

BIO-SEDIMENTARY SIGNATURES OF HIGH-FREQUENCY SALINITY/SUBAERIAL EXPOSURE CHANGES: EXAMPLES FROM THE OXFORDIAN OF PORTUGAL (CABAÇOS FORMATION)

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Abstract. The detailed sedimentary and micropalaeontological analysis of a complex association of continental to marginal-marine deposits from the Oxfordian of Portugal (Cabaços Formation) has allowed the recognition of high-frequency, subtle changes in the environmental conditions. The main factors controlling the palaeobiological responses to such minor-scale fluctuations were also identified. Two factors have shown to be especially significant: subaerial exposure duration and frequency (estimated by assigning type of features to the exposure index) and salinity trends, as suggested by the sedimentary and fossil records. In the west of the basin, salinity fluctuations were much stronger and more frequent (fresh-brackish-restricted marine-hypersaline), and subaerial exposure more marked for longer periods, than in the east of the basin. The microfossil assemblages, as a whole, but in particular the ostracod faunas, show differences in abundance, diversity, dominant species, degree of intrageneric and intraspecific variations, both along the successions and between west and east. The western populations seem to have been much less stable, which suggests that high-frequency changes in salinity (more than its absolute values) and degree of exposure were the most important controls on the palaeobiota.

Riassunto. La dettagliata analisi sedimentaria e micropaleontologica di un complesso d'associazioni di depositi da continentali a marini marginali dell'Oxfordiano del Portogallo (Formazione Cabaços) ha permesso il riconoscimento di sottili cambiamenti ad alta frequenza nelle condizioni ambientali. Sono stati inoltre identificati i principali fattori che controllano le risposte paleobiologiche a tali fluttuazioni di piccola scala. Due fattori si sono dimostrati essere specialmente significativi: durata e frequenza dell'esposizione subaerea (stimata assegnando tipi di caratteri all'indice di esposizione) e gli andamenti della salinità, come suggerito dalla documentazione sedimentaria e fossile. Nella parte occidentale del bacino, le fluttuazioni di salinità erano più forti e più frequenti (da acqua dolce, a salmastro-ristretto a marino iperalino), e l'esposizione subaerea più marcata per periodi più lunghi, che nella parte orientale del bacino stesso. Le associazioni di microfossili, nel com-

plesso, ma in particolare le faune ad ostracodi, mostrano differenze in abbondanza, diversità, specie dominanti, grado di variazioni intrageneriche ed intraspecifiche, sia lungo le successioni che tra la parte occidentale ed orientale. Le popolazioni occidentali sembrano essere state molto meno stabili, il che suggerisce che i cambiamenti della salinità ad alta frequenza (più che i suoi valori assoluti) ed il grado di esposizione erano i controlli più importanti sui paleobiota.

Introduction

An integrated sedimentary and micropalaeontological analysis of a complex association of continental to marginal-marine deposits from the Oxfordian of west-central Portugal (Lusitanian Basin; Fig. 1) was recently developed. The integrated approach of these particular range of facies types, that were studied at several locations in the basin, has allowed the recognition of high-frequency, subtle changes in the environmental conditions not evidenced by previous, less detailed studies. As a consequence, the main factors controlling the palaeobiological responses to those minor-scale fluctuations could be identified.

Two aspects have shown to be especially significant, and are the main focus of this paper: type of subaerial exposure features (hence duration and frequency of exposure) and salinity trends as suggested by the fossil and sedimentary records. Matching of the sedimentary and palaeontological signatures at a basinal scale has also revealed two basic patterns, one recorded in the western successions and the other in the eastern successions. In this paper, a typically western (Pedrógão section; Fig. 1) and a typically eastern (Vale de Ventos section; Fig. 1) successions are presented as «case studies».

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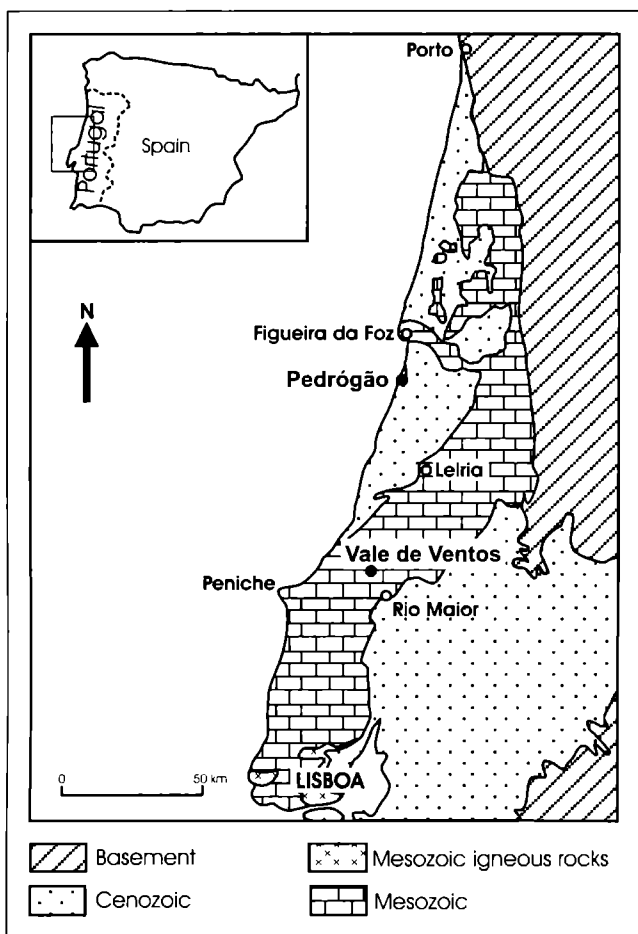


