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Stratigraphy and sequence correlations in the Lower Cretaceous around Lisbon

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Abstract

The cliffs along the Atlantic coast near Lisbon—between Cascais and Guincho Beach, near Ericeira, and north of Cape Espichel—exhibit perfectly preserved Lower Cretaceous formations, with a large variety of sedimentary deposits (siliciclastics and carbonates) and recorded environments (from open distal platform to fluvial systems and palaeosols). These exposures allow the stratigraphic, sedimentological, palaeontological, mineralogical, and geochemical patterns of depositional sequences during the Valanginian–Albian to be analyzed. The series representing the deepest marine environments are found in the vicinity of Cascais, with deposits in more proximal positions being observed both northwards (the Ericeira area) and southwards (Cape Espichel). The cyclic variations in sea level at the second-order scale record the tectonic events linked to the initial episodes of the northward propagation of the opening of the Atlantic. The sea-level changes observed at the third-order scale are registered by transgressive and highstand systems tracts. Lowstand systems tracts are very scarce in these shallow environments.

Keywords: depositional sequences, Lower Cretaceous, Lisbon, Lusitanian Basin

Resumo

As arribas ao longo do litoral atlântico nas proximidades de Lisboa—entre Cascais e a Praia do Guincho, perto da Ericeira e a norte do Cabo Espichel—são constituídas por formações do Cretáceo Inferior, perfeitamente preservadas e expostas, que mostram uma enorme variedade de depósitos (siliciclásticos, carbonatados) e ambientes (desde plataforma distal aberta a sistemas fluviais e paleossolos). A sua observação permite analisar as assinaturas estratigráficas, sedimentológicas, paleontológicas, mineralógicas e geoquímicas das sequências deposicionais do intervalo Valanginiano–Albiano. A série correspondente aos ambientes mais marinhos surge na vizinhança de Cascais; depósitos de posições mais proximais são observados mais a Norte (na área da Ericeira) e a Sul (Cabo Espichel). As variações cíclicas do nível marinho de 2^a ordem registam os eventos tectónicos associados ao primeiro episódio de propagação para noroeste da abertura do Atlântico. As variações do nível marinho de 3^a ordem são registadas por cortejos deposicionais transgressivos e de alto nível marinho. Os cortejos de baixo nível marinho são muito escassos nestes ambientes pouco profundos.

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Palavras-chave: sequências deposicionais, Cretáceo Inferior, Lisboa, Bacia Lusitana

1. Introduction – The Lower Cretaceous of the Lusitanian Basin

1. 1. Morphology of the Lusitanian Basin

In the Lusitanian Basin, the Cretaceous series are found between Aveiro to the north and Setubal to the south. However, the chronology of the preserved deposits is diverse, allowing the deposits to be divided into two parts separated by the Caldas da Rainha or Nazaré parallel, with the Lower Cretaceous series being well documented in the southern part of this area.

The Lusitanian Basin was structured by N/NE–S/SW-oriented Hercynian faults, being wedged

to the east by the Hercynian basement of the Hesperian Massif and rimmed on the western border by marginal basement horsts, such as the metamorphic and granitic Berlenga Island and Farilhões Islands (Figs 1 and 2; the Farilhões Islands, close to Berlenga, are not shown at the map scale used).

The southern part of the basin comprises three morphological units (Rey, 1972) with a tilted block arrangement: i) A central trench with a complete (at the stage scale) and mixed (marine–non-marine, carbonate–siliciclastic) Lower Cretaceous succession. The depth and recorded rate of sedimentation increase to the southwest, and the basin depocenter is

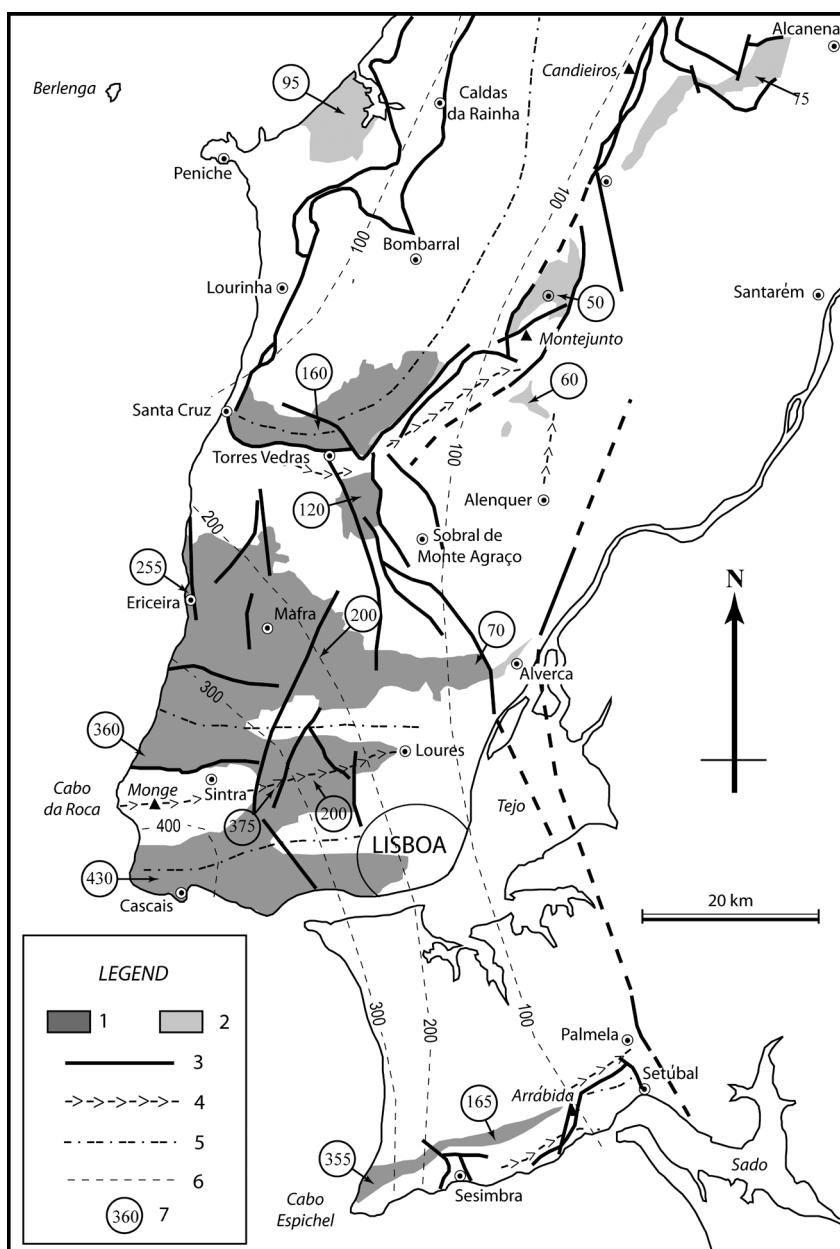


Fig. 1 – Cretaceous outcrops and structural framework of the present-day Estremadura (Rey, 2006). 1: complete series; 2: series with important gaps; 3: main faults; 4: anticlinal axis; 5: synclinal axis; 6: isopach curves; 7: total thickness of the Berriasian–Aptian series.

located generally in the vicinity of Cascais. ii) Eastern and iii) western margins with significant sedimentary unconformities and essentially continental deposits.

1.2. The sedimentary infill

The Lower Cretaceous sedimentary series consists of the following (Figs 3, 4, and 5):

- Ten formations between the Valanginian and the Albian with dominant limestones in the Cascais and Sintra areas (Rey, 1992). The total thickness is about 400 m.
- Thirteen formations north of Cape Espichel. Marine limestones alternate with lagoonal, brackish, and estuarine dolomites and marls, and with fluvial con-

glomerates, sandstones, and mudstones. The total thickness is about 350 m for the Berriasian–Aptian.

- Twelve formations in the Ericeira area. The characteristics of these deposits and the inferred sedimentary environments are similar to those of Cape Espichel, but with a smaller thickness (about 250 m).
- Seven siliciclastic formations between Ericeira and Torres Vedras and east of Loures, mainly non-marine but including minor transitional to shallow-marine deposits.
- Exclusively siliciclastic deposits of the onshore north of the Torres Vedras region, fluvial with rare signs of paralic environments, grading upwards and westwards to Cenomanian epicontinental carbonates. The ages are poorly constrained, and correlations are difficult owing to the isolated distribu-

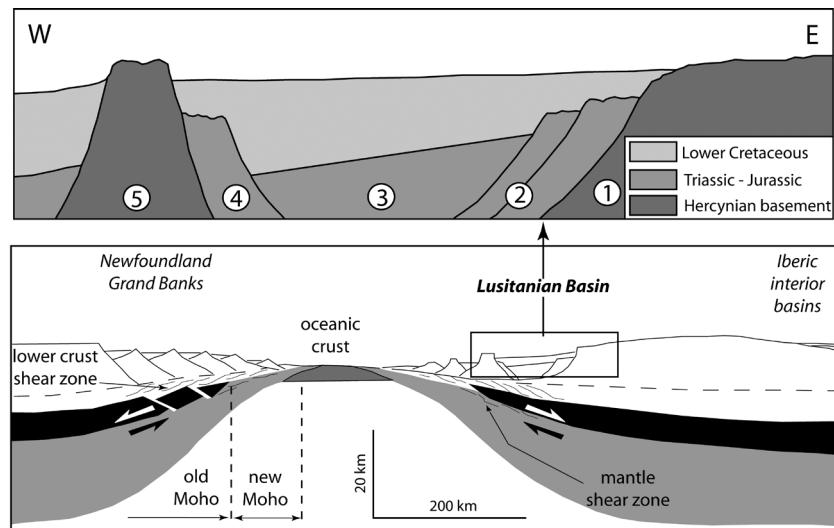


Fig. 2 – Interpretative section of the Lusitanian Basin during the late Aptian and its location along the West Iberian Margin in relation to the oceanic crust (Rey, 2006). 1. Hesperian Massif; 2 and 4. marginal half-grabens; 3. depocentric trough; 5. Berlenga horst.

tion of outcrops such as those at Cercal, Olhalvo, Alcanede, and Galiota.

1.3. Palaeogeographic evolution

Fossils with precise chronostratigraphic constraint are scarce in both marine and non-marine deposits. However, using the concepts of sequence stratigraphy, it is possible to identify time lines and

to draw reliable correlations between outcrops of the various areas (Fig. 5). That way, a brief account of the sedimentary evolution of the basin can be proposed, as follows:

- Latest Jurassic–early Berriasian. The carbonate platform, located in the Cascais and Sintra areas, corresponded essentially to brackish waters, as indicated by the predominant sedimentation of limestones and

AGE	CYCLES T - R	SEQ. 3 rd -order	FORMATIONS, Members		
			Ericeira	Cascais, Sintra	Cap Espichel
ALBIAN	late	A1 11	GALÉ	Ponta da Galé	Ponta da Galé
		A1 10			
		A1 9			
		A1 8			
		A1 7			
		A1 6			
APTIAN	middle	A1 5	GALÉ	Água Doce	?
		A1 4			
		A1 3 to Ap 5?			
BARREMIAN	late	Ap 4	RODÍZIO	RODÍZIO	RODÍZIO
		Ap 3			
		Ap 2			
		Ap 1			
		Ba 6			
		Ba 5			
HAUTERIVIAN	early	Ba 4	CRISMINA	Praia da Lagoa	CRISMINA
		Ba 3		Ponta Alta	
		Ba 2		Cobre	
		Ba 1			
		Ba 0			
		Ba 7			
VALANGINIAN	late	Ba 6	REGATÃO	REGATÃO	REGATÃO
		Ba 5			
		Ba 3			
		Ba 2			
		Ba 1			
		Ba 0			
HAUTERIVIAN	early	Ribeira de Ilhas	GUINCHO		BOCA DO CHAPIM PAPO SECO AREIA DO MASTRO ROCHADOURO
		RIBEIRA DE ILHAS			
		RIBAMAR			
		Ha 4		PRAIA DOS COXOS	
		Ha 3		CABO RASO	
		Ha 2		SANTA SUSANA	
VALANGINIAN	late	Ha 1	SÃO LOURENÇO	MACEIRA	LADEIRAS Lagosteiros
		Va 7		GUIA	
		Va 6		GUIA	
			VALE DE LOBOS	SERRADÃO	VALE DE LOBOS

Fig. 3 – Lower Cretaceous lithostratigraphic units in the southern part of the Lusitanian Basin. Ages, depositional sequences, and second-order transgressive-regressive cycles are shown (Rey, 2006).

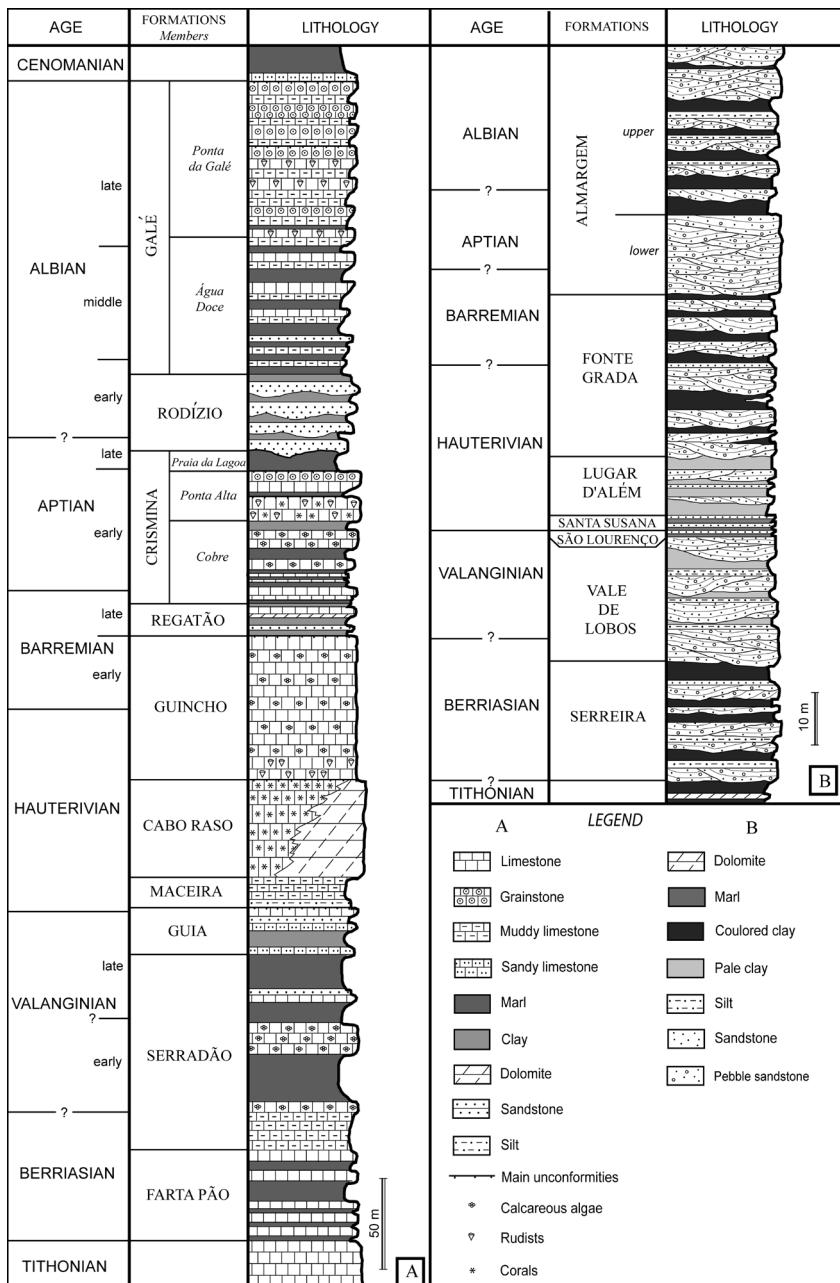


Fig. 4 – Examples of Lower Cretaceous series in the Lusitanian Basin (Rey, 2006). A: Lithostratigraphic column for the Cascais area; B: Lithostratigraphic column for the Torres Vedras area.

marls with liuolids, charophytes, and lagoonal ostracods (“purbeckian facies”). This environment was surrounded to the north, east, and south by a coastal plain (tidal or estuarine flats) with sandstone and mudstone deposition.

- Late Berriasian–early Valanginian. The coastline remained essentially stationary during this period. However, the marine carbonate platform became deeper, with the development of limestones and marls on an open and subtidal ramp, whereas an inflow of coarse, kaolinitic sandstones spread across estuarine and fluvial environments.

- Latest Valanginian–earliest Hauterivian. The relative sea level rose rapidly, and the areas of Cascais, Sintra, and Cape Espichel become an open

shelf, reaching 40 to 50 m depth at the Valanginian–Hauterivian boundary. Jointly with the arrival of cephalopods, the sedimentation was initially calcareous and then turned marly. The sea transgressed markedly to the north and east, with tidal flats reaching the vicinities of Torres Vedras and Alenquer.

- Hauterivian–early Barremian. With the maximum flooding during the early Hauterivian (Fig. 6a), reefal buildups appeared north of Cape Espichel and near Cascais, where the thick Cabo Raso reef developed. Subsequently, the basin gradually became infilled as a result of the progradation of depositional systems. In the Cascais and Sintra areas, the buildups were overlain by limestones with rudists and calcareous algae, characterizing an inner-shelf environment.

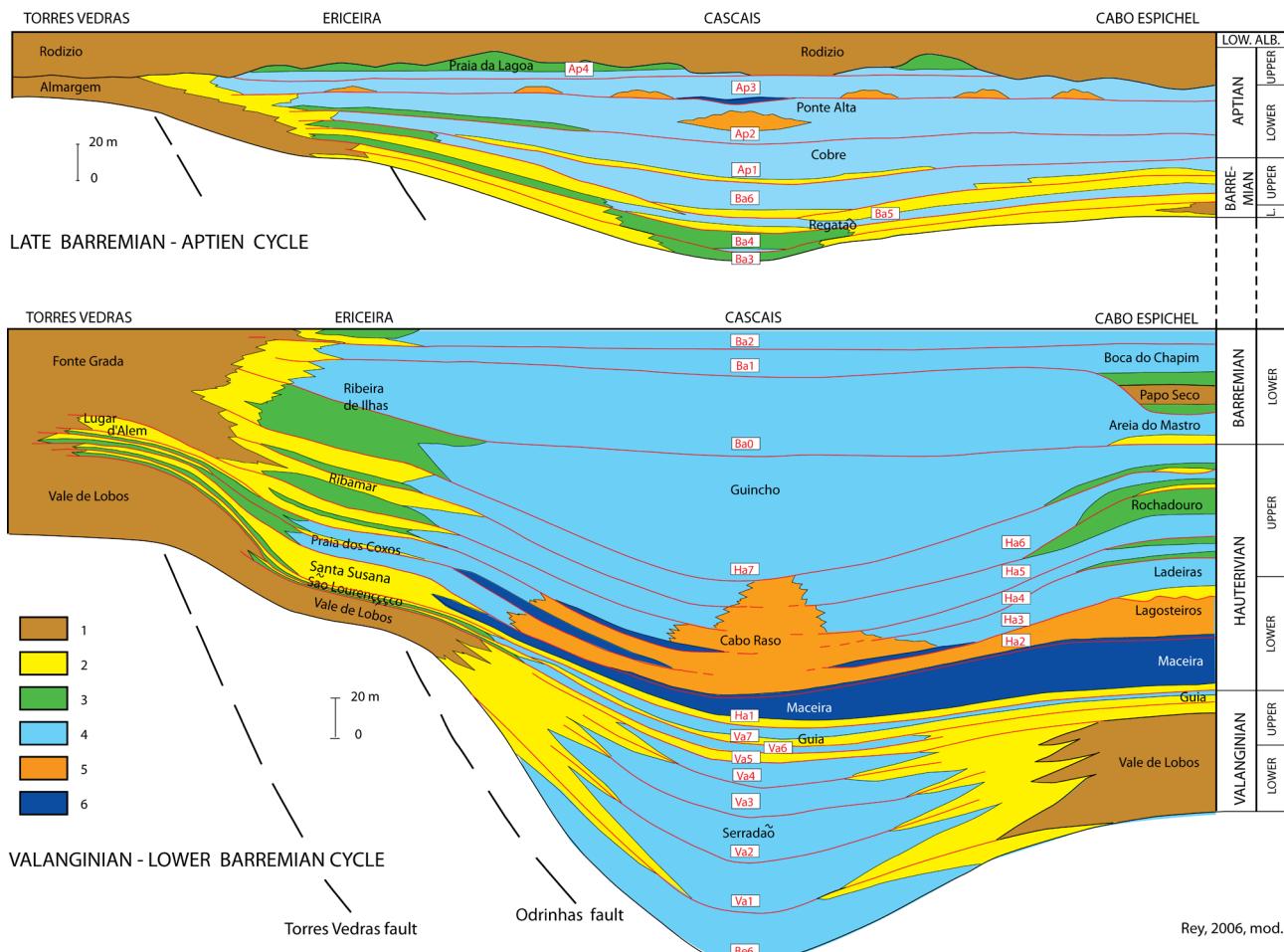


Fig. 5 – Sedimentary infill of the southern Lusitanian Basin between the Valanginian and lower Albian stages (Rey, 2006). The red lines indicate sequence boundaries. 1: fluvial deposits; 2: estuarine to nearshore deposits; 3: lagoon deposits; 4: inner-platform deposits; 5: reefal buildups; 6: outer-platform deposits.

In the Arrábida hills and near Ericeira, subtidal inner marls and limestones with rudists and echinoids were deposited alternating with lagoonal dolomites and sandstones during minor variations in sea level. Eastwards and northwards, braided alluvial plains formed and drained westwards. The maximum regression was reached at the end of the early Barremian.

- Late Barremian (Fig. 6b). The Lusitanian Basin was invaded by non-marine siliciclastic sediments, corresponding to widespread fluvial environments, except in a narrow belt between Ericeira, Cascais, and Cape Espichel, with predominant deposition of sandstones, mudstones, and dolomites in coastal plains and estuarine domains.

