corresponding borings is not uniform and it is not generally consistent with the sediment that presently encloses the boulders.

Several specimens of *P. lithophaga* (with both valves preserved), as well as their bioerosion structures (ichnogen. *Gastrochaenolites*), contain a first generation infilling of clean medium white sand (Fig. 3.6) that was sometimes found in association with an outer plug of dark reddish-brown silty clay, quite similar in colour and texture with the sediment from Units A and C (Fig. 3.2). Other specimens were infilled either by sand (semiconsolidated by reddish-brown clay) or entirely by clay (Fig. 3.3).

The heterogeneous character of the infilling of both shells and borings and the inconsistency of part of the infillings with the enclosing sediment —associated with their (palaeo)ecological interpretation— suggest that the boulders have been associated with two distinct depositional environments: first, a high energy, non-depositional and sand bypassing environment (where the bioerosion structures have been produced) that was later replaced by a quiet, fine grained sediment depositing environment (probably responsible for the death of —at least— part of the endolithic community).

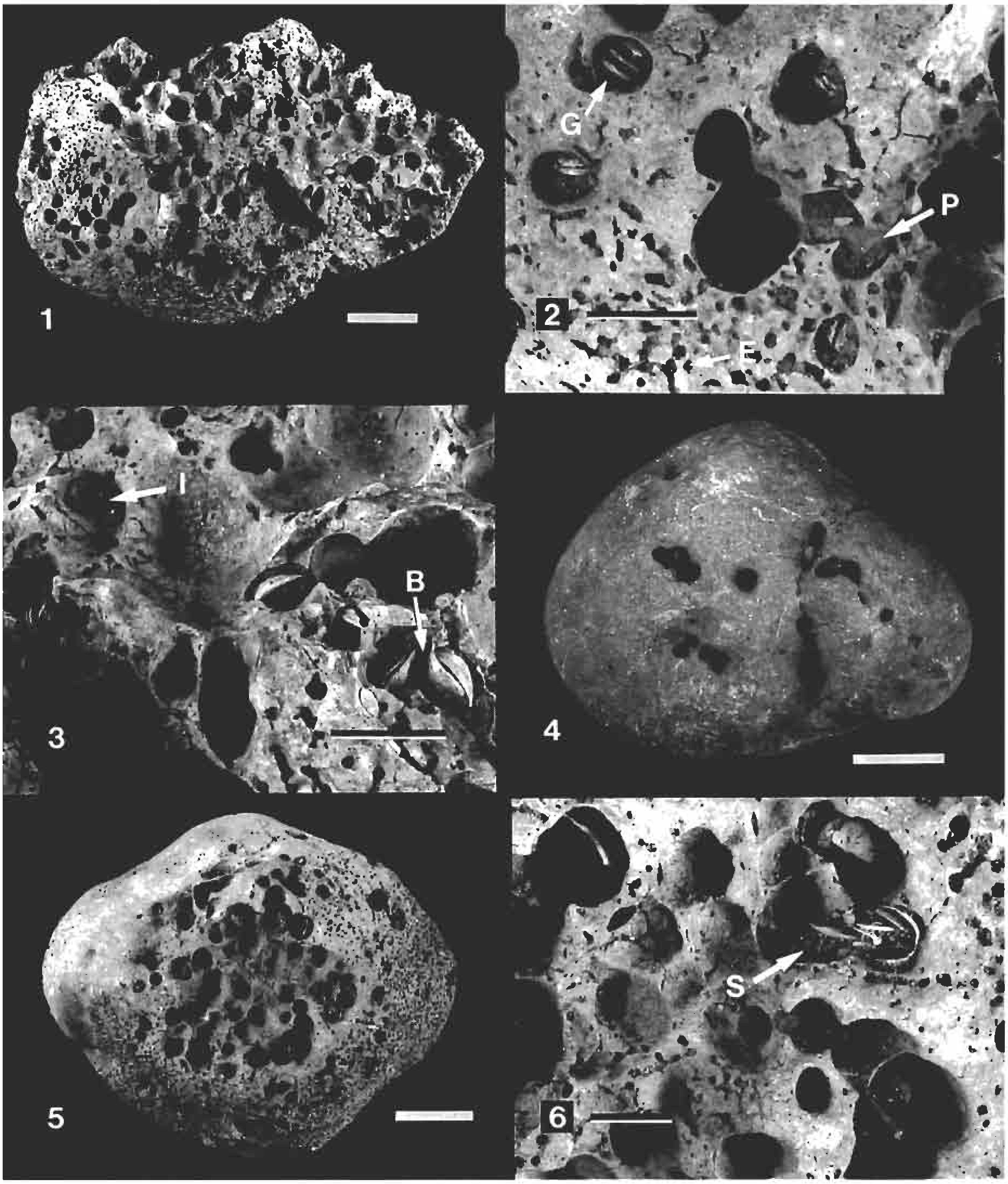

Figure 3. Studied material.