Fig. 1 - Simplified geological map of the Lusitanian Basin (west-central Portugal), with location of the studied field sections (Pedrógão and Vale de Ventos).

Stratigraphical setting

The Lusitanian Basin, in west central Portugal (Fig. 1), is one of the marginal basins associated with the opening of the North Atlantic Ocean. Most of the basin infill is Jurassic in age, but sediments from the Upper Triassic to the Upper Cretaceous occur, with a Tertiary cover. The Middle Jurassic is separated from the Upper Jurassic by a basinwide disconformity and stratigraphical gap which, as regards to ammonoid record, spans at least from the latest Callovian to the end of the early Oxfordian (Lamberti, Mariae and Cordatum zones are not recognised) but, in places, the disconformity surface is developed on Upper Bathonian limestones (Ruget-Perrot 1961; Ramalho 1971; Mouterde et al. 1979; Azerêdo et al. 1998). A disconformity at the Middle-Late Jurassic transition is widespread around Atlantic margin basins, with both eustatic and tectonic explanations for its origin having been proposed (see references in Azerêdo et al. 2002a).

The early Upper Jurassic deposits belong to the informal Cabaços formation, which is composed of varied continental, transitional to marginal-marine and shallow-marine facies types (e.g. Ramalho 1971a; Wilson 1979;

Leinfelder 1983; Wright 1985; Azerêdo et al. 1998, 2002a, b). The Cabaços formation is very rich in ostracods and charophytes, associated with other organisms. It lacks good biostratigraphical markers, but is traditionally attributed to the Middle Oxfordian. The dasycladacean *Heteroporella lusitanica* (Ramalho, 1970) is the best bio-marker, because it has a basinwide occurrence in this formation (Ramalho 1970, 1971a, b, 1981), being succeeded by (locally, apparently equivalent to?) marine beds with Middle Oxfordian ammonites (*Plicatilis* and *Transversarium* zones - cf. Ruget-Perrot 1961; Ramalho 1971a, b; Mouterde et al. 1979). However, *H. lusitanica* is virtually absent in the lowermost part of the Cabaços formation which, therefore, may also encompass the Lower Oxfordian (Azerêdo et al. 2002b).