- Early Aptian–earliest late Aptian (Fig. 6c). A progressive sea-level rise allowed a new carbonate platform with reefal buildups to become established. In the western part of the Arrábida hills, in the Cascais and Sintra areas, as near Ericeira, the same succession is recognized, with a high degree of uniformity of facies in space: inner-shelf limestones and marls are followed by coral and rudist biostromes as-

sociated with grainstones, then by marls with oysters, indicating protected marshes. A coastal fringe of fine sandstones was deposited to the north and to the east.

- Latest Aptian–early Albian (Fig. 6d). A sudden and widespread phase of alluvial sedimentation from braided rivers occupied the entire basin. Conglomerates, sandstones, and mudstones accumulated, cutting into the underlying deposits. The palaeocurrent data and the morphology, size, and nature of particles seem to indicate a double provenance: a prevalent eastward contribution from the Hercynian basement and another from an emerged granitic or gneissic block located near the Atlantic Ocean (similar to the Berlenga Block).

- Middle and late Albian (Fig. 7). The beginning of a widespread, long-term transgression was the main control on sedimentation in the basin during the Albian, and another carbonate platform with reefal buildups developed in the Cascais and Sintra areas. Various environmental domains can be deduced for this stage: an entirely alluvial system; a siliciclastic coastal plain; a marly inner shelf with oysters, orbitolinids, and green algae; and a barrier

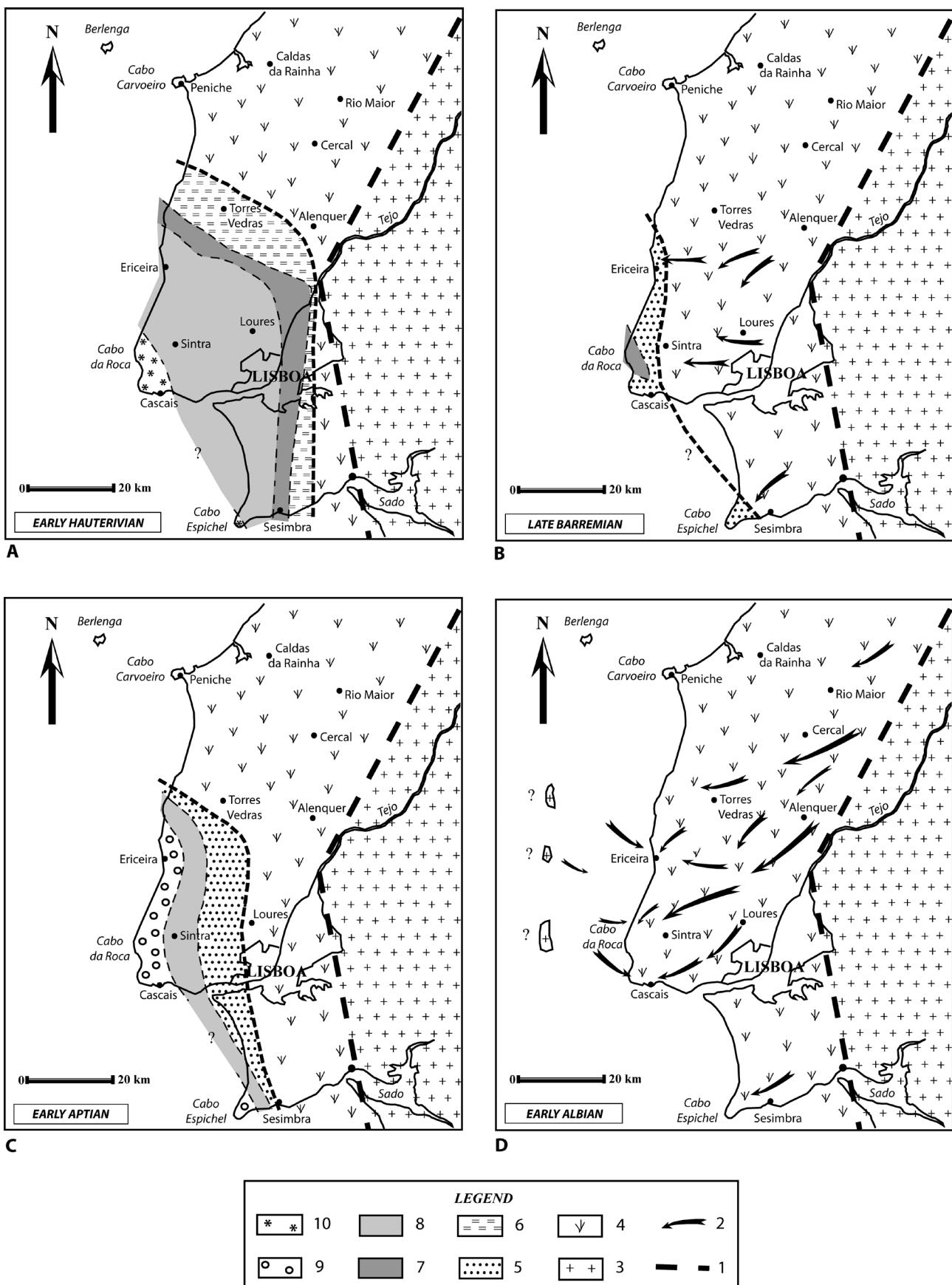


Fig. 6 – Maps of the palaeogeographic evolution of the Lusitanian Basin during the Early Cretaceous (Rey, 2006). 1: basin margin; 2: direction of fluvial drainage; 3: Hercynian basement; 4: fluvial environments; 5: coastal siliciclastic environments; 6: tidal flats; 7: intertidal carbonate platform; 8: inner carbonate platform; 9: middle carbonate platform; 10: reefal build-up.

of shoal calcarenites (grainstones) with rudist patch reefs. During the Albian, these various facies shifted northwards and eastwards but remained restricted in extent south of Torres Vedras. A break in sedimentation, quite clear in the southern sector, marks the Albian–Cenomanian boundary. Within the mainly fluvial deposits, changes in depositional systems interpreted from grain-size characteristics and the distribution of depositional architecture indicate minor sea-level changes and/or small vertical adjustments in the sedimentary supply area.

1.4. Sequence organization

From the Valanginian to the Albian, the marine deposits of the Lusitanian Basin can be arranged (Figs. 3, 5, and 8) into three second-order transgressive-regressive cycles (Rey *et al.*, 2003):

- A Valanginian–early Barremian cycle. The maximum transgression, which occurred during the early Hauterivian, is expressed by the development of reefs near Cascais, by the deposition of intertidal to supratidal marls in the Torres Vedras area, and by the sedimentation of fine siliciclastic deposits in the non-marine environments. A secondary fluctuation in sea level can be recognized in the regressive phase with a peak transgression at the Hauterivian–Barremian transition.

- A maximum regression near the early–late Barremian boundary. This event is revealed in the calcareous series of Cascais by an emersive karstic surface, representing a stratigraphic hiatus, and in the mixed series of Ericeira and Cape Espichel by the influx of an erosional mass of coarse sandstones.

- A late Barremian–earliest late Aptian cycle. The maximum transgression during the early Aptian (middle “Bedoulian”) was less important (in both duration and sedimentary volume) than that of the previous cycle. It is marked by several hardgrounds and condensed levels in the marine series of Cascais–Ericeira.

- A maximum regression during the late Aptian. This interval was expressed by a sudden influx of high-energy clastic and fluvial deposits covering the whole basin. The underlying series were eroded to various depths.

- A latest Aptian–Albian cycle. This cycle includes two sub-cycles (Fig. 7) that can be traced in the marine environments of the southern part of the Lusitanian Basin and likewise in the fluvial environments of the northern part of this basin (Dinis *et al.*, 2002). The first transgression peak, which occurred

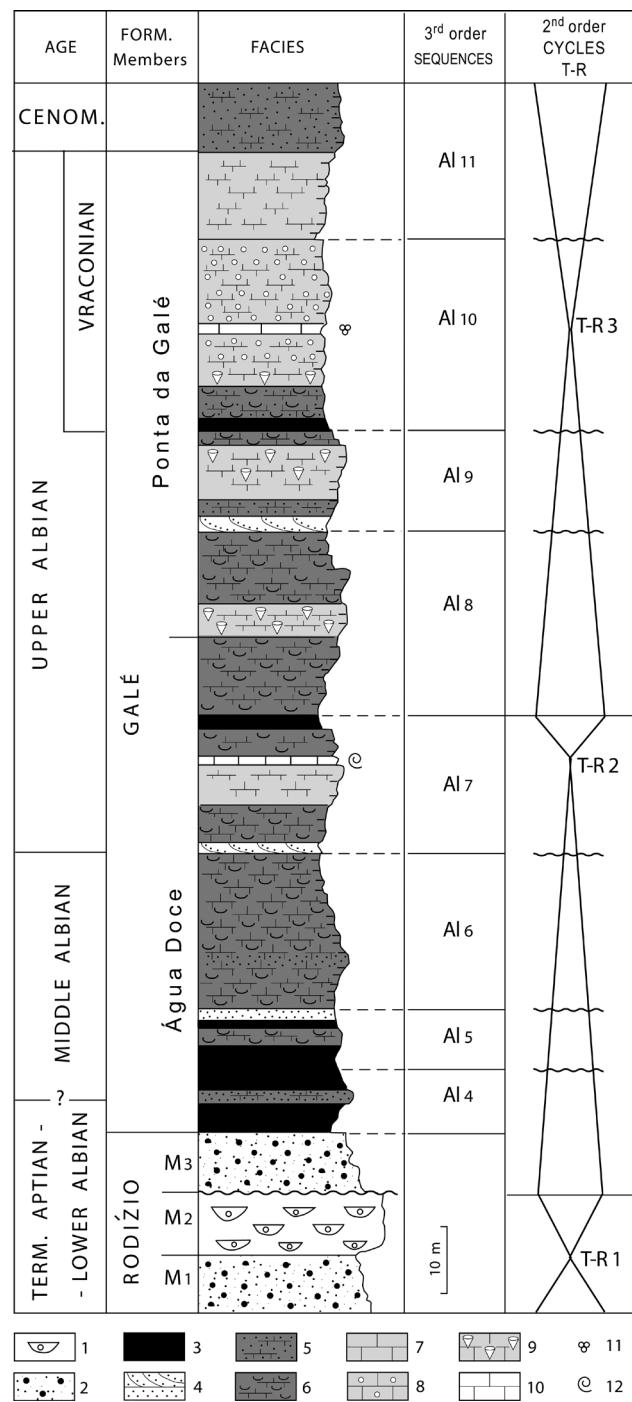
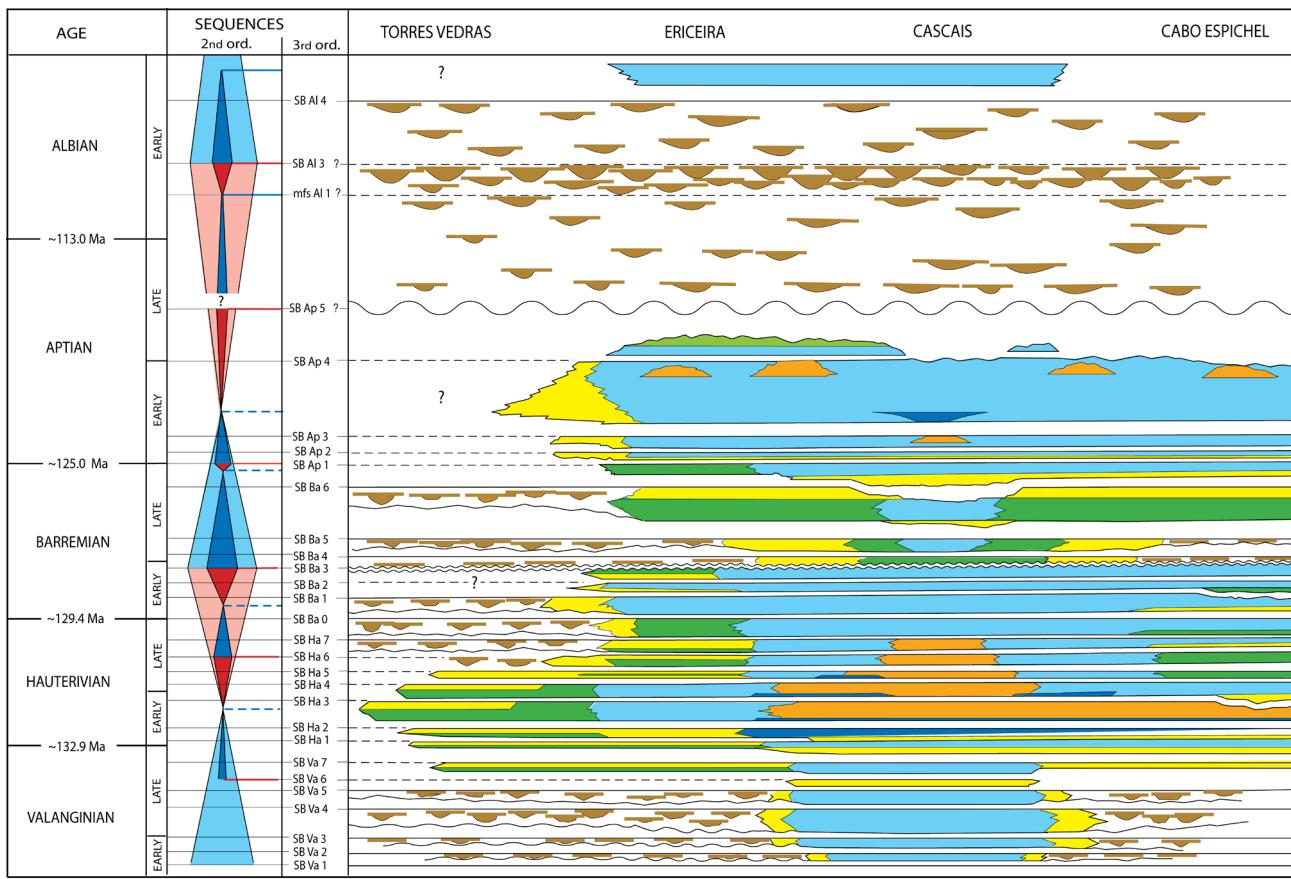


Fig. 7 – The terminal Aptian–Albian in the Cascais area. Synthetic section, sequences, and ages (Dinis *et al.*, 2002). 1: gradational fluvial sandstones and conglomerates; 2: retrogradational fluvial and marsh clays, lignite, and sandstones; 3: peritidal clays and sandstones; 4: coastal sandstones; 5: inner-shelf sandy limestones; 6: inner-shelf marls and limestones with oysters; 7: inner-shelf limestones with orbitolinids; 8: middle-shelf grainstones; 9: middle-shelf limestone with rudists; 10: outer-shelf limestones; 11: planktonic foraminifera; 12: ammonites.

during the earliest late Albian, corresponds, in the Cascais area, to an ammonite level (*Knemiceras uhligi*); the second, which occurred during the Vraconian, is expressed by a thick level of calcareous marls rich in planktic foraminifers from the outer platform.



Rey, 2006, mod.

Fig. 8 – Chronostratigraphy of the Lower Cretaceous in the Lusitanian Basin (modified from Rey, 2006). See Fig. 5 for the legend. Numeric ages are from the International Stratigraphic Chart 2004.

The end of this cycle is represented at the Albian–Cenomanian boundary by an oxidized surface covered by sandy limestones that mark a sudden return to more proximal environments.

The second-order cycles include lower-order Myr-scale cycles that generated third-order depositional sequences (Rey, 1993b). The sedimentological, palaeontological, and stratal patterns of these depositional sequences vary according to their location in the basin and to their positions in the second-order cycles. The lowstand systems tracts are very rarely present and infill incised valleys. Such tracts are generally characterized by a sudden increase in siliciclastic influx. The transgressive systems tracts are recognized in most cases by the development of thinning-upwards and deepening-upwards carbonate and marly beds, by the abundance of bioturbation, and by the common occurrence of hardgrounds on which dinosaur footprints appear locally (Praia dos Lagosteiros and Praia Grande do Rodizio). The highstand systems tracts are essentially calcareous (apart from estuarine environments, where siliciclastic bodies are deposited), with thickening-upwards and shallowing-upwards beds. Palaeosols commonly mark the sequence boundaries. The chronostratigraphic

diagram that is based on this sequence interpretation (Fig. 8) shows the very discontinuous character of sedimentation, formed by hiatuses of most of the lowstand system tracts or by local erosion at the sequence boundaries. Thus, 25 sequences are identified in the Valanginian–early Aptian, and 8 in the Albian. Presently, the third-order depositional sequences are not recognized in fluvial deposits.

A comparison with other western European sedimentary basins shows the same number and ages of second- and third-order sequences and a similar evolution on the North Atlantic margins (Jacquin *et al.*, 1998). The same arrangement of sequences has been recognized in the Parisian Basin (Rusciadelli, 1999). This evolution differs in some respects from that recorded in Tethyan margins (Fig. 9). Therefore, the depositional succession in Portugal, which indicates strong sea-level fluctuations generated by tectono-eustatic processes, reflects the structural evolution of the West European craton and of its Atlantic margins.

1.5. Geodynamic evolution

Four main stages are distinguished in the tectonic–sedimentary history of the Lusitanian Basin dur-

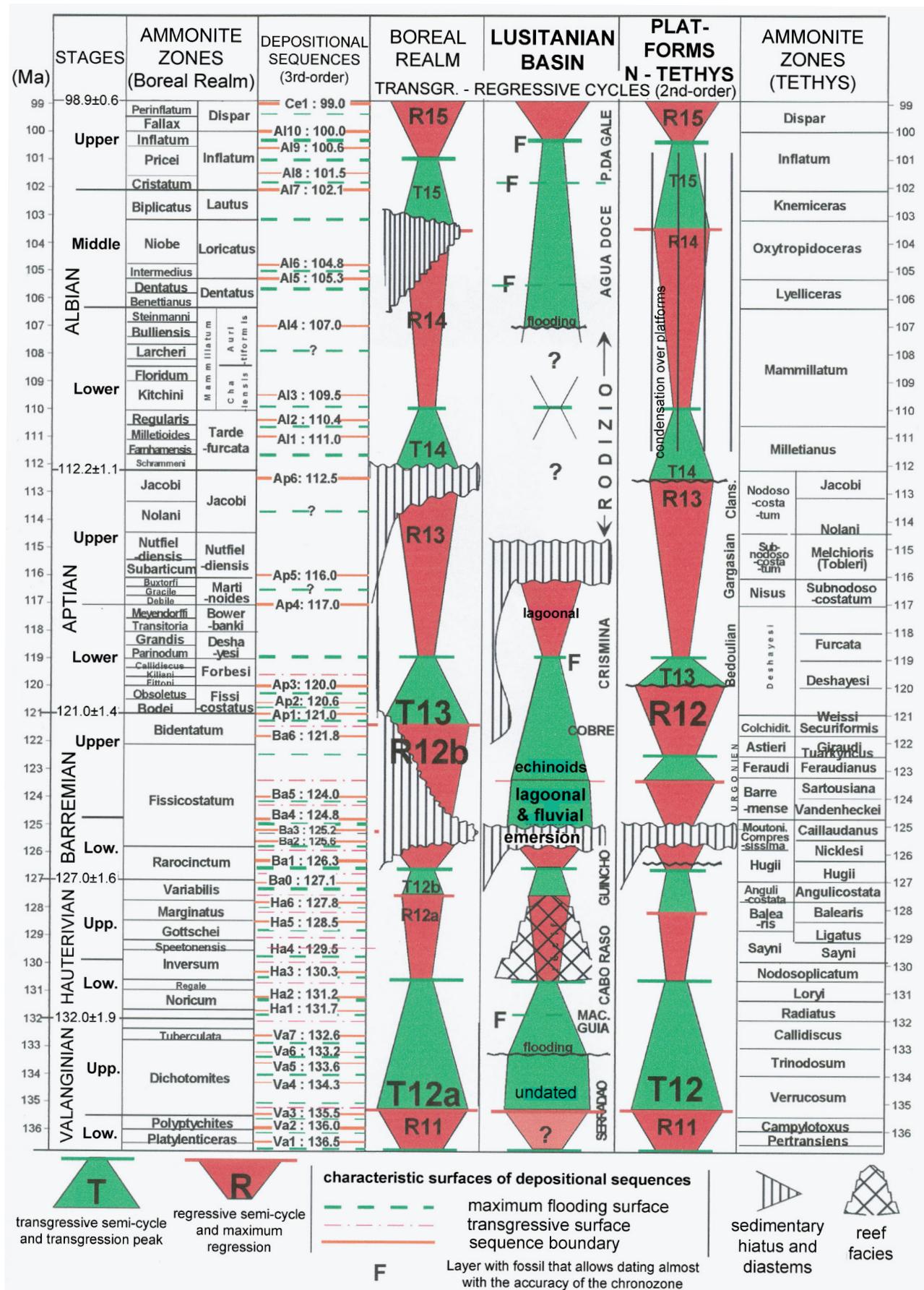


Fig. 9 – Comparison of second-order transgressive-regressive cycles and third-order depositional sequences between the Lusitanian Basin and other western European basins from the Boreal and Tethyan realms (from Rey *et al.*, 2003).