1. Boulder N.º 1.
2. Detail of 1: note the outer plug of silty clay covering *Gastrochaenolites ichnosp.* borings:
P) Silty clay plug; E) *Entobia ichnosp.* borings. G) *Gastrochaenolites ichnosp.* borings.
3. Detail of 1: note the silty clay infilling of *Gastrochaenolites ichnosp.* borings. I) Silty clay infilling;
B) In situ shells of the bivalve *Petricola lithophaga* (Retzius).
4. Boulder N.º 2.
5. Boulder N.º 9.
6. Detail of 5: note the first generation infilling of clean medium sand inside *Gastrochaenolites ichnosp.* borings:
S) Sand infilling. (See text for explanation). Scale bar in 1, 4 and 5: 3 cm; in 2, 3 and 6: 1 cm.

(Palaeo)ecology

The faunal assemblage (both endo- and epilithobionts) associated with the boulders collected from the «chaotic layer» (Unit B, basal subunit) at site N.º4 is dominated by the endolithic bivalve *P. lithophaga* (several dozens of empty shells. Figs. 3.2-3.3) and endolithic clionid sponges (only *Entobia* borings were preserved. Fig. 3.2). Both *P. lithophaga* and the clionids are marine organisms, *P. li-*

thophaga living in mesolittoral and infralittoral environments (Saldanha, 1995) and clionids being restricted to sublittoral environments (Hartmen. 1958 and Rützler. 1975 *fide* Feige & Fürsich. 1991).

The close examination of the boulders has revealed a well-developed macrobioerosion sculpture produced by endolithic bivalves, sponges and polychaetes. The identified ichnoassemblage of bioerosion structures is dominated by tightly packed borings assigned to the ichnogenera *Gastrochaenolites* and *Entobia,* although *Caulostrepsis* and «*Trypanites*-like» structures (the latter only in boulder N.º 1) were also found (Figs. 3.1, 3.5).

According to Bromley (1994: 146): «Macrobioerosion is almost exclusively a marine process.»; moreover «[...] ichnospecies of *Gastrochaenolites* are generally shallow-water trace fossils, and where individuals are crowded and dominate the assemblage only a few meters of water may be inferred.» (op. cit.: 147). On the other hand, all groups of endolithic organisms (endolithobionts) require low rates of sedimentation, especially the endolithic sponges responsible for *Entobia* borings.

Thus, the studied assemblage of faunal and ichnological remains present in the boulders suggests that the boulders where initially associated to a rocky shore environment - a very shallow marine environment with a low rate of sedimentation. This same environment can presently be found in the meso- and upper infralittoral zone in the vicinity of the Boca do Rio beach, where the cliffed coast is the dominant morphological feature.

CONCLUSIONS

In this particular study, taphonomic analysis has enabled us not only to judge the (palaeo)ecological usefulness of both faunal and ichnological elements present but also, and in this case perhaps even more important, to assess the different environmental/sedimentary conditions to which the boulders were successively exposed.

The study of the faunal remains and the bioerosion structures, their taphonomy and (palaeo)ecology. associated with the boulders collected in the «chaotic layer» (Unit B, basal subunit, site N.º 4) of the Boca do Rio lowland (Algarve, Southern Portugal) demonstrates that the boulders were originally exposed to a marine environment and that they most probably originate from the nearby meso- and upper infralittoral zone around the Boca do Rio beach, thus unquestionably linking their deposition in the lowland area to an extreme marine flooding event.

The studied boulders exhibit associations of endo- and epilithic organisms and bioerosion structures that suggest a shallow marine environment associated with sand bypassed rocky shores. an environment that can presently be found in the meso- and upper infralittoral zone in the vicinity of the Boca do Rio beach. From a taphonomic point of view, the different *post mortem* infilling of the shells and the corresponding bioerosion structures are consistent with the hypotheses suggesting that these boulders were lifted from their original location (a shallow open marine environment) and suddenly injected into the middle estuary area by a single high energy event, the tsunami of the Lisbon earthquake of the 1st November 1755. The muddy material which plugs the inner sand rich *post mortem* infillings is due to the incorporation of muddy sediment during the catastrophic event and/or fine grained sedimentation within the estuarine environment.

The results obtained earlier from stratigraphy, grain size analysis, foraminifera and calcareous nannoplankton studies at Boca do Rio, suggest that lithostratigrafic Unit B is quite distinct from the remaining sedimentary horizons encountered. The rest of the sequence (Units A and C) represents the progressive infilling of the valley by fine grained sediments overlying a sandy bottom (Unit D) disturbed by a single depositional event of marine origin (Dawson et al. 1995). The basal Unit D represents shallow marine sedimentation that was slowly replaced by intertidal estuarine (lagoonal?) muds (Unit C) and finally fluvial muds (Unit A) to arrive at the present day situation. Thus, Unit B seems to represent a single, high energy, catastrophic event of marine origin.

This hypothesis is herein confirmed by the taphonomnic and (palaeo)ecological analysis of faunal and ichnological (bioerosion) elements associated with the boulders included in the lower «chaotic layer» of Unit B.

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