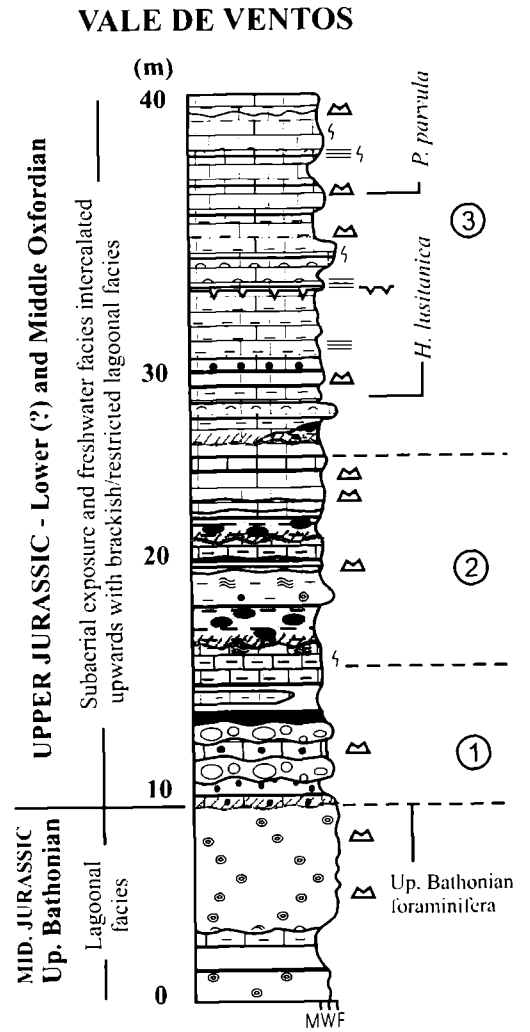
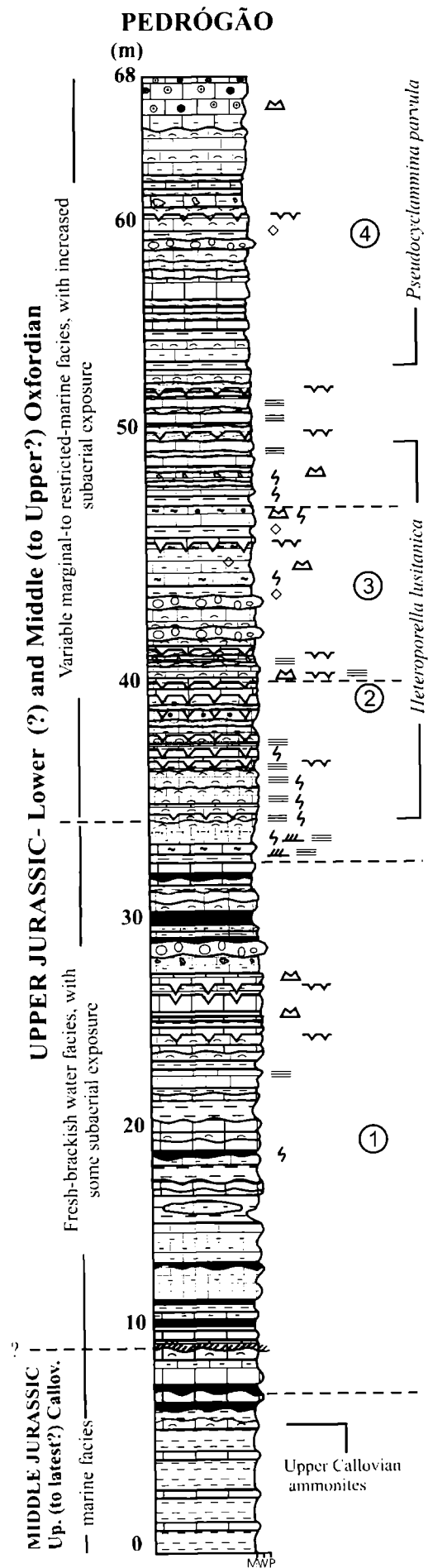
The foraminifera *Pseudocyclammina parvula* Hottinger, 1967 and/or *Alveosepta jaccardi* (Schrodt, 1894) appear in the more marine influenced facies which succeed or laterally replace the lagoonal facies with *H. lusitanica* (Ramalho 1971a, b, 1981; Azerêdo et al. 1998, 2002b). In Portugal, *P. parvula* is reported from the Middle Oxfordian-Tithonian, and *A. jaccardi* from the Middle Oxfordian-Kimmeridgian (Ramalho 1971a, 1981, 1985; Leinfelder 1983; Leinfelder et al. 1988; Azerêdo et al. 2002b).

Selected sections

The two sections selected here (Pedrógão and Vale de Ventos), are those for which current dataset is most complete, thus being the most reliable examples of the applied methodology. They illustrate the two typical patterns of facies evolution and palaeoecological associations recognized in the studied successions: Pedrógão the seaward zone of the basin (west) and Vale de Ventos the landward zone (east). The main relevant features are summarized in Tabs. 1 and 2, in which, in addition, particular topics are highlighted (namely, evidence for subaerial exposure, ostracod assemblages significance and inferred salinity trends). The lithostratigraphical logs for each section are also presented (Fig. 2).

The main previous publications referring to the Oxfordian from Pedrógão and Vale de Ventos sections include: broader facies analysis, with detailed description

Fig. 2 - Lithostratigraphic columns of the studied sections: Pedrógão, western Portugal (left) and Vale de Ventos, eastern Portugal (right). Numbered subdivisions basically correspond to the ostracod associations. The same subdivisions are used in Tabs 1 and 2. Callovian ammonite dating (Pedrógão) after Ruget-Perrot (1961); Bathonian foraminifera dating (Vale de Ventos) after Azerêdo et al. (1998).