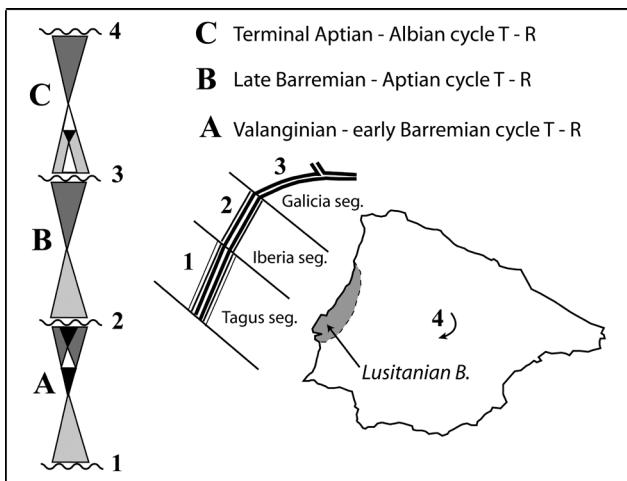


Fig. 10 – Second-order transgressive–regressive cycles in the Lusitanian Basin and their relationship to Atlantic events (modified from Rey, 2006).

ing the Early Cretaceous. These stages are separated by the main events that marked the migration to the north of the opening of the Atlantic along three segments of the western Iberian Margin (Fig. 10): the Tagus, Iberia, and Galicia segments, which are bounded by the Choffat fault and the Figueira da Foz fault, both considered as tectonic structures at the plate scale (Malot & Mauffret, 1990; Pinheiro *et al.*, 1996):

Post-rift thermal subsidence during the latest Jurassic–Berriasian. This regressive cycle is included in a long-term eustatic trend. The subsidence represented a gradual decrease in the level of tectonic activity (including the mainly thermal subsidence) after the climax in extension at around the Oxfordian–Kimmeridgian boundary. Recent dating ($^{206}\text{Pb}/^{238}\text{U}$) and geochemical analysis of the sub-volcanic domes in the northern area (Grange *et al.*, 2008) indicate ages of about 146 to 142 Ma (latest Tithonian–Berriasian) and a decrease in the amount of crustal contamination, corresponding to a stretching or tumescence of the continental lithosphere.

The Neocimmerian crisis. This tectonic event occurred in the Lusitanian Basin at around the Berriasian–Valanginian boundary (the lower part of the Serradão Formation). The event is indicated by:

- A deepening of the carbonate area in the vicinity of Cascais and Sintra.
- The sudden arrival of coarse clastics (up to pebble-sized clasts) at the borders of the marine platform (the Vale de Lobos Formation).
- Angular unconformities of Valanginian fluvial sandstones on Upper Jurassic beds in the Cercal outcrops and on the purbeckian beds on the eastern edge of the Torres Vedras synclinorium.
- Stratigraphic gaps of basal Cretaceous rocks

formed by erosion or non-deposition in the eastern and western margins of the basin, at Olhalvo, Abrigada, and Galiota.

This crisis can be related to the beginning of a mantle-magmatic extensional phase interpreted as the beginning of ultra-slow oceanic accretion in the Tagus sector (Girardeau *et al.*, 1998), corresponding to the initiation of mantle exhumation in the Iberia sector (Dean *et al.*, 2000) as well as to the rifting climax in the northern part of the Iberia sector (Wilson *et al.*, 1996; Whitmarsh & Wallace, 2001) and in the Galicia sector (Reston, 2005), generating a thermal and isostatic adjustment with regional uplift of adjacent regions. This large-scale effect was more intense in the northern (compared with the southern) part of the Lusitanian Basin where basement uplifts, diapiric movements, igneous intrusions (Ferreira & Macedo, 1983; Grange *et al.*, 2008), and local compressions occurred.

The Valanginian–early Barremian stable phase. From the Valanginian to the early Barremian, the Lusitanian Basin was relatively stable. The associated deposits are arranged within a long-term transgressive–regressive cycle that could have resulted from the gradual reduction in tectonic subsidence. During this stage, the oceanic spreading was



Fig. 11 – Locations of the fieldtrip stops. 1: Cascais; 2: Ericeira; 3: Cape Espichel.

expressed only in the Iberia and Tagus sectors, by the exhumation of sub-continental lithospheric mantle (Tucholke & Sibuet, 2007) or by ultra-slow oceanic accretion (Girardeau *et al.*, 1998).

The middle Barremian crisis. The maximum regression and the extended emersion of the Lusitanian Basin that are recorded at the end of the Barremian may have been related to the onset of seafloor spreading in the Iberia sector (Srivastava *et al.*, 2000; Shillington *et al.*, 2005), in which the oldest identified magnetic anomaly is M3 (earliest Barremian; Withmarsh *et al.*, 1996). In the Galicia sector, the middle Barremian crisis appears to have been coeval with the beginning of mantle exhumation (Fuegenschuh *et al.*, 1998; Srivastava *et al.*, 2005) and with the final pulse of continental extension in the Galicia Interior Basin. In the Tagus sector, the crisis corresponded to a significant increase in the rate of seafloor spreading (Srivastava *et al.*, 2000).

The late Barremian–earliest late Aptian stable phase. During the late Barremian–earliest late Aptian, the Lusitanian Basin was stable. The sedimentary deposits were arranged in a new long-term transgressive–regressive cycle that may have resulted from the gradually reducing tectonic subsidence. The subsidence rate would have been lower than in the Valanginian–early Barremian cycle. The maximal transgression, with a smaller extent than that of the previous major cycle, occurred during the mid early Aptian (*Desayesites deshayesi* Zone; Rey *et al.*, 2003). This evolution was recorded in several other European basins (Jacquin *et al.*, 1998) and was most probably synchronous with the global OAE1 (oceanic anoxic event) identified in the Galicia offshore (Tremolada *et al.*, 2006).

The late Aptian crisis. A major tectonic event occurred in the Lusitanian Basin during the late Aptian. A sudden influx of high-energy clastic and fluvial deposits covered the whole basin, and the underlying series were eroded to various depths. Angular unconformities (at the cartographic scale) are recognized, particularly in the eastern margin and in the northern part of the basin (Dinis & Trincão, 1995). The Berlenga Block was uplifted and contributed terrigenous material to the sedimentary supply of the basin.

The consequent unconformity generated by this crisis was the most significant in the process of continental separation between Iberia and Newfoundland, being expressed in all the margins and corresponding to the initiation of seafloor spreading in the Galicia sector (Schärer *et al.*, 2000; Tucholke & Sibuet,

2007; Srivastava *et al.*, 2000). A significant rotation of Iberia started after the M0 anomaly (Ogg, 1988; Malod & Mauffret, 1990; Srivastava *et al.*, 1990), which probably caused the uplift of various blocks (such as the Berlenga Block) in the western margin of the Lusitanian Basin and of extensive sectors of the northwestern part of the Iberian plate by thermal and isostatic adjustment (Hiscott *et al.*, 1990).

The Albian stable phase. The gradual and generalized flooding of the southern part of the Lusitanian Basin during the Albian resulted from a global sea-level rise well known with respect to various stable platforms. However, a tectonic control was also likely: the development of the unconformity at the base of the upper Albian separates two Albian cycles (Dinis, 1999) and was probably related to the onset of oceanic crust production in the eastern Bay of Biscay. These two cycles also appear on platforms considered as stable in the Paris Basin (Rusciadelli, 1999), the London Basin, and the North Sea (Jacquin *et al.*, 1998).

The Austrian crisis. This major unconformity is related to a regressive episode within the carbonate platform. The development of this unconformity can be related to an increase in compression of Iberia with Africa (Martin-Chivelet, 1995) and transpression in the Pyrenees (Olivet, 1996; Canérot *et al.*, 2005). The regression was widespread, being recognized in the Boreal and the Tethyan main cycles (Jacquin *et al.*, 1998). According to Uchupy & Emery (1991), this regression was coeval with the onset of oceanic crust creation northwest of the Galicia triple junction.

1.6. Conclusion

The Lower Cretaceous is represented in the Lusitanian Basin by a thin sedimentary succession, where carbonate and siliciclastic deposits alternate in both time and space, representing transitions between marine and non-marine environments. The characteristics and distribution of the deposits were controlled by two major influences:

- A global influence, with a eustatic sea-level fall during the Early Cretaceous followed by a sea-level rise during the Albian and Cenomanian. All the third-order depositional sequences described in the European basins are recognized; and

- A regional influence, related to the successive stages of evolution of the North Atlantic, and particularly to the northwards migration of oceanic accretion. The successive appearance of seafloor in the Tagus, Iberia, and Galicia segments provided a rhythm to the

second-order transgressive-regressive cycles until the Albian. Following that, the sedimentation in the western margin of Portugal recorded the compressive interactions between the African and Euro-Asiatic plates and the occurrence of magmatic episodes.

2. Fieldtrip Guide

The adopted numbering for third-order sequences corresponds to that proposed in the chart of European basins (1998). However, two additional sequences are recognized here, the first denoted "Ha 7" at the top of the Hauterivian and the second denoted "Al 11" at the top of the Albian.

Abbreviations for all figures:

SB: Sequence boundary; TS: Transgressive surface; mfs: Maximum flooding surface. LST: Lowstand system tract; TST: Transgressive system tract; HST: Highstand system tract

A. The Lower Cretaceous near Cascais

Location

The surroundings of Cascais present the most marine and thickest Lower Cretaceous deposits. Therefore, the outcrops of this area can be used as

a knowledge reference for most of the depositional sequences in the Lusitanian Basin.

The basal units of this series (the Farta Pão and Serradão formations, dated Berriasian and Valanginian *pro parte*) are found only in the hinterland with poor-quality outcrops, and they are not studied during this fieldtrip. In contrast, the cliffs along the Atlantic Ocean, between Boca do Inferno and Praia Grande do Guincho, allow an extremely detailed description to be made of the entire stratigraphic succession between the uppermost Valanginian and the Albian-Cenomanian boundary. The outcrops observed on this fieldtrip are divided into two groups (Fig. 12):

- Maceira Bay, located 1 km west of Cascais (Figs 13 and 14), presents the uppermost Valanginian–basal Hauterivian deposits (Sequences Va6 to Ha 1); and

- The bays and capes alternating from the vicinity of the Crismina fortress to Praia Grande do Guincho, on the southern side of the Alcabideche syncline, exhibit the upper Barremian, Aptian, and Albian formations (Sequences Ba 3 to Al 11).

The reefal complex of Cabo Raso (upper Hauterivian), strongly crystallised and cut by many faults, is not able to be analyzed in detail and is therefore unable to be the subject of a sequence interpretation. The plateau extending between Praia Grande do

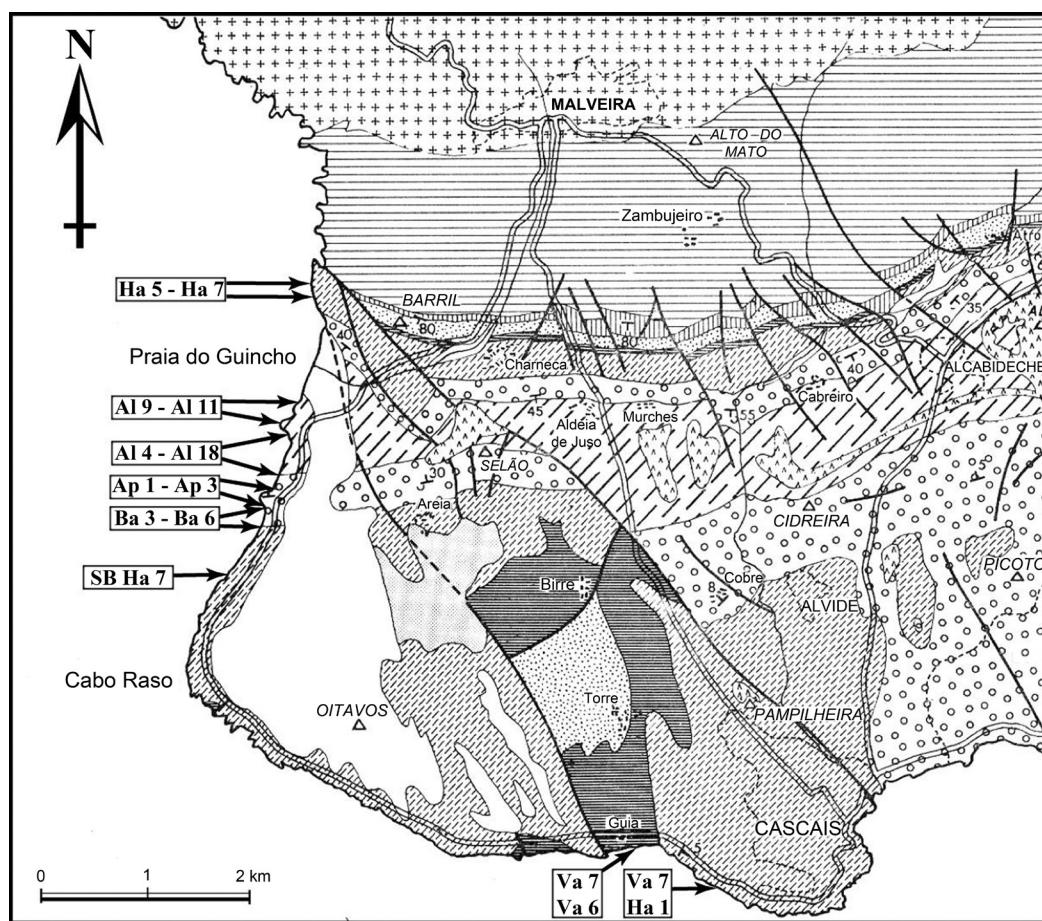


Fig. 12 – Geological map of the Cascais area and the locations of depositional sequences (from Rey, 2006).



Fig. 13 – The Neocomian cliff at Guia, in the western part of Maceira Bay.



Fig. 14 – The Neocomian cliff of Mexilhoeira, in the eastern part of Maceira Bay.

Guincho and Praia do Abano, on the northern side of the Alcabideche syncline, allows the upper Hauterivian–lower Barremian series to be studied, but it is not visited on this fieldtrip owing to time constraints.

2.1. Neocomian sequences

2.1.1 Sequence Va 6

Definition

This thin sequence marks the return to marine conditions in the Cascais area. It illustrates perfectly the main characteristics of a depositional sequence without a lowstand system tract on an open, shallow platform.

Age

Late Valanginian. The sequence is devoid of good chronological markers and is dated by its stratigraphic position.

Composition (Figs 15 and 16)

Sequence boundary and transgressive surface:

A horizontal surface separates a bed of sandy limestone from a bed of sandy marls 0.10 m thick and containing bivalve debris.

Transgressive system tract:

This tract consists of three thinning-upwards

parasequences, each with a thin bed of black laminated sandy marls and a bed of bioturbated sandy limestone, topped by an oxidized surface. The decreasing thickness and the increase in the levels of oxidation and bioturbation for successive parasequences show a retrograding evolution on the upper shelf. The fauna is diverse and includes oysters, brachiopods, gastropods (*Nerinea* and *Natica*), bivalves (*Pterotriongia* and *Fimbria*), and lituolids.

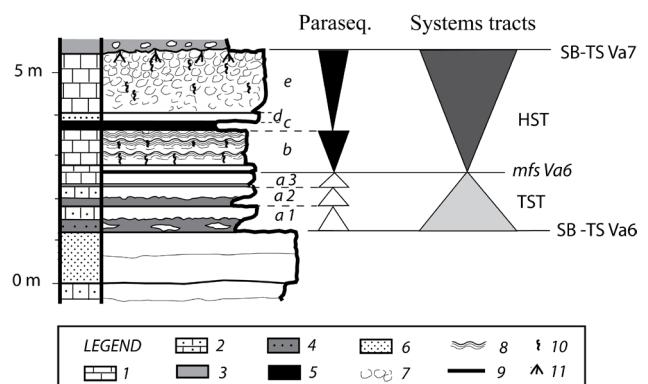


Fig. 15 – Sequence VA 6 at Guia: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: sandy limestone; 3: marl; 4: sandy marl; 5: black mudstone; 6: sandstone; 7: pedogenetic nodules; 8: algal films; 9: oxidized surface; 10: bioturbation; 11: root prints.

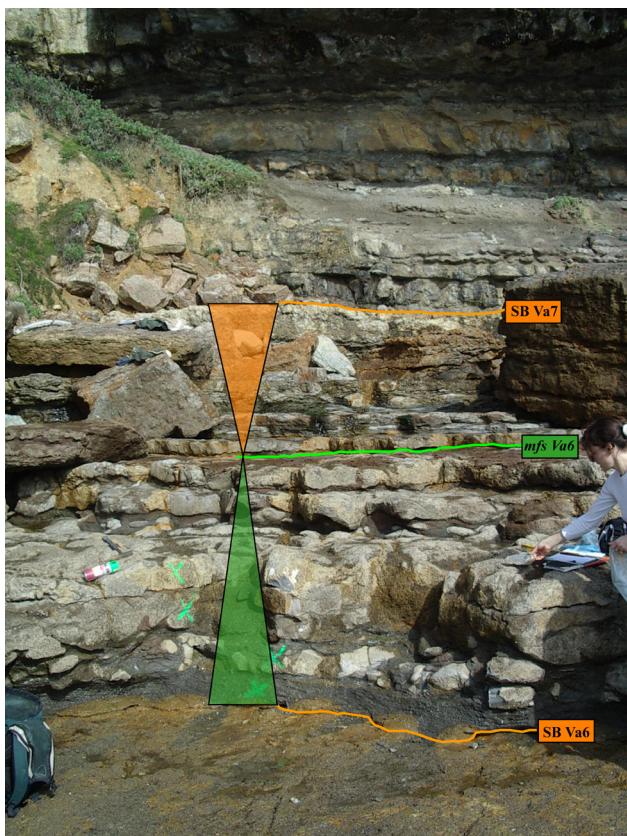


Fig. 16 – General view of sequence Va 6 at Guia.

Maximum flooding surface:

The uppermost and thickest ferruginous crust with important horizontal bioturbation (*Thalassinoides*) filled with limonite (Fig. 17).

Highstand system tract:

This tract indicates a shallowing-upwards evolution of limestones and marls arranged in two parasequences. The upwards decrease in depositional depth is expressed by fossils (brachiopods and oysters in the lower part; algal films, *Ptygmatis*, and oncrolites in the upper part) and by sedimentary structures (laminations and wave ripples in the lower part, pedogenetic nodules and carbonate concretions in the upper part). The uppermost level is bored by roots at the top (Fig. 17), indicating a palaeosol and therefore the full infilling of the available space.

2.1.2. Sequence Va 7

Definition

Sequence Va 7 represents a marked and rapid marine transgression in the Lusitanian Basin, corresponding to the maximum rate of sea-level rise at the second-order scale. Therefore, it is a backstepping sequence with a thick transgressive system tract and a very thin highstand system tract, both deposited on an open platform. As the available space had been en-

tirely filled by the sediment supply of the previous sequence, the beginning of this new cycle is expressed by the pedogenetic alteration of the Va 6 highstand system tract and by the gap representing the missing Va 7 lowstand system tract.

Age

Latest Valanginian–earliest Hauterivian. The Valanginian–Hauterivian boundary is characterized by ammonite and echinoid assemblages (Rey & Busnardo, 1969) and is located between the condensed interval and the highstand system tract.

Composition (Figs 19–22)

Sequence boundary and transgressive surface:
An exposure surface overlain by yellow sandy

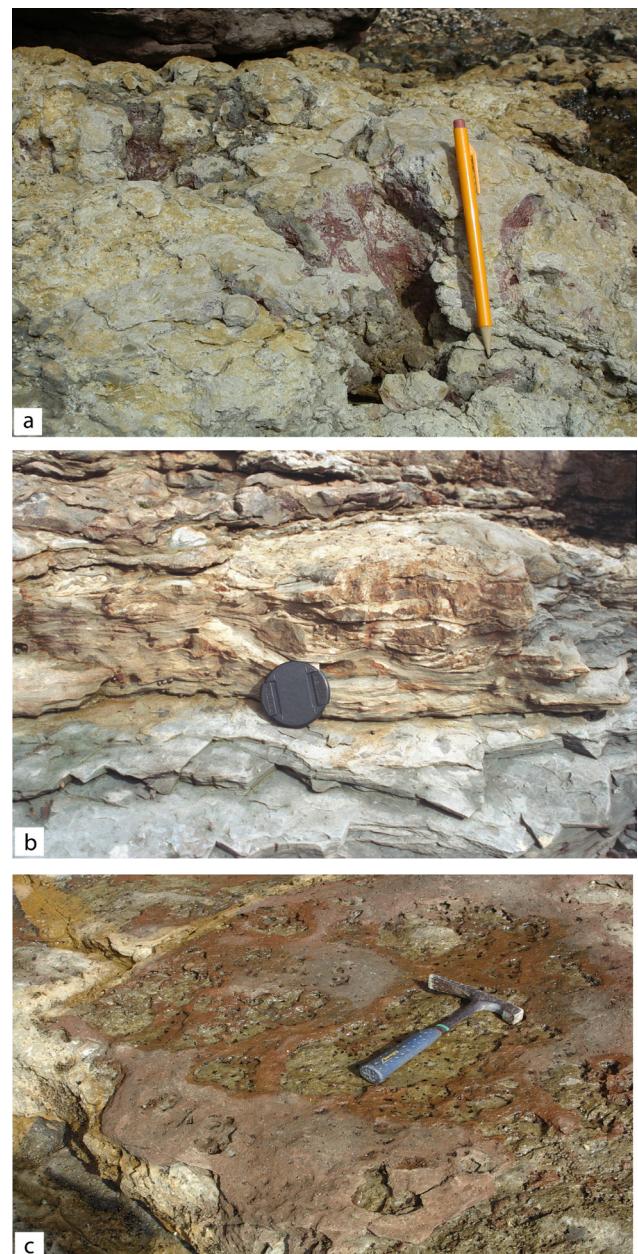


Fig. 17 – Details of sequence Va 6 at Guia. a: root prints at the top of the highstand system tract; b: algal films in the highstand system tract; c: iron crust on the maximum flooding surface.

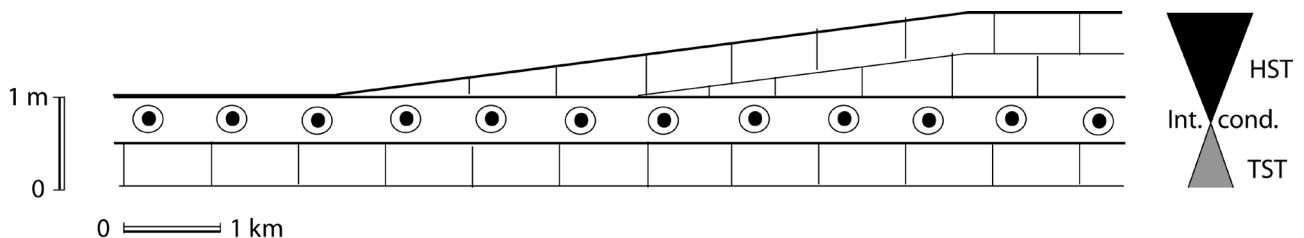


Fig. 18 – Downlap of the Va 7 HST between Boca do Inferno and Torre da Marinha (Rey, 2006)

clays that have reworked the underlying level (Fig. 21).