Key

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|--|---|--|--|
| | Mudstone: Wackestone: Packstone/Floatstone | | Microbial laminites/microbial laminitic clasts |
| | Limestone | | Pedogenic conglomerate |
| | Marly limestone | | Lignitic marls/clays |
| | Bioclastic limestone | | Marls/clays with ferruginous crusts |
| | Ferruginous limestone | | Evaporites relicts and moulds |
| | Litho/intraclastic limestone | | Parallel lamination |
| | Oolitic limestone | | Cross lamination |
| | Black-pebble limestone | | Bioturbation |
| | Oncolithic limestone | | Highly irregular ferruginous surface/ferruginous surface |
| | Marl/clay | | Undulated bedding |
| | Pedogenic limestone/limestone with pedogenic clasts | | Desiccation cracks |
| | | | Fenestrae |

and interpretation of sedimentary features and palaeoenvironments (Azêredo et al. 1998, 2002a); thematic papers on ostracods, including faunal lists of the species found in the different settings, and description of new genera and species (Cabral et al. 1998, 1999; Colin et al. 2000; Cabral & Colin 2002); thematic works on charophytes (Grambast-Fessard & Ramalho 1985; Pereira et al. 1998, 1999, 2003; Pereira 2002) and on palynomorphs (Barron et al. 1999; Barron & Azerêdo 2003); and an overview of micropalaeontological assemblages and palaeocological signatures across the Middle-Late Jurassic boundary in the Lusitanian Basin (Azêredo et al. 2002b).

Pedrógão section

The Pedrógão beach section is located 30 Km to the south of Figueira da Foz (Fig. 1). The lowermost levels of the succession (Fig. 2) are rich in ammonoids and brachiopods from the Late Callovian (Athleta Zone, in Ruget-Perrot 1961; Alméras et al. 1991). Upwards, a strongly marked irregular surface was recently documented, being interpreted as the local expression of the major Middle-Late Jurassic event (Azerêdo et al. 2002a).

Main data on the lithofacies, sedimentary structures, bedding patterns and fossil content are presented in Tab.1, where subdivisions 1 to 4 are equivalent to those in the log of Fig. 2 and were basically defined by the ostracod associations (Cabral et al. 1998). The Pedrógão succession clearly reflects a marked regressive change from an open marine setting (Callovian) into varied, shallow-water, coastal settings in the Oxfordian, from fresh-brackish paralic to marginal-marine restricted environments.

Discussion: The complex depositional system inferred for the Cabaços Formation in the west of the basin, here represented by Pedrógão, would have been mostly a low-energy, protected coastal system, freshwater-dominated as regards to the lowermost part of the succession, passing upwards into increasingly variable, highly fluctuating brackish to hypersaline conditions. The lower levels suggest only episodic to intermittent subaerial exposure, but passing upwards most frequent and lengthier subaerial exposure is clear. The evidence for this is multiple (Tab. 1). However, some aspects warrant further discussion.

In subdivision 1 (Tab. 1), the rarity of levels exhibiting exposure features, coupled with the common lignitic material, suggest that the sediment was predominantly wetted by low-circulation waters, though mostly oxygenated enough to support abundant non-marine benthic fauna and flora communities. Lower oxygen phases allowed organic matter preservation and probably massive death, or weakening, of organisms. Some of the stratified microfossil coquinas may represent such events, but other, including crudely oriented sediment laminae, most likely correspond to inundation events, as coquinas are even more common upwards.

Subdivision 2 corresponds to sediments very frequently exposed, but also frequently flooded, as evidenced by the repeated interlayering between bioturbated/fossiliferous deposits and levels with well-developed exposure features, in particular, the desiccation cracks on bedding surfaces. These mud-cracks are mostly 10-20 cm wide (locally 25-30 cm) shallow polygons, and the cracks are locally infilled with bioclastic sediment. According to the exposure index of Ginsburg et al. (1977), wide, shallow desiccation polygons indicate areas subaerially exposed for 60-100% of the time. The irregular fenestrae fall into the same category of the exposure index. The rare thin-layers of clotted micrite and algal/microbial laminae may be assigned to areas with 70-100% of exposure time, whereas the also rare thin microbial laminites suggest that, though locally significant, exposure phases were usually not long enough to favour more common and thicker microbial mats (because of frequent flooding and biological destruction). Smooth mats are typical of areas with less than 10% flooding frequency in the Trucial Coast (Kinsman & Park 1976), and Ginsburg et al. (1977) assigned smooth-flat lamina-

tion to zones with more than 90 % exposure time. The planar, stratiform morphology is also indicative of very low or absent tide or wave activity, hence of protected, low-energy settings (Purser 1980; Tucker & Wright 1990). The extremely rare cross-laminated layers also show that currents (storm, flooding, tides?) were only episodic.

Fluctuating water salinity, from transitional fresh-brackish, into brackish at times slightly more marine influenced, is evidenced by the range of fossil taxa (ostracods and charophytes, as below, but also dasyclad, foraminifera, serpulids, mollusks), the variations in their relative abundance and, in particular, by the changes in the ostracod fauna. In fact, this records the disappearance of the previously dominant oligohaline genus *Theriosynoecum*, whereas the euryhaline species *Sinuocythere pedrogaensis* Cabral and Colin, 2000 becomes dominant.

The sedimentary packet corresponding to subdivisions 3 and 4 of Tab.1 clearly show an increasing trend of subaerial exposure and of salinity fluctuations, between brackish-restricted marine and hypersaline phases. For instance, microbial laminites are much more common and thicker upwards. This is most probably linked with increasing exposure, but may also have been enhanced by higher-than-normal salinities, as these would inhibit grazing organisms on the mats, even if these were flooded. The observed microbial laminites dominantly include smooth-laminated stratiform types, but also a few low-relief (usually less than 4 cm, locally upwards 6-8 cm) domal stromatolites, with some desiccation breccias and tepee structures. All these features are diagnostic of very intense exposure (e.g. Purser 1980; Tucker & Wright 1990). Accordingly, laminar fenestrae (crinkled fenestral lamination) and sheet cracks occur (features diagnostic of 75-100% exposure, in Ginsburg et al. 1977), besides irregular fenestrae, vuggy porosity, desiccation cracks and key-stone-vugs with vadose cements in the grainy layers. The significant development of pedogenic features at some beds is obviously diagnostic of prolonged exposure phases. Evaporite relicts, calcite evaporite pseudomorphs and collapse-breccias indicate hypersalinity, probably due to both strong evaporation and reduced tidal flow and water renewal.

The palaeobiota signatures from this part of the succession (subdivisions 3 and 4) also suggest high-frequency salinity changes. In fact, the always abundant ostracod assemblages are increasingly less diversified towards the top, where monospecific ostracodites are common, locally closely associated with evaporite layer. The dominant species (*S. pedrogaensis*) also shows an increasing trend of its carapace sizes and a reticulate ornamentation that lacks in the same species in the lower part of the succession. However, marine incursions are reflected by the record of a marine species (*Galliacytheridea* n. sp. 1). This restricted marine influence may also be inferred, for example, from the more common occurrence of agglutinated foraminifera (including *Pseudocyclamina parvula*), limited presence of the ichnofossils *Thalassinoides* and *Rhizocorallium*, and rare echinoid remains. It may also be noted that the palynofacies shows lower-diversity and marine influence (Barron et al. 1999; Barron & Azeredo 2003). *H. lusitanica* is present but becomes rarer, and disappears at the base of subdivision 4, like the ichnofossils, which may be related to increased exposure and/or variable salinity. Charophytes also display much less diversified assemblages than below (Pereira et al. 1999, 2003; Pereira 2002).

Tab. 1 - Main features of the Oxfordian Cabaços formation from Pedrógão (western Portugal), highlighting the sedimentary and palaeobiota evidence for subaerial exposure and salinity variations. Numbered subdivisions basically correspond to ostracod associations (as in the log Fig. 3). F, B, M and H mean fresh, brackish, marine and hypersaline, respectively.