Transgressive system tract:

Two parts can be recognized in this particularly thick system tract:

- the lower part (Figs 19 and 21) consists of black laminated marls alternating with undulating beds of marly limestones, or of bioturbated silty-sandy and lignite-rich limestones, and of lenses of coarse sandstones. The deposits are arranged into a cyclic parasequence representing an estuarine environment. A thin bed of sandy limestones with trigoniids, small gastropods (*Ptygmatis*), and brachiopods is found in the lower third of the tract; this bed marks a maximum deepening in a fourth-order cycle (or perhaps an additional third-order cycle).

- the upper part (Figs 19 and 22) is represented by undulating beds of oolitic, gravelly and sparitic cemented limestones from the middle- and outer-shelf areas. From the base to the top, the thickness of the beds decreases and the faunal diversity increases: gastropods (naticids and nerineas), bivalves (oysters and pectininids), echinoids (*Pygurus*, *Salenia*, and *Cidaridae*), brachiopods, and corals, with ammonites, belemnites, and nautiloids at the top. The oxidized surfaces become progressively more marked and closer together upwards, and the degree of bioturbation (*Thalassinoides*, Fig. 22b) also increases.

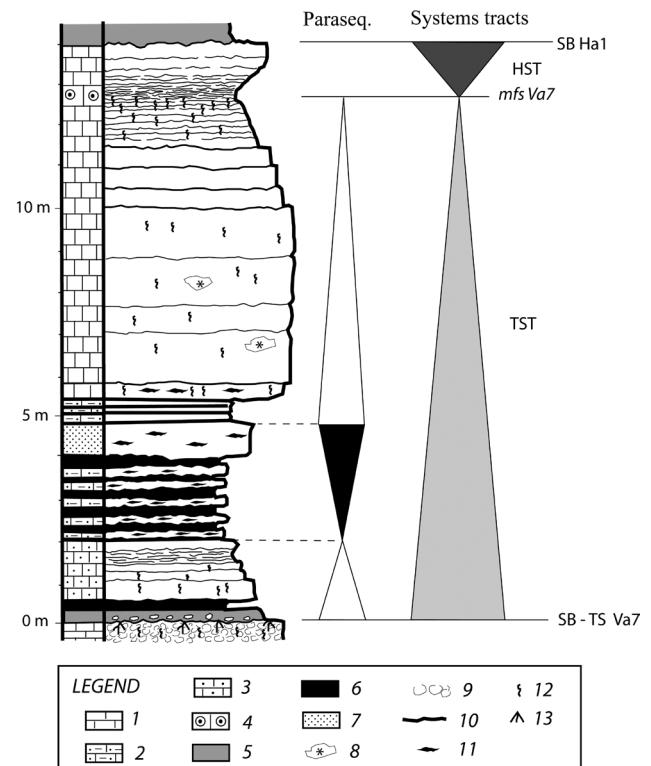


Fig. 19 – Sequence Va 7 at Guia (lower part, lowest 10 m) and Mexilhoeira (upper part): lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: sandy-muddy limestone; 3: sandy limestone; 4: ferruginous ooliths; 5: marls; 6: black mudstone; 7: sandstone; 8: corals; 9: pedogenetic nodules; 10: oxidized surface; 11: lignite; 12: bioturbation; 13: root prints.

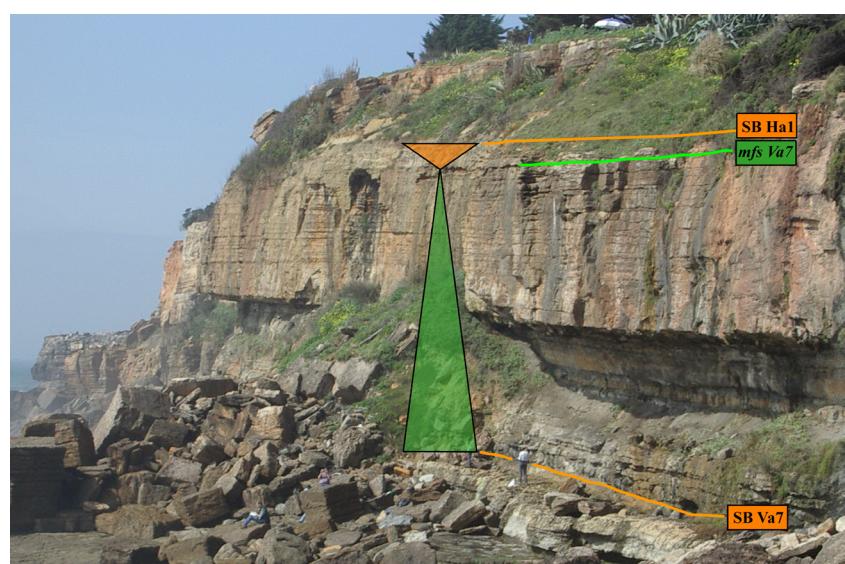


Fig. 20 – General view of sequence Va 7 at Guia.

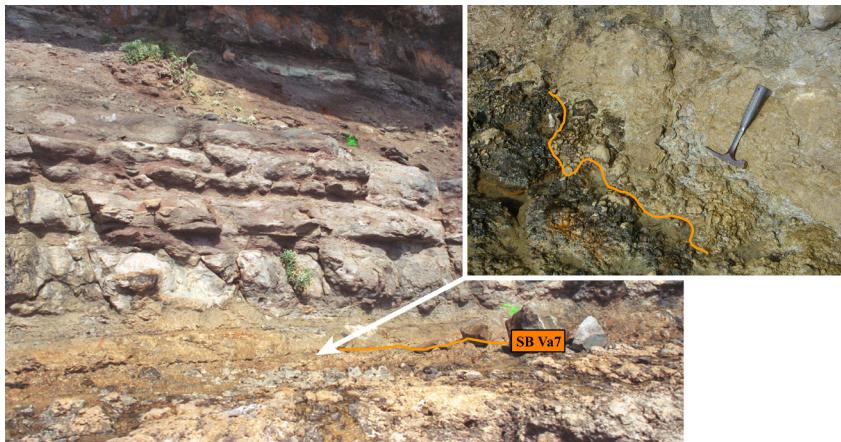


Fig. 21 – The sequence boundary and the basal part of sequence Va 7 at Guia.

These observations indicate a decrease in the sedimentation rate over time and a deepening-upwards sedimentary evolution.

Maximum flooding surface:

The maximum flooding surface is expressed by a 0.5-m-thick condensed interval (Fig. 22c and d). This interval contains a very abundant and varied fauna in a ferruginous oolite: ammonites (*Phylloceras*, *Bochianites*, *Neolissoceras*, *Olcostephanus*, and *Neocomites*), nautiloids, belemnites, echinoids (*Rhabdocidaris*, *Holectypus*, and *Collyropsis*), brachiopods, corals (*Montlivaltiidae*), nerineas, naticids, tritoniids, and oysters (including *Alectryonia*). This horizon is recognized across the entire southern part of the Lusitanian Basin and corresponds to an extensive drowning surface.

Highstand system tract:

This tract (Fig. 22a) is composed of microclastic limestones, 1.40 m thick, stacked in thickening-upwards beds with sparse bioturbation, ammonites (*Phylloceras*, *Lytoceras*, *Neolissoceras*, *Olcostephanus*, *Spitidiscus*, and *Crioceratites*), nautiloids, naticids, and oysters. This system tract disappears 500 m to the west (Fig. 18) at Torre da Marinha, where it is replaced by an iron crust, with a characteristic “downlap” configuration.

2.1.3. Sequence Ha 1

Definition

This sequence is characterized by the following:

- On the one hand, by the presence of a lowstand system tract. Because the highstand system tract of the underlying sequence Va 7 is very thin and the inferred marine environment quite deep, an available space for sediment input was preserved after the sea-level fall at the sequence boundary.

- On the other hand, by the aggrading pattern of the transgressive and highstand systems tracts. The

stacking of deposits approximately compensates for the sea-level rise, and the environment of a distal ramp does not change between the transgressive surface and the sequence boundary. Thus, the facies and stratal patterns are similar in the transgressive system tract and the highstand system tract, without major unconformities.

Age

The assemblage of ammonites (Rey & Busnardo, 1969) and echinoids collected in this sequence indicates an early Hauterivian age.

Composition (Figs 23–25)

Sequence boundary:

An irregular surface, with bores filled by silty marls of the overlying level (Fig. 24b).

Lowstand system tract:

Massive grey silty marls with muscovite, containing calcitic geodes (pseudomorphism of vaporates?) on the top. Fossil remains (echinoids, ammonites, brachiopods, and serpulids) are scarce and flattened, probably because of the high rate of sedimentation.

Transgressive surface:

A surface marked by the development of bioturbation on the terminal part of the marls (Fig. 24c) and by the appearance of thin and discontinuous marly limestones.

Transgressive system tract:

Three shallowing-upwards parasequences, each consisting of alternations of bioturbated muddy limestones and calcareous marls arranged in thickening-upwards beds (Fig. 24a). The limestones contain pellets, intraclasts, and bioclasts in a micritic matrix. The fauna is rich: ammonites (*Phylloceras*, *Lytoceras*, *Neolissoceras*, *Olcostephanus*, *Spitidiscus*, *Crioceratites*, and *Neocomites*), nautiloids, echinoids (*Salenia*, *Goniopygus*, *Rhabdocidaris*, *Pseudocidaris*, *Collyropsis*, *Holectypus*, *Pyrina*, and *Toxaster*), brachiopods, naticids, bivalves, and ser-

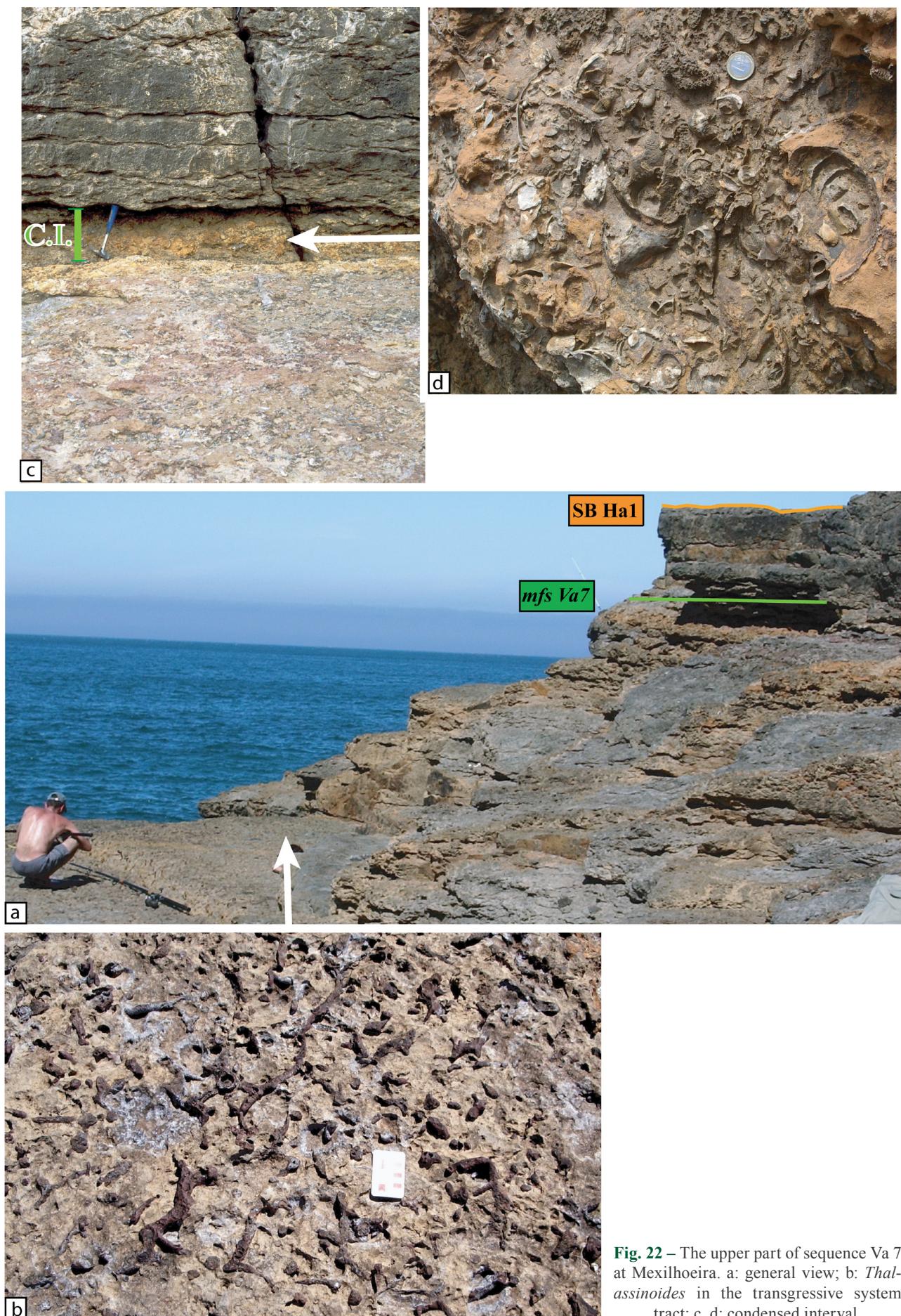


Fig. 22 – The upper part of sequence Va 7 at Mexilhoeira. a: general view; b: *Thalassinoides* in the transgressive system tract; c, d: condensed interval.

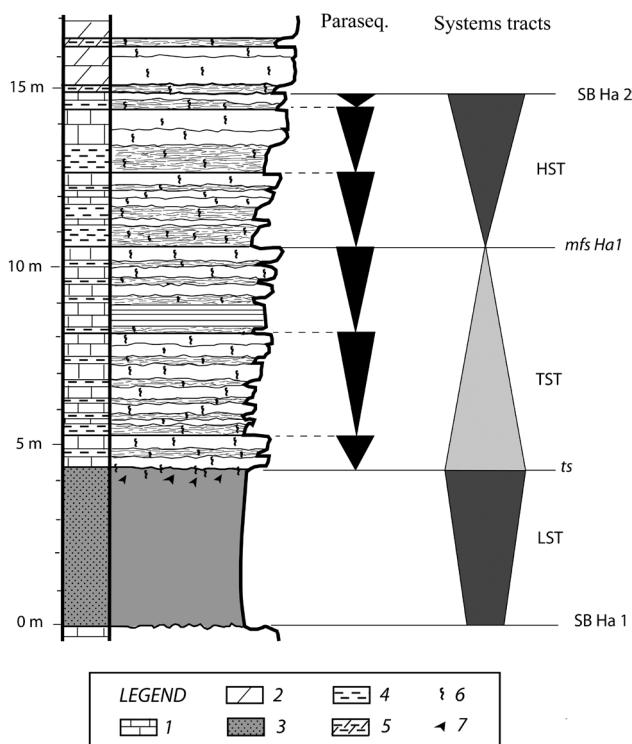


Fig. 23 – Sequence Ha 1 at Mexilhoeira: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: dolomite; 3: silty marl; 4: muddy limestone; 5: muddy dolomite; 6: bioturbation; 7: evaporite.

pulids. The thickness of the parasequences increases from the base to the top of the tract.

Maximum flooding surface:

Poorly expressed, this surface may be located around the most clayey level.

Highstand system tract:

Three shallowing-upwards parasequences, each constituted by bioturbated calcareous marls in the lower part and by bioturbated muddy limestones in the upper part (Fig. 24a), with the same lithological patterns and faunal content as in the underlying transgressive system tract. However, the calcareous beds are thicker, with stratifications less marked, and the thickness of parasequences decreases from the base to the top of the tract.

Overlying sequence boundary:

The highstand system tract of sequence Ha 1 is cut by a toplap. The unconformity is particularly obvious along the cliff between Mexilhoeira and Boca do Inferno (Fig. 14). This surface is the sequence boundary of sequence Ha 2, and it separates the calcareous marls of the uppermost part of sequence Ha 1 from dolomitic limestones that represent the lowermost deposit of sequence Ha 2 (a transgressive system tract, 1.50 m thick, overlain by a marly level that might represent the maximum flooding surface).

2.1.4. Mineralogical analyses of the Neocomian Sequences

Sequences Va 6 to Va 7 (base): Guia section (Fig. 26)

Regarding the sequence organization of the section, the following observations can be made:

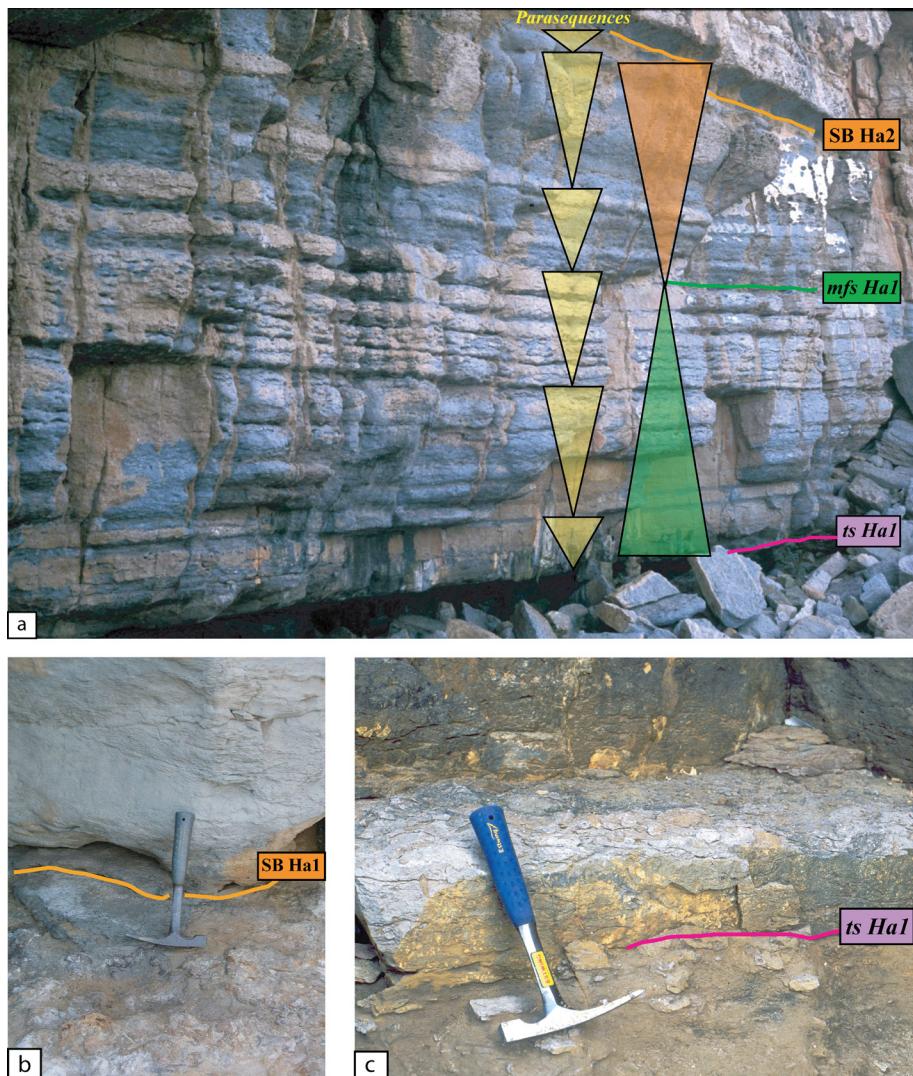
- The maximum flooding surface in Va 6 is marked by a peak in pyrite (the maximum value of the entire section), associated with a ferruginous level.
- there is a substantial increase in illite compared with kaolinite (higher values of I/K) immediately above the mfs (Va 6).
- illites with lower crystallinity (high ICI – illite crystallinity index) also occur immediately above the mfs.
- the top of the section (TST Va 7) shows a relative increase in kaolinite ($I/K < 1$) and a slight increase in illite crystallinity.

Sequences Va 7(top) to Ha 1: Mexilhoeira section (refer to Fig. 27)

Regarding the sequence organization of the section, the following observations can be made:

- The base of the section (sequence Va 7) shows a predominance of kaolinite relative to illite ($I/K < 1$), as occurs at the top of the Guia section. However, this ratio is rapidly reversed upwards, with values of $I/K > 1$.
- The proximity of the maximum flooding surface of Va 7 is marked by a significant enrichment of illite with respect to kaolinite and by a decrease in illite crystallinity. At the base of the HST, an increase in illite crystallinity is observed (minimum ICI throughout the section) and also in the relative abundance of kaolinite.
- The Ha 1 sequence boundary indicates a marked change in the mineralogical assemblages: the total sample assemblages are characterized by the complete disappearance of calcite (and the appearance of dolomite) and a marked increase in phyllosilicates and coarse detrital minerals; the insoluble residue shows a greater diversity in the assemblages, highlighting the increase in both pyrite and siderite; and the clay fraction shows a peak in illite (relative to kaolinite).
- The mineralogical assemblages in the LST of sequence Ha 1 maintain these characteristics: high phyllosilicate contents (particularly in the middle part) and quartz; abundant pyrite and siderite; anhydrite, although in trace amounts, is present in all samples; a significant predominance of illite over kaolinite; and illites with low crystallinity.

Fig. 24 – Details of sequence Ha 1 at Mexilhoeira; a: parasequences of the transgressive and highstand systems tracts; b: sequence boundary; c: transgressive surface.