LITHOFACIES <i>(Subdivisions as in the log of Fig.2)</i>	SEDIMENTARY SIGNATURES		PALAEOBIOTA SIGNATURES		SALINITY TRENDS
	<i>Evidence for subaerial exposure</i>	<i>Other</i>	<i>Ostracods</i>	<i>Other</i>	<i>F - B - M - H</i>
④ Alternance of: fossiliferous, bioclastic and marly limestones, locally ferruginous or bituminous, thin to relatively thick microbial laminites, pedogenic limestone and conglomerates and evaporite layers. A few bioturbated beds at the base, and oolitic/intraclastic limestone at the top.	Desiccation cracks (wide, shallow polygons). Thicker microbial laminites (stratiform mats and a few very low-relief, filamentous-cyanobacteria rich protostromatolites). Clear pedogenic fabrics. Evaporite evidence. Vadose features (meniscus cement, keystone-vugs) at the top. <i>(Marked exposure)</i>	Common slightly irregular, undulated bedding surfaces. Thickening-upwards beds of packstones (dominantly) and wackestones (very rarely mudstone). At the top, oolitic/intraclastic packstone with vadose features.	Most abundant, including common ostracodites (some within microbial mats). <i>S. pedrogaensis</i> occurs almost exclusively (reticulate, but larger-sized carapaces than below), commonly in monospecific assemblages (namely as in the ostracod coquinas), locally closely associated with evaporites.	Last occurrence of the dayclad near the base. Ichnofossils (<i>Rhizocorallium</i> , <i>Thalassinoides</i>) also limited to these lowermost levels. Foraminifera more common (namely first appearance of <i>Pseudocyclammina parvula</i>). Decreasing abundance and lowest diversity of charophytes. Lower-diversity, marine-influenced palynofacies. Common gastropods and bivalves. Rare echinoid fragments.	
③ Fossiliferous, bioclastic and marly limestones, locally ferruginous or bioturbated; a few sandy marl layers, thin microbial laminites (including stromatolitic/peloidal micrite bindstone), pedogenic limestones and conglomerates, and evaporite beds. Rare intraclastic/oolitic levels.	Irregular and laminar fenestrae and vuggy-porosity. Keystone-vugs (within the intraclastic/oolitic beds). Desiccation cracks (wide, shallow polygons). Evaporite relicts and fabrics. Stratiform and a few very low-relief stromatolitic (protostromatolites) microbial mats, locally brecciated, and forming tepees. Clear pedogenic fabrics, namely nodules, brecciation. <i>(Marked exposure)</i>	Medium to thick-bedded, wackestones (mostly), with a few higher-energy deposits (plane-laminated packstones, with laminae formed either by bioclasts or by whole-fossil accumulations). Presence of reworked porostromate/stromatolitic fragments at a few levels.	Most abundant, lower-diversity assemblages, dominated by reticulate, slightly larger forms of <i>S. pedrogaensis</i> . Also <i>Galliaecytheridea</i> n. sp. 1 (marine species), <i>Klieana</i> n. sp. 2 and <i>Darwinula</i> spp.	Rarer <i>H. lusitanica</i> and agglutinated foraminifera (<i>Pseudocyclammina</i> sp., Verneuilinidae). Abundant but lower-diversity charophyte assemblages (gyrogonites). Gastropods (locally abundant small-sized shells) and bivalves. Disappearance of <i>Botryococcus</i> towards the top.	
② Fossiliferous, commonly bioturbated, bioclastic and intraclastic/oncolidal limestones, locally ferruginous, with a few marly and thin microbial laminite layers. Rare ferruginous surfaces.	Very common (increasing upwards) desiccation cracks (wide, shallow polygons). Rare, thin stratiform microbial mats and clotted micrite layers. Sporadic irregular fenestrae. <i>(Frequent, but intermittent exposure)</i>	Medium to thin-bedded, mostly wackestones and packstones, with intercalations of event deposits (plane- and cross-laminated layers). Fossil concentrations at some bedding surfaces. Bioturbation at many levels.	Most abundant, including a few ostracodite layers. Relative dominance of <i>S. pedrogaensis</i> , but showing small-sized, almost smooth carapaces. Disappearance of the genus <i>Theriosynoecum</i> .	Abundant dasyclad stems (1 sp., <i>Heteroporella lusitanica</i>), locally in coquinas. Some benthic foraminifera (<i>Kurnubia palastiniensis</i> , Verneuilinidae). Abundant charophytes (but less than below), mostly gyrogonites. Common thick-shelled bivalves and gastropods. Serpulids (locally in buildups). Very rare echinoid fragments.	
① Marls, sandy marls, lignitic marls/clays, marly and bioclastic (locally ferruginous or bioturbated) limestones, rare pedogenic limestone conglomerate. Ferruginous irregular surfaces, including a major disconformity near the base.	A major irregular, probably dissolution surface (palaeomicrokarst?). Desiccation cracks, irregular fenestrae and intraformational dissolution fabrics at a few levels. Locally, weakly developed pedogenic features. <i>(Episodic exposure)</i>	Medium to thick-bedded, often irregularly bounded layers. Often, organic-matter rich sediments. Stratified microfossil coquinas (ostracodites and "charophytes"). Detrital quartz common.	Most abundant and moderate-diversity fresh-brackish water assemblages (locally, ostracodites). Dominance of <i>Theriosynoecum</i> (oligohaline genus, with several species). Also <i>Klieana</i> n. sp. 1.. large-sized carapaces of <i>Darwinula</i> n. sp. 1 and <i>D.</i> n. sp. 2., and small-sized, smooth carapaces of the euryhaline <i>Sinuocythere pedrogaensis</i> .	No marine fossils. Abundant charophytes (highest diversity), including stem and/or gyrogonite coquinas. Gastropods (locally abundant small-sized shells). Bivalves. Plant remains, terrestrial-dominated palynofacies, including the freshwater alga <i>Botryococcus</i> . Reptile teeth.	

Vale de Ventos section

This section is located in the eastern zone of the Lusitanian Basin (Fig. 1). The succession (Fig. 2) comprises, at the base, Middle Jurassic inner marine limestones (Upper Bathonian, dated by foraminifera - Azerêdo et al. 1998), which are truncated by a ferruginous palaeokarstic surface, coupled with an angular unconformity relative to the overlying levels (Oxfordian Cabaços formation).

Main data on the lithofacies, sedimentary structures, bedding patterns and fossil content are presented in Tab. 2, where subdivisions 1 to 3 are equivalent to those in the log of Fig. 2 and were basically defined by the ostracod associations (Cabral et al. 1999). The Vale de Ventos succession represents an inner marine lagoonal system in the Middle Jurassic, interrupted by tectonic uplift, erosion and subaerial exposure, succeeded by the establishment of shallow-water, continental and transitional settings (fresh to brackish, lacustrine and restricted lagoonal environments) during the Oxfordian.