- The transgressive surface (ts) is marked by changes in the mineral assemblages: the disappearance of dolomite, replaced by calcite; a marked decrease in siliciclastic minerals; the disappearance of anhydrite; an increase in kaolinite (compared with illite); and increased illite crystallinity.
- Close to the maximum flooding (mfs) of Ha 1, a small peak in illite abundance is identified ($I/K = 2.3$; sample 22) meaning that (as in Va 7) the position of the mfs may be a little lower than that indicated in the column.
- The top of the HST of Ha 1 and the Ha 2 sequence boundary are marked by increases in dolomite and phyllosilicates, and the lowermost levels of Ha 2 show a relative increase in kaolinite ($I/K < 1$).

2.2. The Reefal Complex of Cabo Raso

The Cabo Raso (Cape Raso) outcrops show a recrystallized and dolomitized complex, dated as

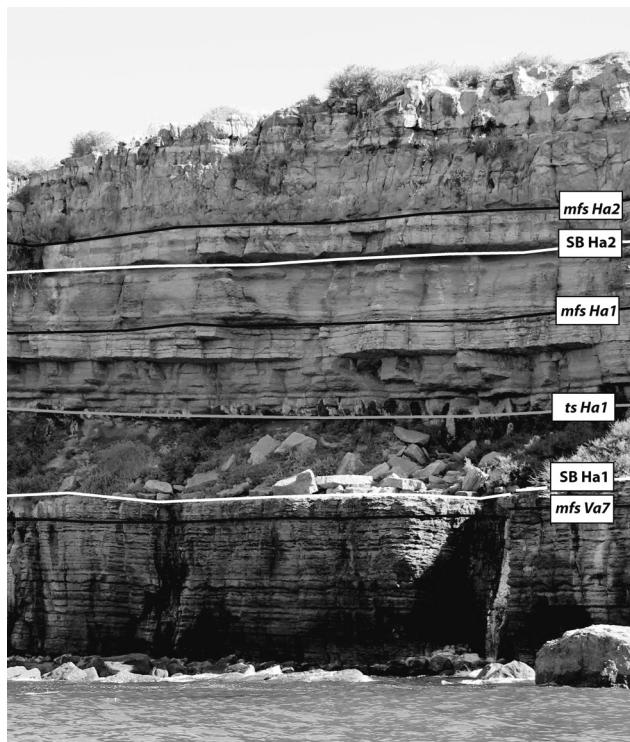


Fig. 25 – General view of sequence Ha 1 near Mexilhoeira.

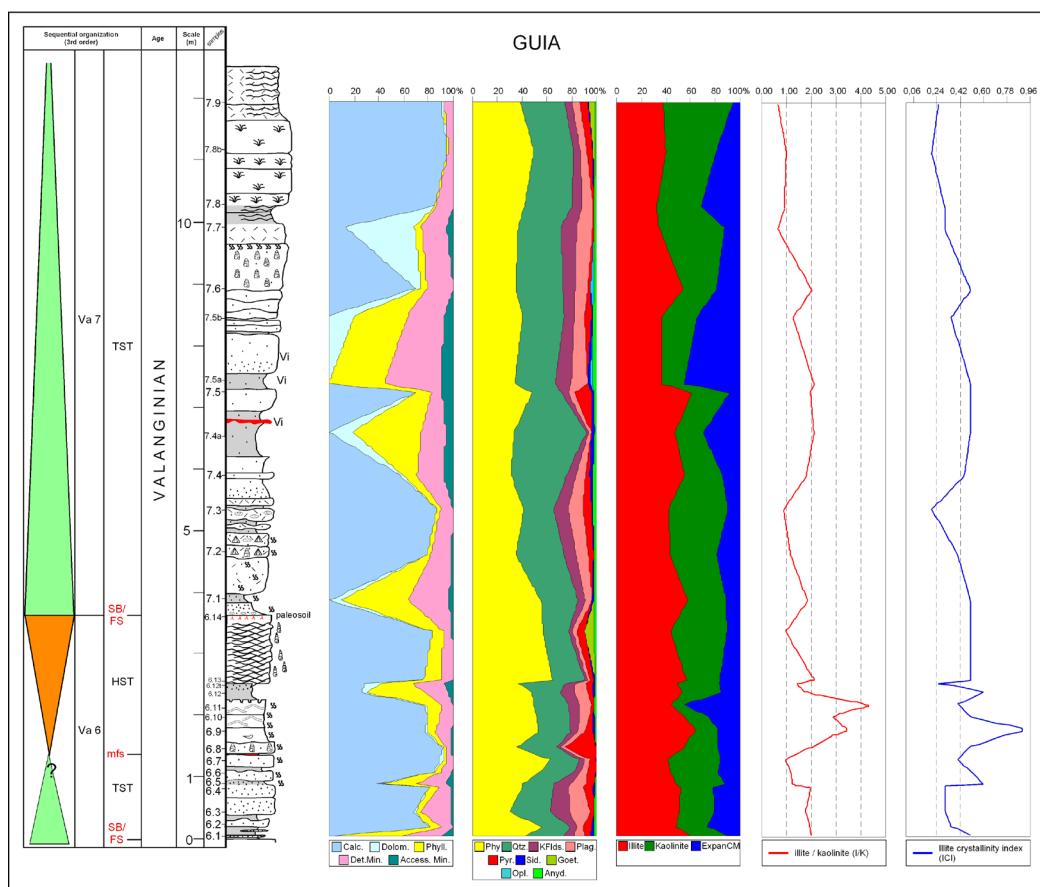


Fig. 26 – Results obtained from the Guia section (sequences Va 6 and Va 7): mineralogical assemblages of the total sample, insoluble residue, and <2 mm fraction; illite/kaolinite ratio (I/K); and illite crystallinity (Kubler/Segonzac index – ICI).

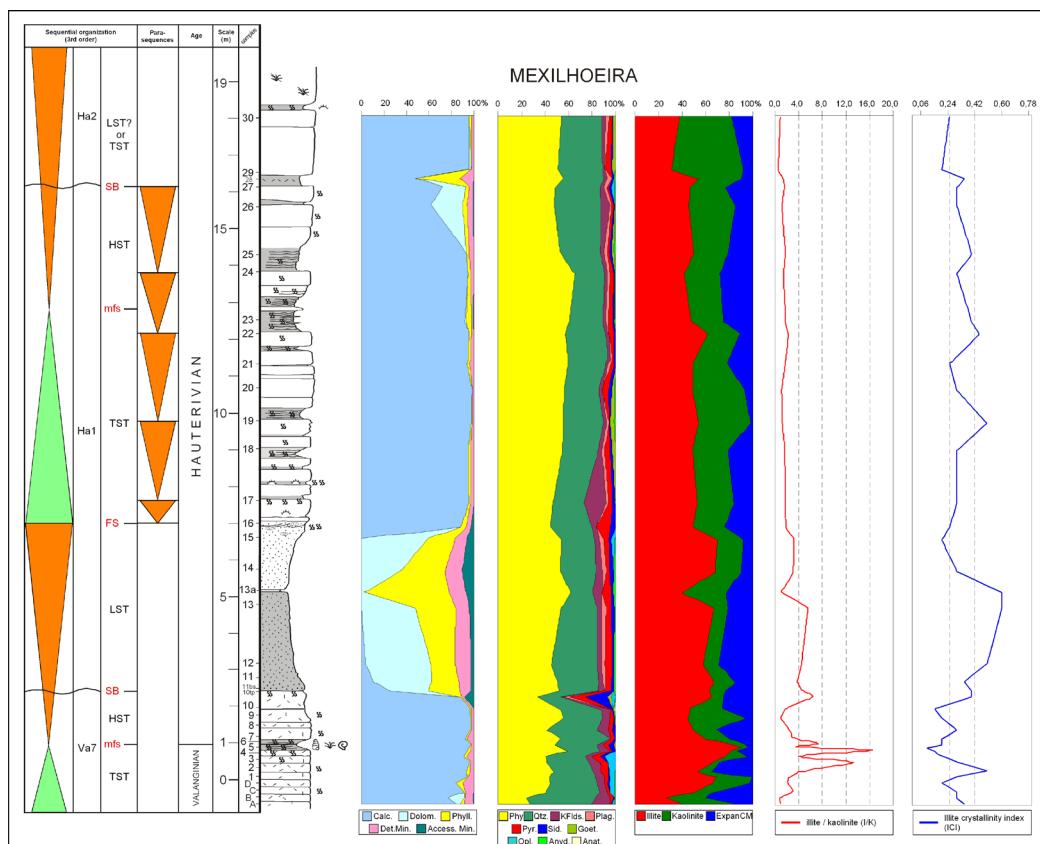


Fig. 27 – Results obtained from the Mexilhoeira section (sequences Va 7 and Ha1): mineralogical assemblages of the total sample, insoluble residue, and <2 mm fraction; illite/kaolinite ratio (I/K); and illite crystallinity (Kubler/Segonzac index – ICI).

Hauterivian. The complex was built during the maximum inundation in the second-order transgressive-regressive cycle (Fig. 6). The original micritic cement is locally preserved. The palaeontological assemblage consists of stromatoporoids, chaetetids, and scleractinia (*Astrocoenidae*, *Stylinidae*, *Thamnopeltidae*, and *Calamophyllidae*), associated with *Cidariidae* spines and bioturbation. The colonies are encrusted, dome shaped, or ball shaped, with average diameters of 10 to 20 cm (Fig. 28a). These colonies are quite dense, with a bafflestone arrangement. Rather than a bioconstruction, this unit represents an active bioaccumulated unit and has a thickness of ~50 m.

The sequence stratigraphy within the Cabo Raso Formation has not yet been fully analyzed. The only identified element is the Ha 7 sequence boundary, which is located at the top of the reefal complex (Fig. 28b) and overlapped by a 2-m-thick level of limestone breccias (Fig. 28c) with broken, laminated and well-sorted rudists, nerineas, and corals. This level is recognized across the entire Cascais and Sintra areas. Above this bed, limestones with large nerineas and rudists (*Requienidae*, *Monopleuridae*, and *Caprotinidae*) represent back-reef environments.

2.2.1. Sequences Ba 3, Ba 4, and Ba 5

Definition

Above the major unconformity that marks the end of the second-order transgressive-regressive cycle of the Valanginian–early Barremian and which represents the Ba 3 sequence boundary, three sequences represent the beginning of the second-order transgressive-regressive cycle of the late Barremian–Aptian. The first two sequences (Ba 3 and Ba 4) are aggradational and are indicative of a lagoonal area, whereas the third sequence (Ba 5) shows some shallow-marine levels, indicating a retrogradational evolution.

Age

Late Barremian. Lacking good chronological markers, these sequences are dated mainly on the basis of their stratigraphic position, below the Barremian–Aptian boundary.

Composition (Figs 29 and 31)

Sequence Ba 3

Sequence boundary and transgressive surface:

Uppermost surface of the sequence Ba 2 limestones. This surface is eroded, microkarstified, and even brecciated north of Praia Grande do Guincho (Fig. 30).

Transgressive system tract:

Yellow dolomiticites covered by a level of green clay.

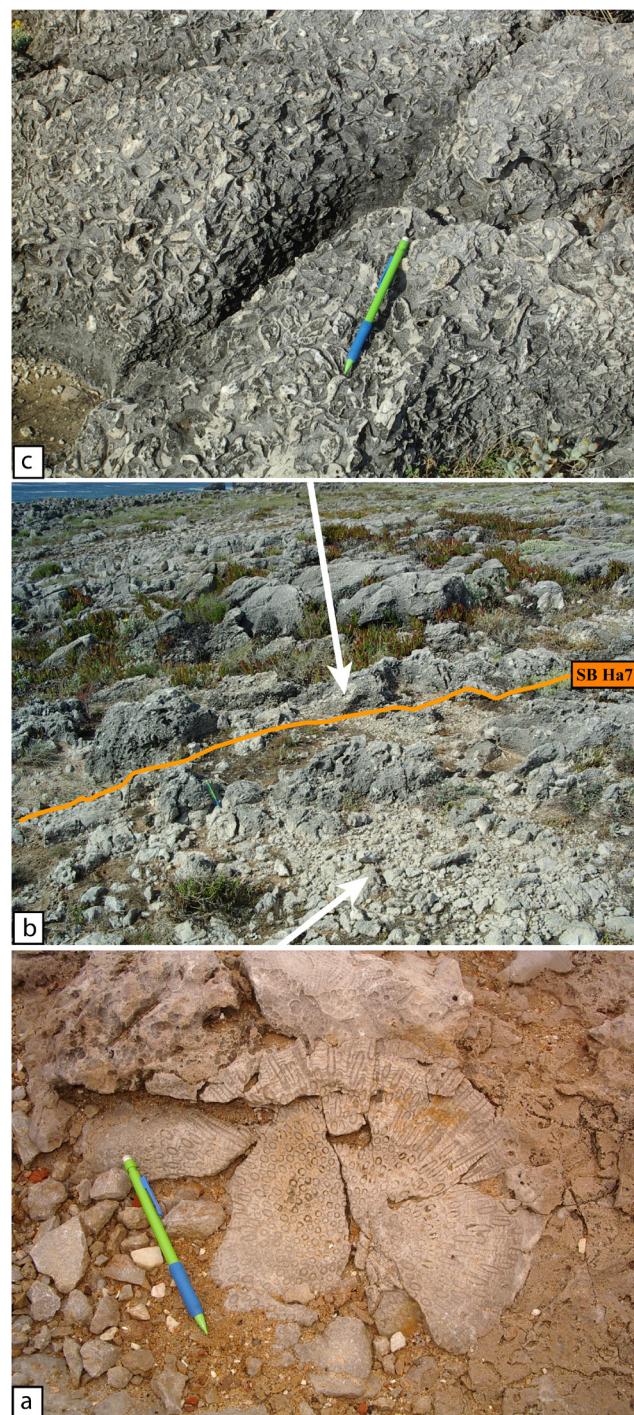


Fig. 28 – The top of the Cabo Raso Formation, between Cabo Raso and Crismina. a: corals in the upper part of the formation; b: top surface of the build-up and sequence boundary of sequence Ha 7; c: fragments of rudists and nerineas at the base of sequence Ba 0.

Maximum flooding surface:

Bed of fine sandstone inserted within green clays (?).

Highstand system tract:

Two parasequences, each composed of green clays in the lower part and yellow dolomiticites in the upper part. Compared with the lower parasequence, the upper one has smaller thicknesses of clays and greater thicknesses of dolomiticites. Algal structures,

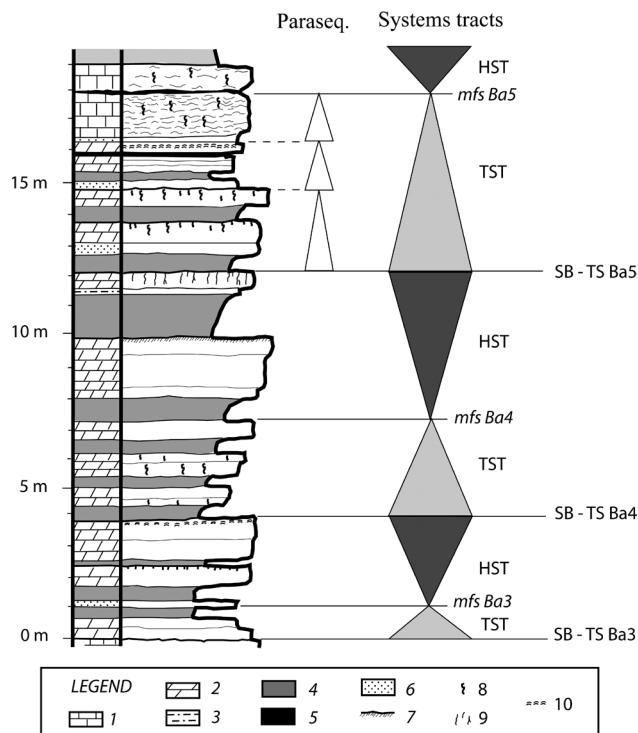


Fig. 29 - Sequences Ba 3, Ba 4, and Ba 5 at Crismina: lithology, stratonomy, and sequence arrangement. 1: limestone; 2: dolomite; 3: siltstone; 4: green and blue clay; 5: black mudstone; 6: sandstone; 7: palaeosol; 8: bioturbation; 9: rhizoconcretions; 10: algal films.

such as algal chips, appear at the top of the lower parasequence.

Sequence Ba 4

Sequence boundary and transgressive surface:
An abrupt contact between dolomiticites and clays.

Transgressive system tract:

Three parasequences, each composed of yellow and bioturbated dolomiticites alternating with green or blue argillaceous marls.

Maximum flooding surface:

Poorly expressed, this surface might be located at the base of one of the most argillaceous levels.

Highstand system tract:

Two parasequences, each composed of green or blue clays in the lower part and yellow dolomiticites in the upper part. The beds are thicker than in the transgressive system tract. Pedogenetic alterations or rhizoconcretions appear at the tops of these two parasequences.

Sequence Ba 5 (Fig. 31a)

Sequence boundary and transgressive surface:
Red clay underlying the uppermost bed of dolomites with root prints of the underlying sequence (Fig. 33b).

Transgressive system tract:

This tract consists of three deepening-upwards parasequences:



Fig. 30 - The Ba 3 sequence boundary north of Praia Grande do Guincho and at Crismina.

- The first and lowest parasequence is composed of white sandstones with load casts and red clays, then of bioturbated dolomites alternating with blue clays.

- The second consists of sandstones, bioturbated dolomitic limestones, black marls with bioturbations, and yellow dolomites with algal structures and internal moulds of bivalves.

- The third is composed of sandstones and yellow vacuolar limestones with strong bioturbation, gastropods (including *Trochactaeon*, *Glaucina*, and *Pyrazus*), echinoids (*Heteraster* and *Trochotiara*), bivalves (*Cyprina*, *Astarte*, and oysters), and foraminifiers (*Choffatella*).

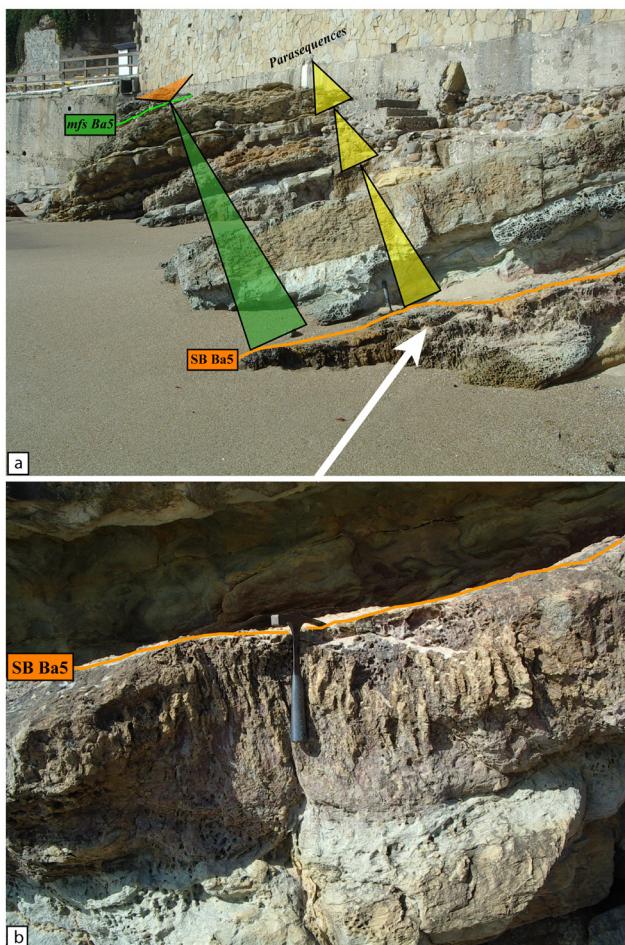


Fig. 31 - The Ba 5 sequence at Crismina. a: general view; b: rhizoconcretions beneath the sequence boundary.

From the base to the top of the tract, the thickness of sandy beds decreases and the progressively marine character of the deposits is expressed.

Maximum flooding surface:

A discontinuous interbed of green clay.

Highstand system tract:

Two levels can be distinguished:

- A lower level of white micritic bioturbated limestone with nerineas, oysters, and green algae.
- An upper level studied during the 1960s but now obscured owing to the construction of a wall. This level consists of purple and blue clays alternating with beds of fine yellow sandstones. Presently, only the uppermost part of this level can be seen (Fig. 32), characterized by the stacking of several palaeosols (including pedogenetic nodules, calcretes, and mottled horizons).

2.2.2. Sequence Ba 6

Definition

This thick sequence corresponds to an extensive marine transgression in the southern part of the Lusitanian Basin (Fig. 6). Therefore, it is a backstepping

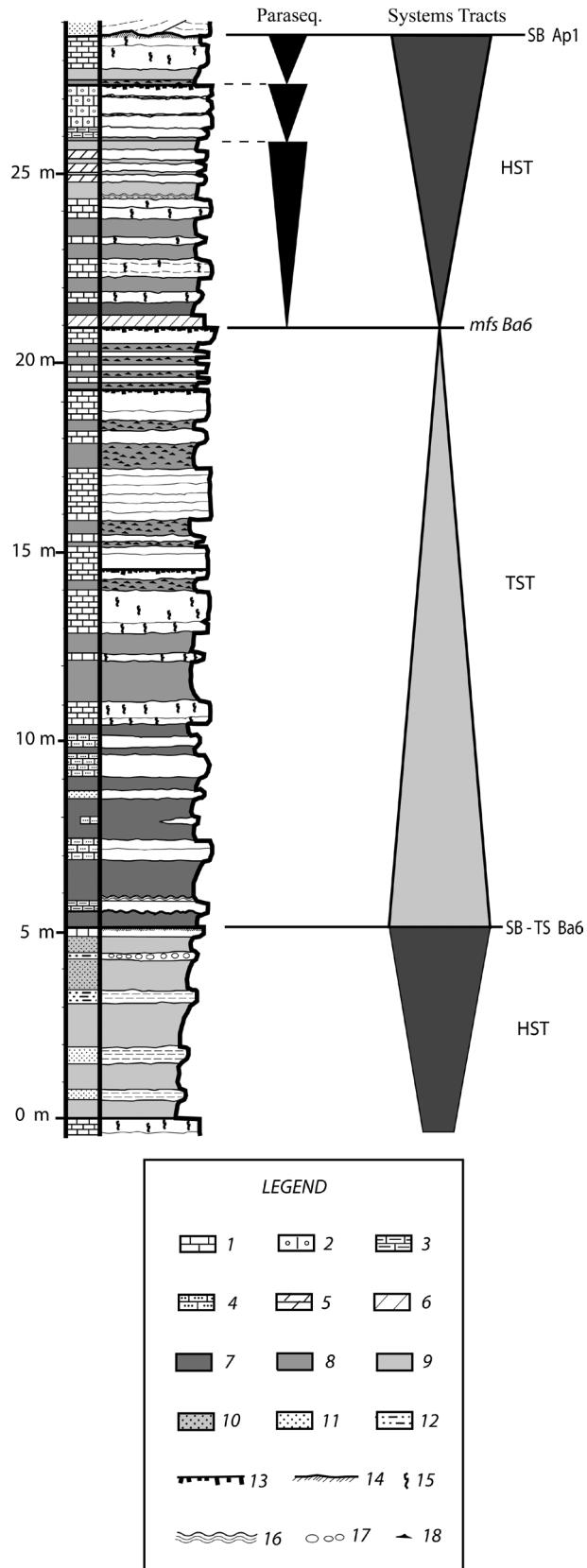


Fig. 32 - Sequence Ba 6 at Crismina: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: bioclastic limestone; 3: muddy limestone; 4: sandy limestone; 5: dolomite; 6: diagenetic dolomite; 7: marl; 8: calcareous marl; 9: clay; 10: sandy clay; 11: sandstone; 12: silt; 13: hardground; 14: palaeosol; 15: bioturbation; 16: algal film; 17: pedogenetic nodules; 18: palorbitolinids.

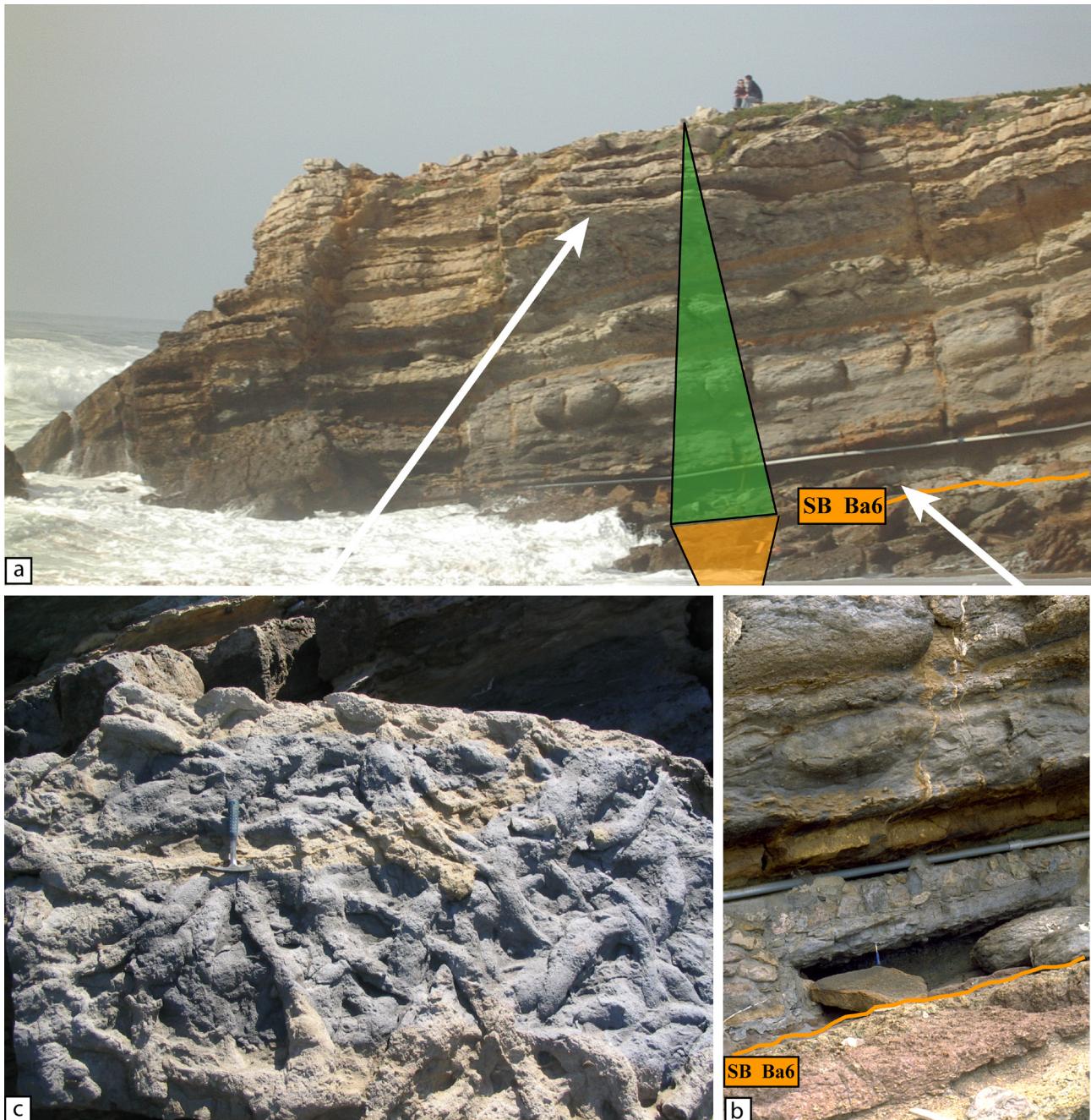


Fig. 33 – Transgressive system tract of sequence Ba 6 at Crismina. a: general view; b: sequence boundary; c: *Thalassinoides*.

sequence with a transgressive system tract much thicker than the highstand system tract.

Age

Latest Barremian–earliest Aptian. The boundary between the Barremian and Aptian may be located at the top of the transgressive system tract, with the appearance of *Heteraster oblongus* in addition to the presence of *Palorbitolina lenticularis* and *Choffatella decipiens*.

Composition (Figs 32–34)

Sequence boundary and transgressive surface:

Grey marls covering a palaeosol of mottled limestone (Fig. 33b).

Transgressive system tract (Fig. 33a):

Two parts are distinguished:

- A lower part composed of grey marls alternating with poorly differentiated beds of sandstones, argillaceous limestones, or sandy limestones with oysters and *Choffatella*. Algal films appear at the base of this system tract.

- An upper part represented by grey or yellow marls interbedded in several shallowing-upwards parasequences with bioclastic limestones that show large horizontal bioturbations (*Thalassinoides*, Fig. 33c), gastropods (nerineas, *Natica*, and *Pyrazus*, amongst others), bivalves (oysters and *Lucina*), bra-

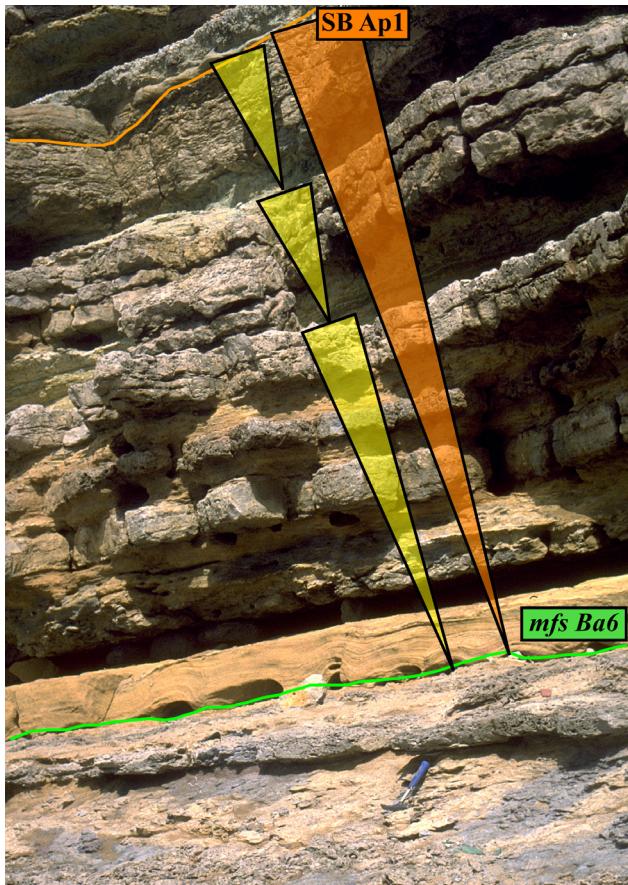


Fig. 34 – Sequence Ba 6 at Crismina. Maximum flooding surface and highstand system tract.

chiopods, echinoids, *Choffatella*, and calcareous algae. The uppermost surfaces of beds are hardened. Palorbitolinids are abundant in the upper two-thirds of this part.

Maximum flooding surface:

An upper surface of a calcareous bed with abundant *Heteraster oblongus* (Fig. 34).

Highstand system tract (Fig. 34):

This tract includes three shallowing-upwards parasequences that decrease in thickness from the base to the top:

- The first parasequence is composed of grey marls¹, bioturbated yellow calcareous marls, and micritic limestones with dominant *Choffatella* and palorbitolinids. The top of the parasequence contains dolomites and green laminated marls that present algal films.

- The second parasequence has a thin marly bed at its base, which is overlain by an argillaceous limestone bed and then by three beds of grainstone show-

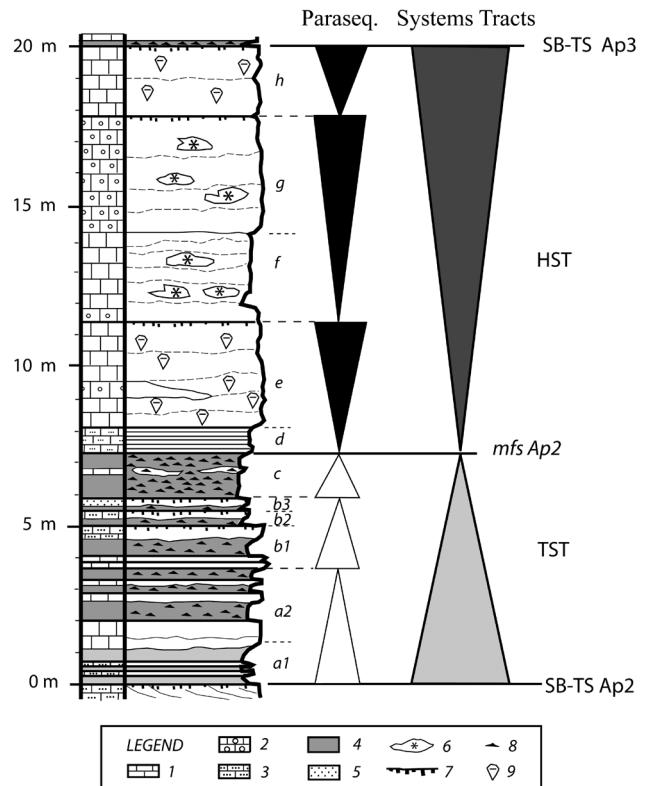


Fig. 35 – Sequence Ap 2 at Ponta Alta: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone (mudstone and wackestone); 2: limestone (grainstone); 3: sandy limestone; 4: calcareous marls; 5: sandstone; 6: corals; 7: hardground; 8: palorbitolinids; 9: rudists.

ing hummocky cross-stratifications. The upper surface of the uppermost bed is bored.

- The third parasequence contains a bed of grey marls with palorbitolinids at the base, overlain by grey marls. In the upper part there is a level of gravelly, bioturbated grey limestone with inconspicuous stratification.

2.2.3. Sequence Ap 2

Definition

This backstepping sequence shows an arrangement of deposits and facies associated with a middle-platform environment.

Age

Early Aptian, indicated by the association *Palorbitolina lenticularis–Choffatella decipiens*.

Composition (Figs 35 – 37)

Sequence boundary and transgressive surface:

A bored surface covered by green marls that are laterally replaced by yellow dolomites near sills of dolerite (Fig. 38b).

Transgressive system tract:

This tract consists of three deepening-upwards and thinning-upwards parasequences. The first

¹The marls or clays from the base of this system tract are locally replaced by ochre dolomites near a sill of dolerite. This replacement corresponds to a process of late diagenesis induced by the intrusion of volcanic rocks. This change is quite common in the Crismina series. The yellow dolomites of sequences Ba 3 and Ba 4 show the same features.



Fig. 36 - Sequence Ap 2 at Ponta Alta. a: general view; b: sequence boundary; c: maximum flooding surface.

parasequence (levels *a1* and *a2*) is composed of green marls alternating with bioturbated micritic limestones and calcareous marls with palorbitolinids. The second (levels *b1* to *b3*) consists of marls with palorbitolinids, alternating with sandy limestones and sandstones. The third (level *c*) contains a brown palorbitolinid-rich marl and represents a true condensed interval.

Maximum flooding surface:

Top of the condensed interval (Fig. 38c).

Highstand system tract:

This tract contains five levels, which from the base to the top are as follows:

- level d: thin beds of sandy limestones with palorbitolinids, *Choffatella*, and echinoids (*Spatangoidea*).
- level e: micritic limestone with rudists (*Requienidae* and *Caprotinidae*) and large nerineas (Fig. 39a), including lenses of grainstone. The upper surface of this level shows dissolved shells and a filling of grainstone (Fig. 39c), which indicate an emersive episode.

nidae and *Caprotinidae*) and large nerineas (Fig. 39a), including lenses of grainstone. The upper surface of this level shows dissolved shells and a filling of grainstone (Fig. 39c), which indicate an emersive episode.

- level f: grainstone and microclastic limestone with stromatoporoids and sparse corals (*Astrocoenidae*, *Montlivaltiidae*, and *Faviidae*; Fig. 39b).

- level g: grainstone with corals, topped by an emersive surface.

- level h: micritic limestone with rudists (*Requienidae*), nerineas, and scarce corals. Fossils are dolomitized at the top of the uppermost bed.

During the deposition of this highstand system tract, the sedimentary basement was located very close to the sea surface, with the result that the absolute sea-level rise (or basin subsidence) was able to

create an available space that was quickly infilled by the bio-sedimentary production.

Mineralogical analyses of Sequence Ap 2 (at Crismina)

The following observations can be made (Fig. 38):

- The sequence boundary of Ap 2 is marked by a relative abundance of quartz and K feldspars, above which there is a slight decrease in these minerals, and then an enrichment towards the top of the TST.
- In the lowermost several metres of this transgressive interval, the clay mineral assemblages show a marked increase in low-crystallinity illite, reflecting the inherited origin and degradation induced by relatively prolonged transport. Towards the top of the transgressive tract, the abundance and the degree of structural order of the illites decrease.
- The maximum flooding surface is represented by minimal carbonate (calcite), a greater abundance of phyllosilicates, and the presence of pyrite.
- The lowermost levels of the highstand (HST) show the greatest abundance of coarse detrital minerals and the lowest abundance of phyllosilicates. Within these phyllosilicates, there is a relative abundance of expansive clay minerals (ECMs).
- Throughout the rest of the HST, a carbonate platform is represented, with bioclastic limestones and very reduced siliciclastic input.
- Despite the reduced amount of insoluble residue, it is possible to observe fluctuations in the content of the insoluble residue and of the $<2\text{ }\mu\text{m}$ fraction, especially in certain levels (some of which are recognized in the field description as corresponding to emersion surfaces): a first level, at 8 m (sample 12), with maximum quartz and kaolinite and minimum illite (with high crystallinity); another, at 10 m (sample 14), corresponding to a minimum of quartz, a strong presence of pyrite, and an abundance of illite ($I/K = 1.37$); a third level, at 18 m (sample 19), corresponding to the phyllosilicate maximum and to the minimum of coarse detrital minerals; and finally, at the top of the section, coinciding with the sequence boundary, a new minimum of coarse detrital minerals, abundant pyrite, and a peak in relative illite abundance ($I/K = 1.28$). These fluctuations in the mineralogical signature are interpreted as being related to high-

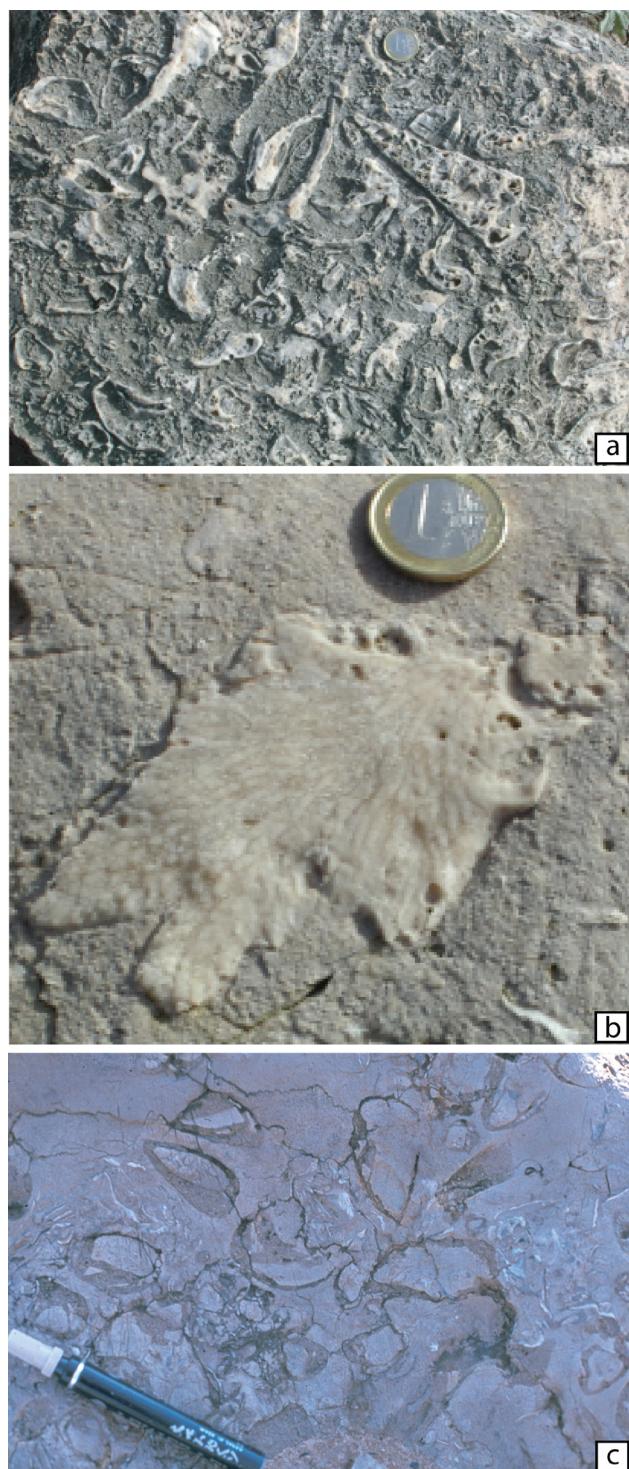


Fig. 37 - Fossils of the highstand system tract in sequence Ap 2 at Ponta Alta. a: nerineas; b: scleractinia; c: dissolved shells of rudists.

er-order sequence fluctuations (at the parasequence level).

2.2.4. Sequence Ap 3

Definition

Sequence Ap 3 contains the transgressive peak of the late Barremian–early Aptian cycle. It is high-

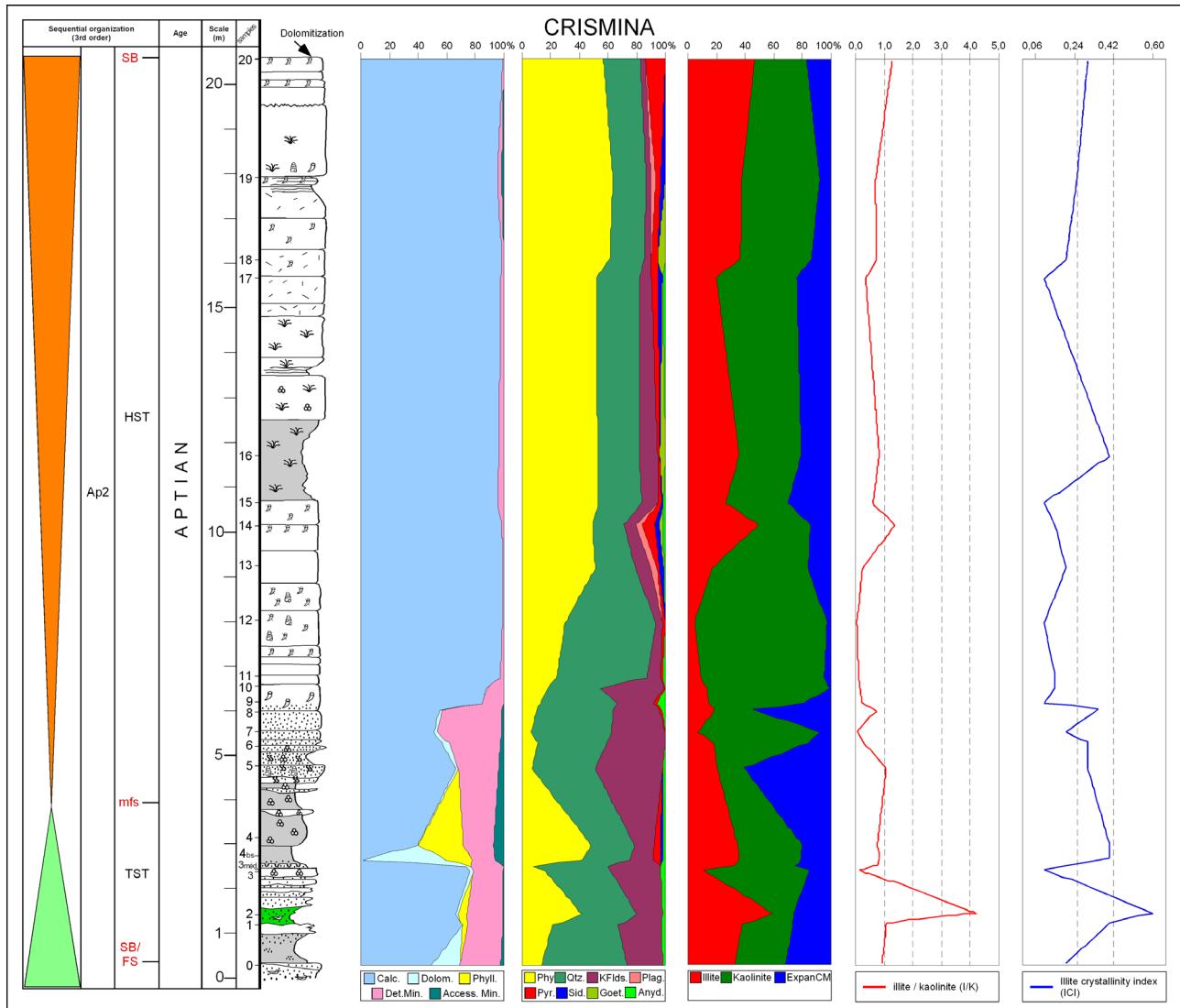


Fig. 38 – Results obtained from the Crismina section (sequence Ap 2): mineralogical assemblages of the total sample, insoluble residue, and $<2\text{ }\mu\text{m}$ fraction; illite/kaolinite ratio (I/K); and illite crystallinity (Kubler/Segonzac index – ICI).

ly retrogradational and corresponds to the maximum extent of sedimentary facies in the Lusitanian Basin (Figs 5 and 6). The depositional environments were deeper, extending to the outer platform.