Discussion: The depositional system inferred for the Cabaços Formation in the east of the basin, here represented by the Vale de Ventos section, would have been mostly a low-energy, protected inland system, clearly very shallow, freshwater-dominated as regards to the lowermost part of the succession, passing gradually upwards into fluctuating freshwater-oligohaline and into slightly more-marine influenced, restricted lagoonal conditions.

The lowermost levels suggest marked subaerial exposure, but passing upwards less frequent, intermittent exposure is evidenced (Tab. 2). Some aspects are addressed below.

In the levels corresponding to subdivision 1 (Tab. 2), besides the basal ferruginous palaeokarstic surface, the relatively thick packet of limestone and conglomerate beds with abundant black-pebbles and varied well-developed pedogenic features, indicate that the sediments were unequivocally subjected to prolonged subaerial exposure. The black-pebbles comprise homogeneous micrite clasts, dense, organic-rich, laminated micrites attributed to fragments of microbial-mats (similar mats occur as layers higher in the successions) and fragments of darkened porostromates. Black-pebbles, as a whole, are a diagnostic feature of settings frequently affected by subaerial exposure (e.g. Esteban & Klappa 1983; Strasser & Davaud 1983). Features such as rhizocretions, alveolar-septal texture, nodules, circumgranular cracking, peloidal laminated crusts and coatings, all of which occur in these levels, are unequivocally due to pedogenesis (e.g. Esteban & Klappa 1983; Wright 1983). The lignitic clay layer occurs above the pedogenic beds and is discontinuous, which may represent a small, normally wetted peat zone. The most significant palaeobiota evidence of freshwater conditions (ponds, marshes) are the occurrence and predominance, exclusively in these deposits, of several forms of a mainly freshwater ostracod family (Candonidae), together with rarer specimens of the oligohaline genera *Theriosynoecum* and *Darwinula* (smaller-sized carapaces than in the west). Rich charophyte assemblages and total absence of marine organisms are also relevant facts.

Further up in the succession (subdivision 2, Tab. 2) evidence for subaerial exposure stills exists, but the typical structures and pattern of exposure differ. In fact, pedogenesis related fabrics are not recorded but at one level, whereas irregular fenestrae are more common.

LITHOFACIES <i>(Subdivisions as in the log of Fig. 2)</i>	SEDIMENTARY SIGNATURES		PALAEOBIOTA SIGNATURES		SALINITY TRENDS
	<i>Evidence for subaerial exposure</i>	<i>Other</i>	<i>Ostracods</i>	<i>Other</i>	<i>F - B - M</i>
③ An irregular ferruginous surface at the base, overlain by a discontinuous layer of ferruginous marl with iron crusts. Fossiliferous, bioclastic and argillaceous limestones, locally bioturbated, sporadically with black-pebbles. A few microbial laminites.	Rare desiccation cracks (wide, shallow polygons). Irregular and laminar fenestrae and keystone-vugs, more common in the uppermost levels. Rare stratiform microbial mats and clotted micrite layers. <i>(Episodic exposure)</i>	Mostly thin- to very thin-bedded mudstones, wackestones and packstones. A few microlaminated, bioclastic and stratified microfossil coquinas within microbial or clotted micrite layers (event deposits, locally erosional-based and crudely graded).	Very rich assemblages of <i>S. candeirosensis</i> and <i>Klieana</i> n. sp. 3, increasingly abundant towards the top. Rarer occurrences of the genera <i>Theriosynoecum</i> and <i>Darwinula</i> .	Common occurrence of the dasyclad <i>Heteroporella lusitanica</i> (though rarely abundant). A few benthic foraminifera (namely <i>Pseudocyclamina parvula</i> and <i>Kurmibia palastiniensis</i>), more common in the uppermost beds. Decreasing abundance and lowest-diversity of charophytes. Rarer porostromates. Common gastropods (locally large-sized shells) and bivalves.	
② Bioclastic/black-pebble/oncoidal limestones and argillaceous limestones, usually ferruginous, marls with iron crusts and rare microbial laminite layers. A few irregular ferruginous surfaces.	Ferruginous surfaces draped by iron crusts, locally associated with pervasive iron staining, dolomitized or fenestral limestones. Fenestrae relatively common. Sporadic pedogenic fabrics. Rarer black-pebbles. Rare thin, stratiform microbial laminites. <i>(Intermittent exposure)</i>	Common slightly irregular bedding surfaces. Textures ranging from mudstone to floatstone, but more commonly wackestone. Well-laminated oncoids.	Increasing abundance and diversity of the assemblages. Disappearance of the Candonidae and drastic decrease of <i>Darwinula</i> . Predominance of <i>Theriosynoecum</i> (several spp.) and <i>S. candeirosensis</i> .	Most abundant and higher-diversity charophyte assemblages (gyrogonites and stems). Porostromates. Plant remains. Gastropods common. Rare bivalves.	
① Palaeokarstic, ferruginous surface and angular unconformity at the base. Black-pebble, pedogenic limestones and conglomerates, lignitic clays, marls and argillaceous limestone.	Palaeokarstic ferruginous surface. Well-developed pedogenic features, including alveolar-septal texture, nodules, rhizocretions, brecciation. Irregular fenestrae. Abundant black-pebbles. <i>(Marked exposure)</i>	Some beds exhibit thickness variations and irregular or gradational boundaries. Mudstone-wackestones to floatstones, with oncoids, reworked porostromate fragments and clotted micrite.	Relatively abundant, moderate-diversity limnic assemblages, dominated by the mainly freshwater Candonidae (2 genera and 4 spp.). Also <i>Simuocythere candeirosensis</i> (brackish-oligohaline sp.). Rarer, small-sized <i>Darwinula</i> n. sp. 1 and <i>D. n. sp. 3</i> and <i>Theriosynoecum</i> spp. (oligohaline).	Absence of marine organisms. Most abundant charophytes (gyrogonites). Porostromates. Gastropods.	

Tab. 2 - Main features of the Oxfordian Cabaços formation from Vale de Ventos (eastern Portugal), highlighting the sedimentary and palaeobiota evidence for subaerial exposure and salinity variations. Numbered subdivisions basically correspond to the ostracod associations (as in the log Fig. 3). F, B and M mean fresh, brackish and marine, respectively.

This suggests shorter, more intermittent periods of exposure relative to deposits below. The rare thin, stratiform microbial mats may represent the more exposed areas of perilacustrine marginal belts and/or patchy marsh zones surrounding the more widespread, almost permanent lacustrine systems. Rarer black-pebbles are related to this scenario. Iron staining, though not diagnostic, is also a common feature associated with exposure phases, as noted, for instance, by Leinfelder (1983). The fact that it is pervasive at many beds, and associated with ferruginous surfaces draped by iron crusts, ferruginized burrows, dolomitized or fenestral limestones points out to frequent, successive wetting and drying. The increasing abundance and diversity of the ostracod assemblages probably reflects such conditions, of more permanent subaqueous environment. The disappearance of the Candonidae, drastic reduction of *Darwinula* and increase of the brackish-euryhaline species *Simuocythere candeeiroensis* Cabral & Colin, 2000 (thus, different species in the same genus, relative to Pedrógão) suggest somewhat restricted water exchange. Charophytes also show the most abundant and highest-diversity assemblages in this part of the succession.

The described environmental situation has gradually developed upwards (subdivision 3) into more typically brackish lagoonal, restricted-marine influenced setting, with subaerial exposure episodically or locally occurring, but not very persistently. Desiccation cracks, although forming 10-15 cm wide, shallow polygons, thus in the range of 60-100% exposure time (Ginsburg et al. 1977) as at Pedrógão, are very rare and succeeded by microlaminated bioclastic and microfossil coquina, suggesting rapid flooding or storm action producing micro-scale event deposits. Fenestrae (irregular and laminar) and stratiform microbial and clotted micrite laminites are more common, but not widespread. The change towards a brackish-restricted lagoonal setting, only infrequently exposed, is also clearly evidenced from the palaeobiota: rich assemblages of the euryhaline ostracods, though rare *Darwinula* and *Theriosynoecium* still occur, appearance of the dasyclad *H. lusitanica* and of a few benthic foraminifera (including *P. parvula*), decreased diversity and abundance of charophytes, more common macrofauna.

Conclusions

The detailed sedimentary and micropalaeontological analysis of a complex association of continental to

marginal-marine deposits from the Oxfordian of Portugal, in particular of two selected sections, has allowed the recognition of high-frequency, subtle changes in the environmental conditions and of the main factors controlling the palaeobiological responses to those minor-scale fluctuations. In the west, fluctuations of salinity were much stronger and more frequent, and subaerial exposure more marked for longer periods, than in the east of the basin. The microfossil assemblages, as a whole, but in particular the ostracod faunas, show differences in abundance, diversity, dominant species, degree of intrageneric and intraspecific variations, both along the successions and between west and east.

The western assemblages show higher total diversity, defining more and more distinct (different genera) associations with palaeoecological significance, including monospecific associations with very high numbers of individuals, and also exhibit size and ornamentation variations in the same species. The eastern assemblages are less diversified (little variation at the generic level), allowing fewer and less clearly defined associations to be established, though there are species changes in the same genus. In conclusion, populations seem to have been less stable in the west, which suggests that the high-frequency changes in salinity and degree of exposure were the most important controls on the palaeobiota.

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