Age

Early Aptian. The appearance of *Praeorbitolina cormyi* at the base of this sequence more precisely indicates the Deshayesi Zone ("middle Bedoulian"; Hardenbol *et al.*, 1998).

Composition (Figs 39–42)

Sequence boundary and transgressive surface:

Hardground with burrows, iron crust, and dolomitized fossils (Fig. 41a and b).

Transgressive system tract:

This tract consists of six retrograding and thin parasequences (Fig. 42a), including a lower bed of marls and an upper bed of limestones, topped by an oxidized surface. It is a condensed interval, with

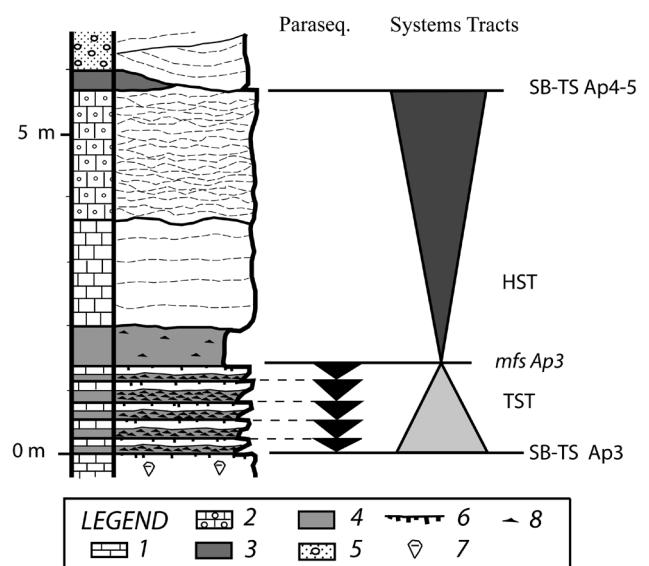


Fig. 39 – Sequence Ap 3 at Ponta Alta: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone (mudstone and wackestone); 2: limestone (grainstone); 3: marl; 4: calcareous marl; 5: sandstone; 6: hardground; 7: rudists; 8: palorbitolinids and praeorbitolinids.



Fig. 40 – Sequence Ap 3 and the Aptian–Albian outcrops at Galé, between Ponta Alta and Praia Grande do Guincho.

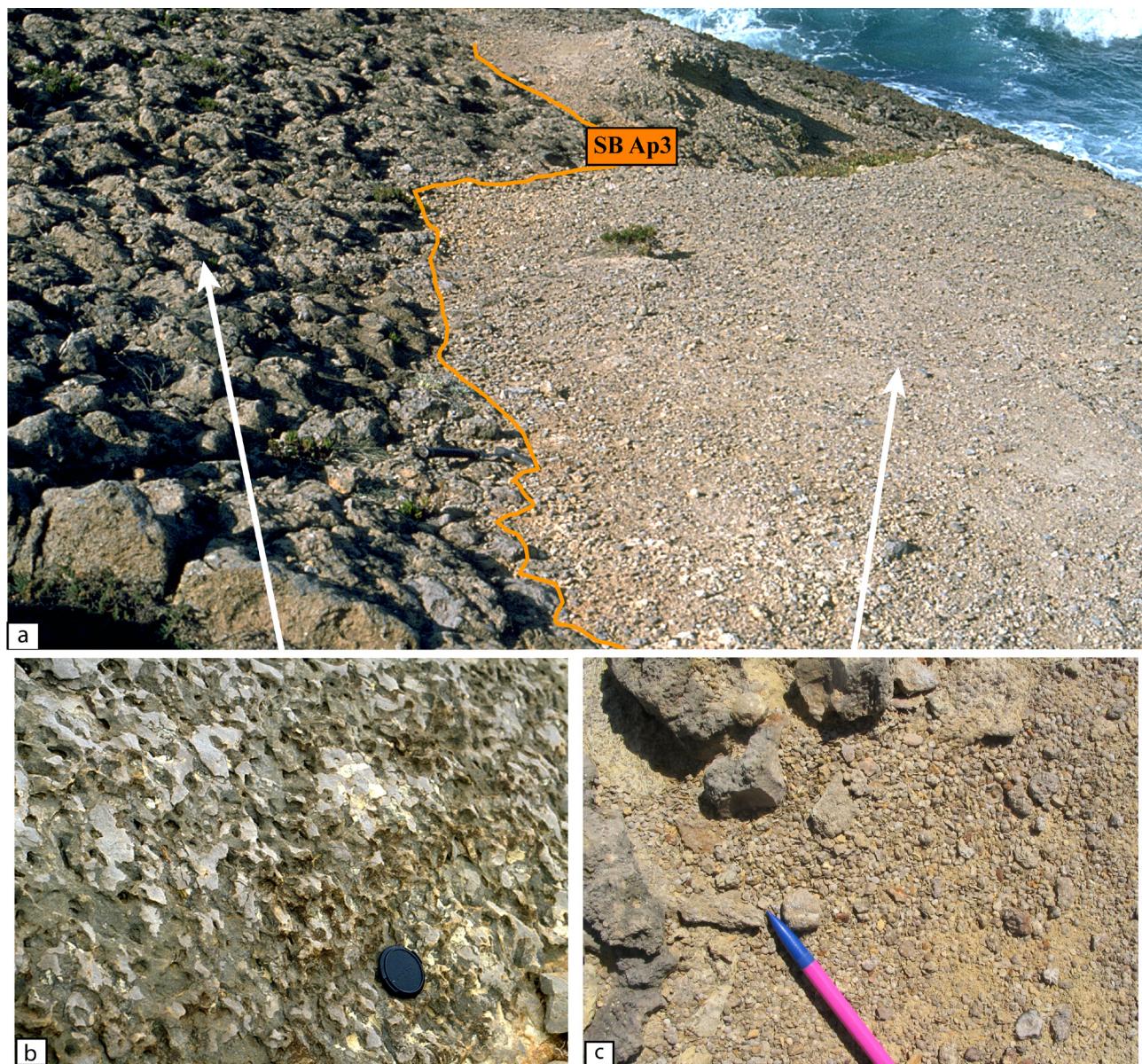


Fig. 41 – The Ap 3 sequence boundary at Ponta Alta. a: general view; b: hardground with burrows, iron crust, and dolomitized fossils; c: sand of orbitolinids in the transgressive system tract.

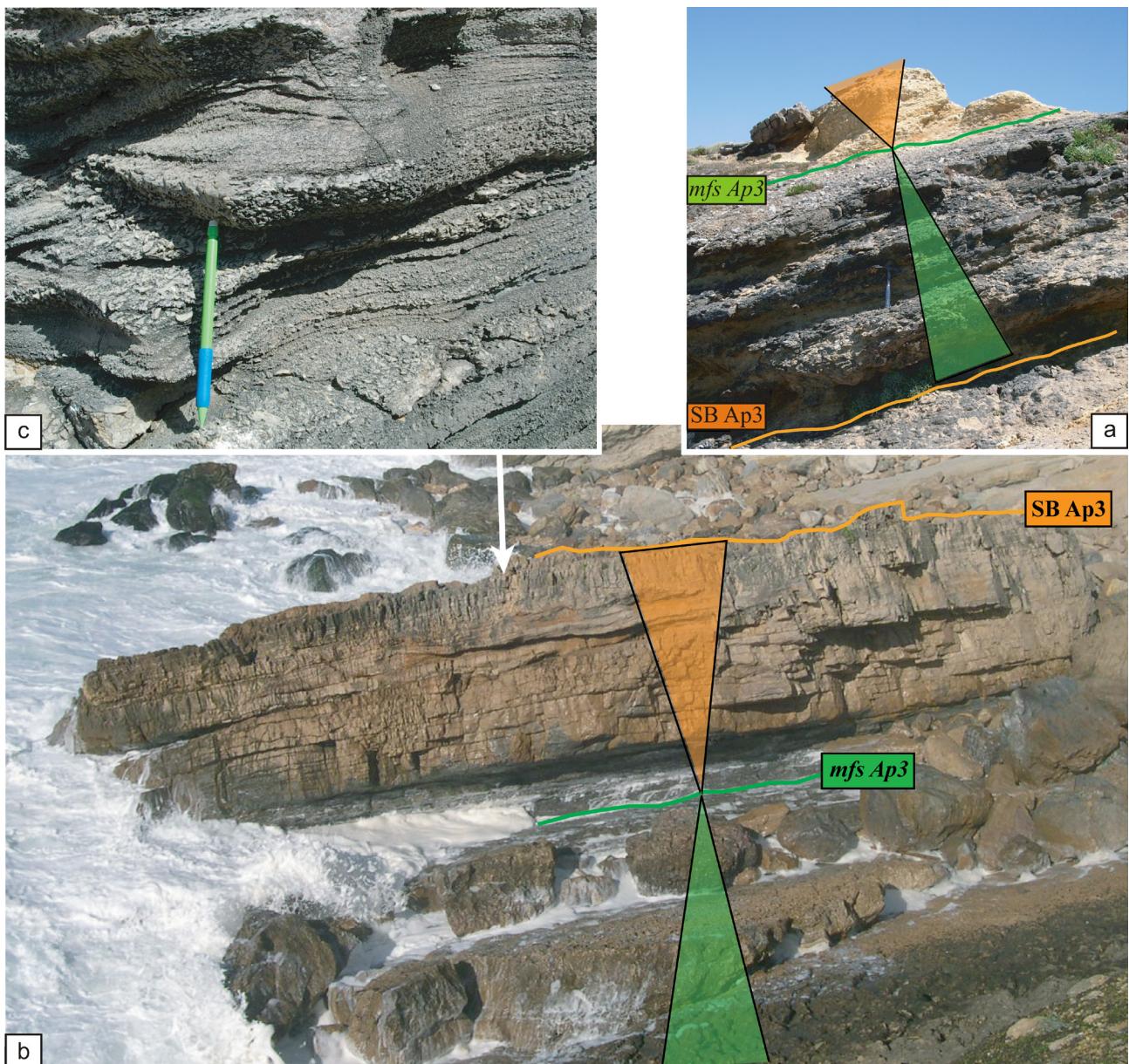


Fig. 42 – Sequence Ap 3 north of Ponta Alta. a: transgressive system tract and base of the highstand system tract; b: part of the transgressive system tract and highstand system tract; c: bioclasts cross-bedded at the top of the highstand system tract.

abundant and diverse fauna: contiguous orbitolinids (*Palorbitolina* and *Praeorbitolina*) (Fig. 41c), corals, bryozoa, brachiopods, echinoids (*Salenia*, *Pyrina*, and *Heteraster*), bivalves (oysters, pectinids, and rudists), and nerineas.

Maximum flooding surface:

The uppermost and most marked oxidized surface.

Highstand system tract:

This tract comprises three parts:

- i) yellow and brown marls with sparse orbitolinids and bioturbations (Fig. 42a).
- ii) mudstones and wackestones, with *Choffatella* and palorbitolinids, topped by a wavy surface (Fig. 42b).
- iii) grainstones accumulated in a massive body

with cross-stratification (Fig. 42c). The bioclasts of rudists, corals, and echinoderms are the most numerous. The upper surface of this level is bored and oxidized. The unit most likely represents the fore-reef of a biostrome identified a few kilometres to the east, north of Cascais (Rey, 1972).

2.3. The Rodízio Formation

This formation comprises white cross-bedded coarse and fine sandstones, grey silts, and purple or white clays with lignite debris (about 30 m thick; Fig. 40), arranged in fining-upwards elementary sequences. The basal surface is erosive and truncates the underlying deposits of the Crismina Formation.

The Rodízio Formation was deposited in fluvial environments during the latest Aptian to early Albian. Recognized across the Lusitanian Basin (Fig. 6), this formation represents a regressive peak at the second-order scale and the late Aptian crisis related to an Atlantic event, namely, the initiation of seafloor spreading in the Galicia sector.

2.3.1. Sequence Al 7

Definition

This backstepping sequence was formed in a ramp setting, with subtidal environments. The sequence presents a remarkable transgression peak (Fig. 7) within the Albian transgressive-regressive second-order cycle that is recognized upwards to the fluvial deposits of the northern part of the Lusitanian Basin (Dinis *et al.*, 2002).

Age

Late Albian. This sequence is accurately dated by:

- the last appearance datum of *Simplorbitolina manasi-conulus* (the boundary between the middle and late Albian) in the lowermost beds of this unit (Berthou & Schroeder, 1979).

- the presence of a reference bed with *Knemiceras uhligi*, an ammonite that indicates the Inflatum Zone, at the top of the transgressive system tract (Rey *et al.*, 1977).

Composition (Figs 43 and 44)

Sequence boundary and transgressive surface:

An abrupt contact between grey clays (the top of sequence Al 6) and a bed of prograding sandy limestones (the base of sequence Al 7).

Transgressive system tract:

This tract includes three levels (Fig. 44b) that indicate a deepening-upwards evolution:

- level a: a bed of sandy limestone with oblique stratification.

- levels b1–b2: two parasequences of calcareous marls and bioturbated marly limestones with oysters, gastropods, orbitolinids (*Mesorbitolina*), miliolids, *Hensonina*, and *Dasycladacea*. The last appearance datum of *Simplorbitolina manasi/conulus* is contained in this level.

- levels c1–c2–c3–c4: four parasequences, each beginning with a layer of orbitolinid-rich marls covered by argillaceous then bioturbated micritic limestones with echinoids (*Heteraster* and *Tetragramma*), bivalves, *Colomiella*, and *Hensonina*. The uppermost bed of this system tract contains *Knemiceras uhligi* (Fig. 44c).

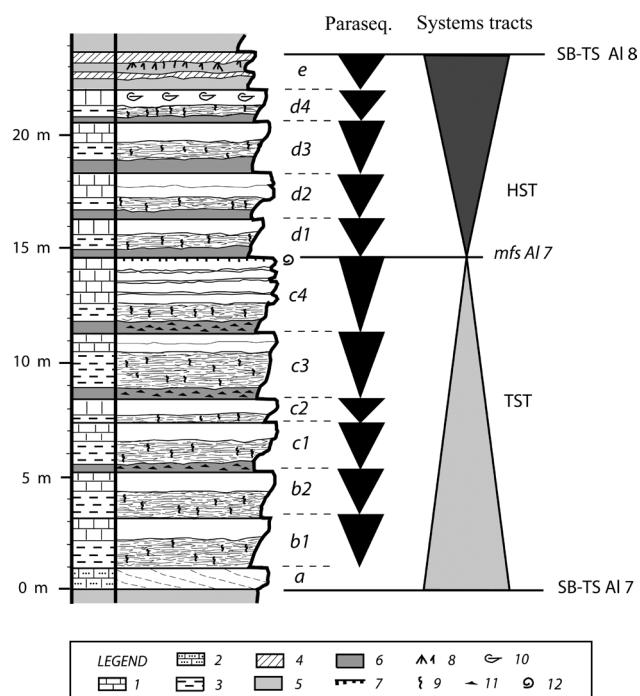


Fig. 43 – Sequence Al 7 at Praia da Água Doce. Lithology, stratigraphy, and sequence arrangement (Rey, 2006). 1: limestone; 2: sandy limestone; 3: muddy limestone; 4: calcrete; 5: clay; 6: marl; 7: hardground; 8: rhizoconcretions; 9: bioturbations; 10: oysters; 11: orbitolinids; 12: ammonites.

Maximum flooding surface:

A bored surface at the top of the *Knemiceras uhligi* bed.

Highstand system tract:

This tract comprises two parts (Fig. 44d), showing a shallowing-upwards evolution:

- levels d1–d2–d3–d4: four metre-scale parasequences of marls, calcareous marls, and bioturbated limestones with oysters and miliolids.

- level e: green and purple argillaceous marls interbedded with two horizons of calcrete and rhizoconcretions (Fig. 46b), which indicate the total infilling of the available space.

2.3.2. Sequence Al 8

Definition

This sequence is distinguished, on the one hand, by a transgressive system tract with facies progressively deeper and more distal (and therefore showing an appreciable increase in the amount of available space), and, on the other hand, by the first appearance in the highstand system tract of rudist levels in the middle platform. Overall, it constitutes an aggrading sequence.

Age

Late Albian, with the assemblage *Orbitolina* (*Mesorbitolina*) *texana*–*Orbitolina paeneconica*.

Composition (Figs 45–46)

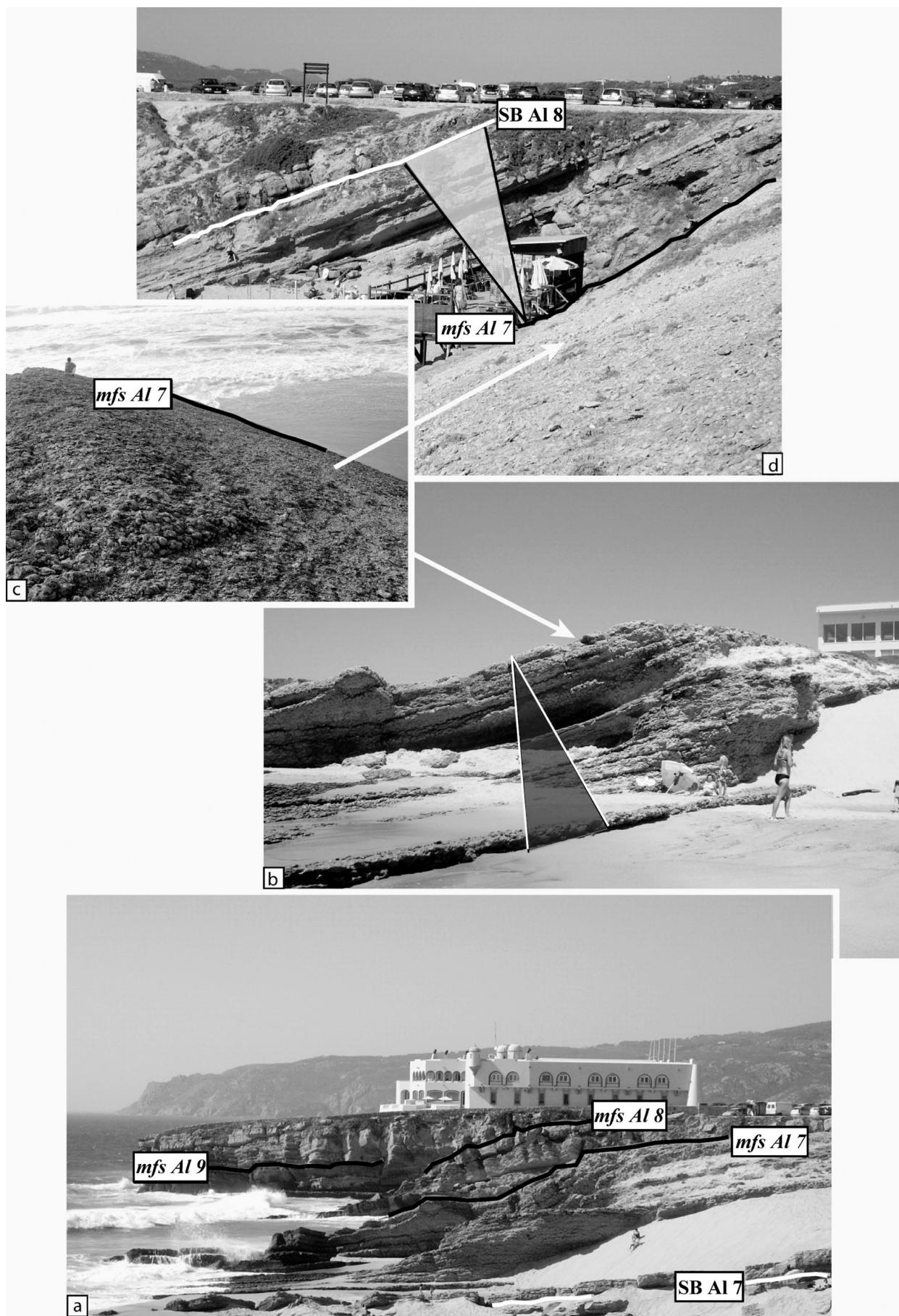


Fig. 44 – Sequence Al 7 at Praia da Água Doce a: general view of sequences Al 7 to Al 9; b: transgressive system tract; c: maximum flooding surface (*Knemiceras uhligi* bed); d: highstand system tract.

Sequence boundary and transgressive surface:

The upper surface of the uppermost calcrete in sequence Al 7 (Fig. 46b).

Transgressive system tract:

The deepening-upwards trend is expressed by the following succession:

- level a: yellow clays with calcareous horizontal bioturbation.
- level b: micritic limestones with oncoids (*Bacinaella*), then oyster lumachella.
- level c: yellow laminated silty clay.
- level d: black clay.
- level e: marls and bioturbated argillaceous limestones with bivalves, miliolids, and green algae.
- level f: calcareous marls and bioturbated argillaceous limestones with oysters, moulds of bivalves, calcareous algae, echinoids (*Diplopodia*), *Hensonina*, and orbitolinids.

Maximum flooding surface:

A bed of yellow orbitolinid-rich, calcareous marls (level g).

Highstand system tract:

This tract comprises two levels with a shallowing-upwards evolution:

- level h: white micritic limestones with rudists (*Sphaerulites* and *Polyconites subverneuili*, Fig. 46c), *Dicyclina* and *Hensonina*, and nerineas. The uppermost bed, topped by a perforated hardground, contains pectinids.
- level i: oyster marls alternating with thinning-upwards beds of argillaceous limestones with calcareous algae and orbitolinids.

B. The Lower Cretaceous near Ericeira

Location

During the Early Cretaceous, the surroundings of Ericeira were located on the northern edge of the marine area (Fig. 6). The sedimentation was composite, with both siliciclastic and carbonate components being deposited in the prevailing coastal environments.

The stratigraphic succession is well exposed along the cliffs that border the Atlantic between Ericeira and São Lourenço (Fig. 47). The beds are near-horizontal or with shallow dips to the south. However, several faults parallel to the coast cut the series and require a rigorous analysis in the various blocks. For this fieldtrip, we observe only the interval between the terminal Valanginian and the Hauterivian (sequences Va 7 to Ha 6). The basal units of the

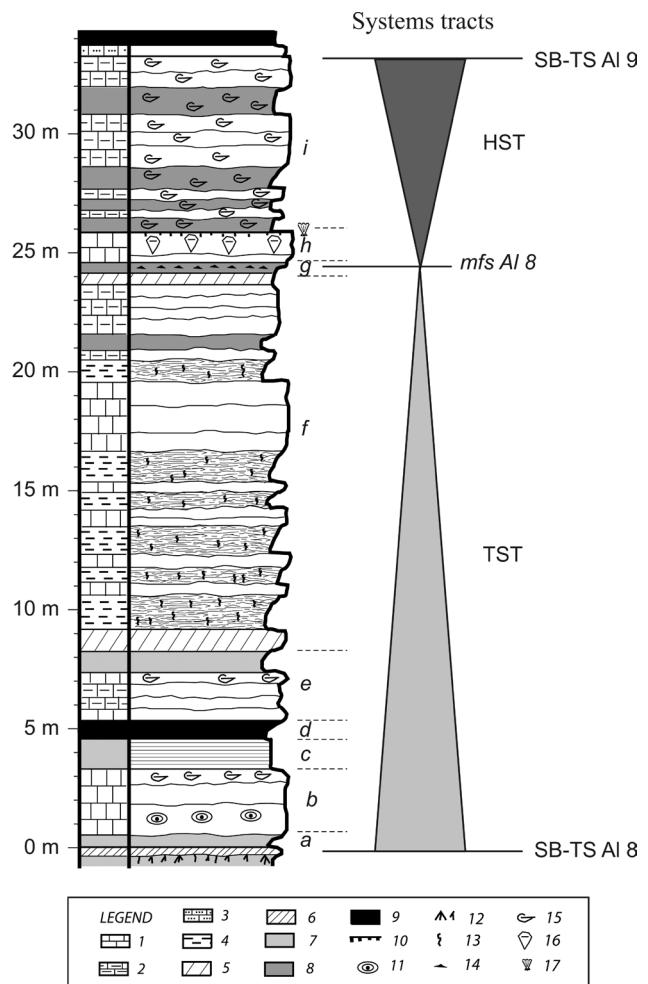


Fig. 45 – Sequence Al 8 at Ponta da Galé. Lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: muddy limestone; 3: sandy limestone; 4: calcareous marl; 5: dolomite; 6: calcrete; 7: clay; 8: marl; 9: black clay; 10: hardground; 11: oncolites; 12: rhizoconcretions; 13: bioturbations; 14: orbitolinids; 15: oysters; 16: rudists; 17: pectinidae.

Cretaceous (the Porto da Calada and Vale de Lobos formations) are not considered because they are poorly dated and because the sequence interpretation has not yet been completed. The Barremian is difficult to observe because of tidal movements. The Aptian series is found in Ericeira and to the south of this town with the same facies as in the Cascais area.

2.4. The Santa Susana p.p., Praia dos Coxos and Ribamar p.p. formations

2.4.1. Sequence Ha 2

Definition

This thin carbonate sequence was deposited in the most distal part of the inner platform. Coeval with the reefal formations in the Cascais and Cape Espichel areas, the sequence records the maximum transgression around Ericeira in the late Valangin-

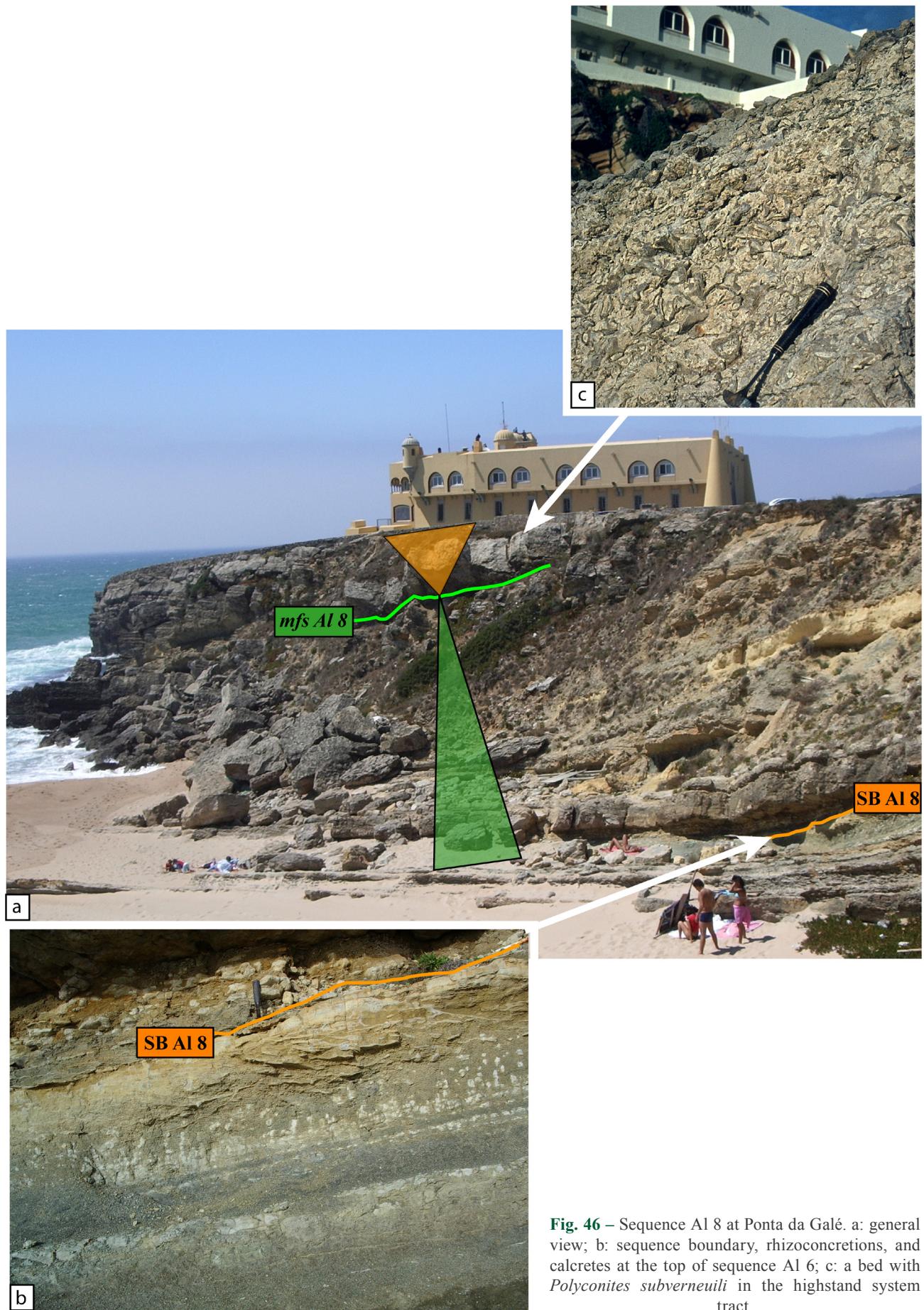


Fig. 46 – Sequence Al 8 at Ponta da Galé. a: general view; b: sequence boundary, rhizoconcretions, and calcretes at the top of sequence Al 6; c: a bed with *Polyconites subverneuili* in the highstand system tract.

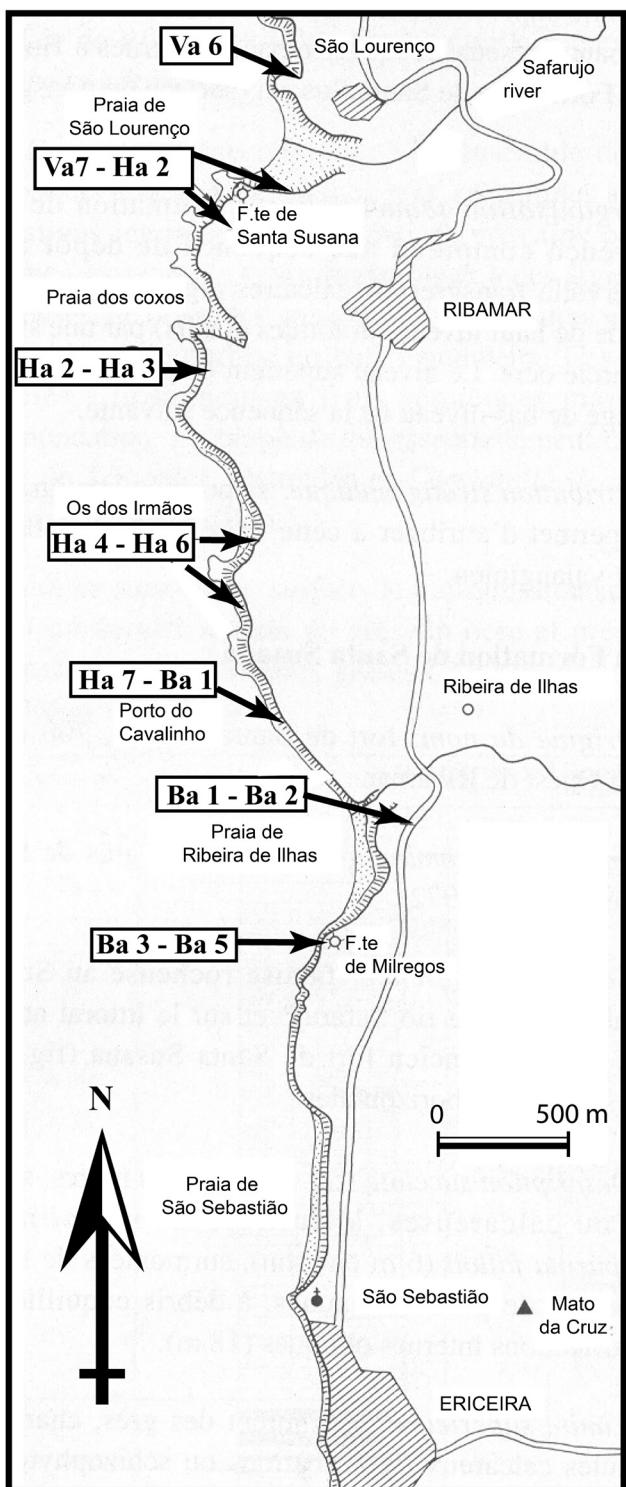


Fig. 47 – The locations of depositional sequences north of Ericeira

ian–early Barremian cycle.

Age

Early Hauterivian. Lacking good chronological markers, this sequence is dated mainly by its stratigraphic position and by correlations with the outcrops surrounding Cascais.

Composition (Figs 48–49)

Sequence boundary and transgressive surface:

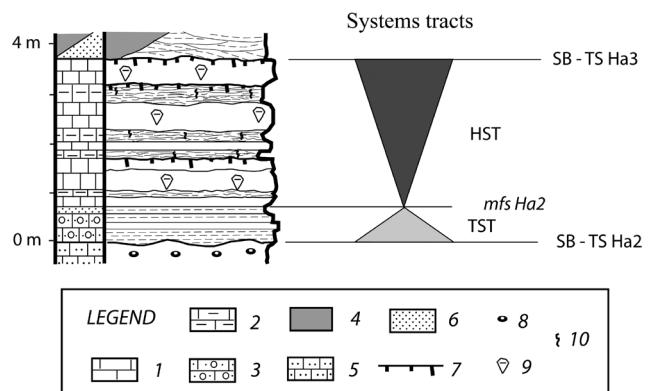


Fig. 48 – Sequence Ha 2 at Praia dos Coxos: lithology, stratigraphy, and sequence arrangement (Rey, 2006). 1: limestone; 2: muddy limestone; 3: sandy grainstone; 4: marl; 5: sandy limestone; 6: sandstone; 7: hardground; 8: nodular bioturbation; 9: rudists; 10: bioturbation.

A well-expressed erosional surface that cuts into the sandy limestones of the underlying highstand system tract (Fig. 49).

Transgressive system tract:

This tract is represented only by a level of sandy breccia–grainstone with an irregular oblique stratification. The thickness of the level varies markedly depending on location. The level contains a reworked fauna of gastropods and bivalves.

Maximum flooding surface:

The maximum transgression is expressed by a thin bed of calcareous sandstone.

Highstand system tract:

This tract consists of four or five beds of light-grey limestones (“wackestone–packstone”) interbedded with bioturbated argillaceous limestones (Fig. 49). The limestone beds contain a fauna comprising rudists (*Requienia*) and large nerineas associated with sparse colonies of corals. Several bed surfaces are hardened and oxidized.

2.4.2. Sequence Ha 3

Definition

This thin aggrading sequence was deposited on an inner platform in a more proximal position compared with the previous sequence. It therefore indicates the beginning of the regression in the late Valanginian–early Barremian transgressive–regressive cycle.

Age

Hauterivian, as indicated by the presence of the echinoid *Trochotiara bourgueti*. The very probable assigning to the late Hauterivian is deduced by sequence correlations.

Composition (Figs 50–52)



Fig. 49 – Sequence Ha 2 south of Praia dos Coxos.

Sequence boundary and transgressive surface:

Bored hardground covered by an iron crust (Fig. 52a and b).

Transgressive system tract:

This tract comprises two parts:

- a lower part of green and red clays overlain by lignite-rich clays (north of Praia dos Coxos) and laterally replaced by a body of white, fine, well-sorted and cross-bedded sandstones (south of Praia dos Coxos), corresponding to a tidal bar (Figs 51 and 52a and c).

- an upper part of argillaceous limestones or “wackestone”, beige to bluish, strongly bioturbated, and poorly stratified, alternating with more argilla-

ceous beds. From the base to the top, the limestones thicken upwards and bioturbation increases. The fauna is diversified: gastropods (*Glauconia*), naticids, bivalves (trigoniids and oysters), echinoids (*Toxaster* and *Trochotiarra*), and *Choffatella* (Fig. 52a).

Maximum flooding surface:

Hardground on the uppermost limestone bed in the transgressive system tract.

Highstand system tract:

This tract presents the same facies and same fossils as does the upper part of the transgressive system tract, but bioturbation and faunal density decrease upwards.

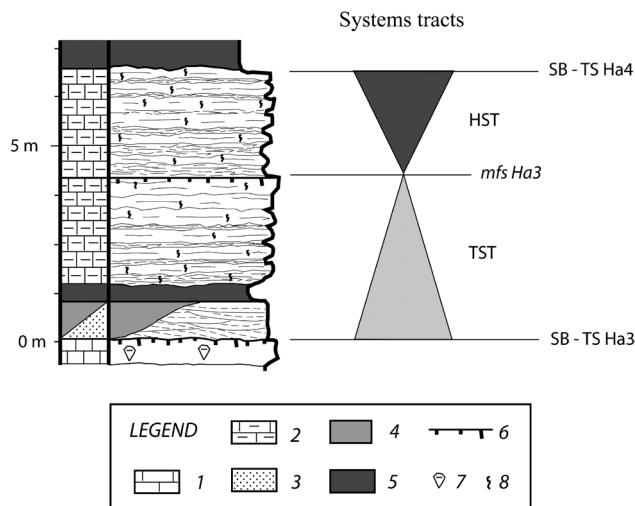


Fig. 50 – Sequence Ha 3 at Praia dos Coxos: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: muddy limestone; 3: sandstone; 4: marl; 5: clay; 6: hardground; 7: rudists; 8: bioturbation

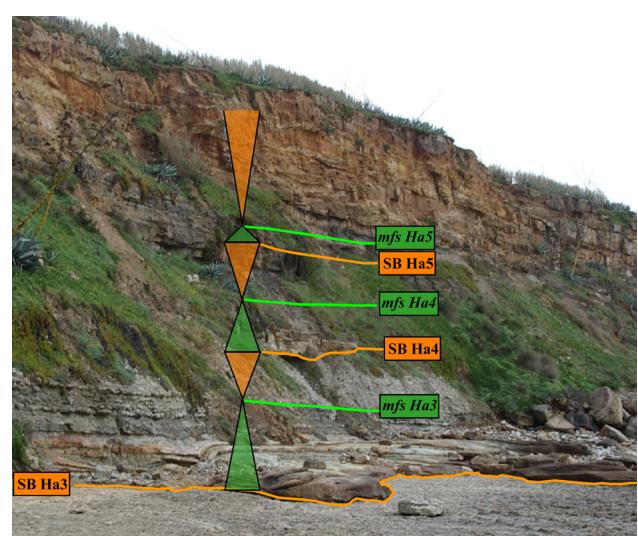


Fig. 51 – General view of sequences Ha 3, Ha 4, and Ha 5 at Os Dois Irmãos.

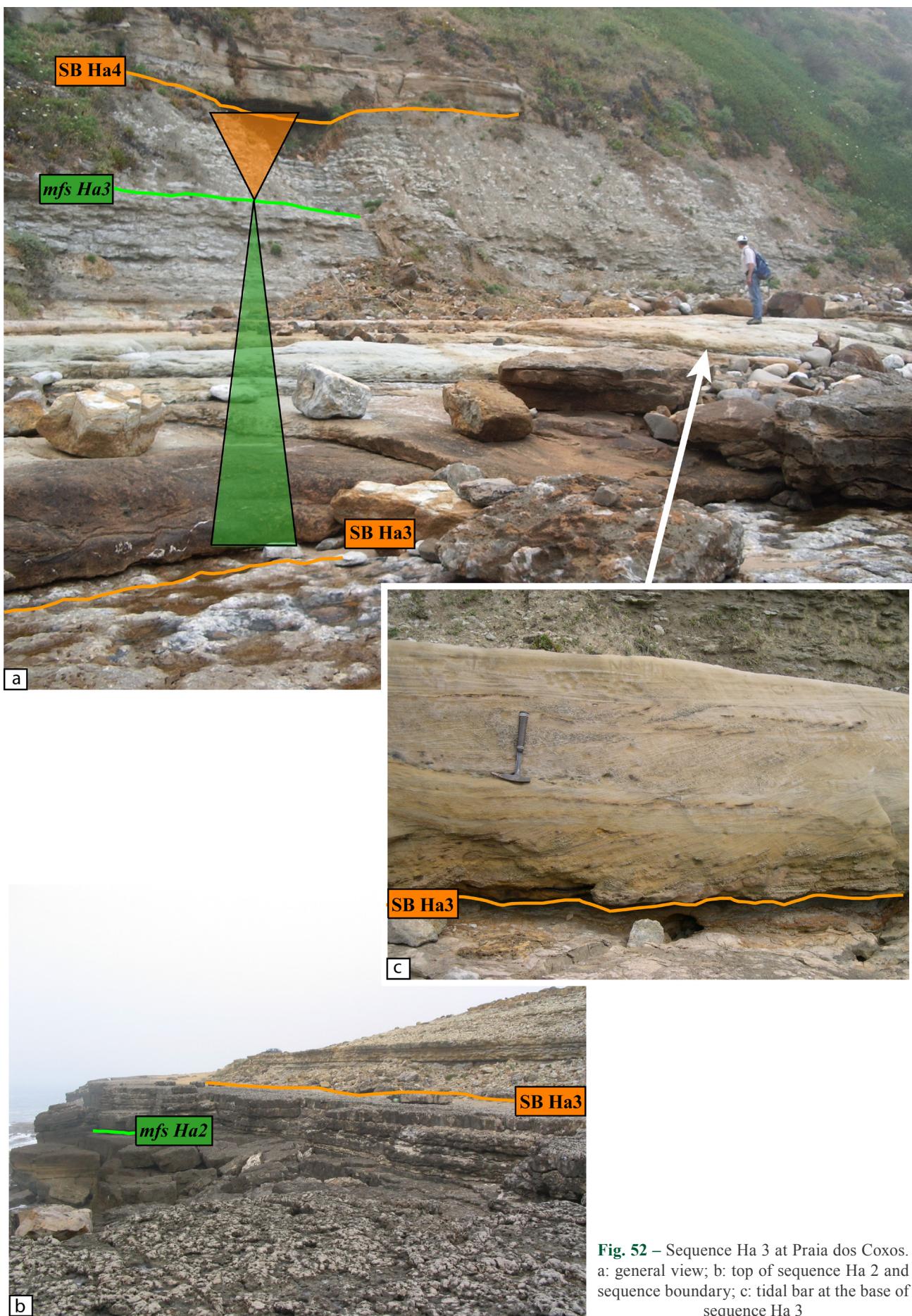


Fig. 52 – Sequence Ha 3 at Praia dos Coxos.
a: general view; b: top of sequence Ha 2 and sequence boundary; c: tidal bar at the base of sequence Ha 3

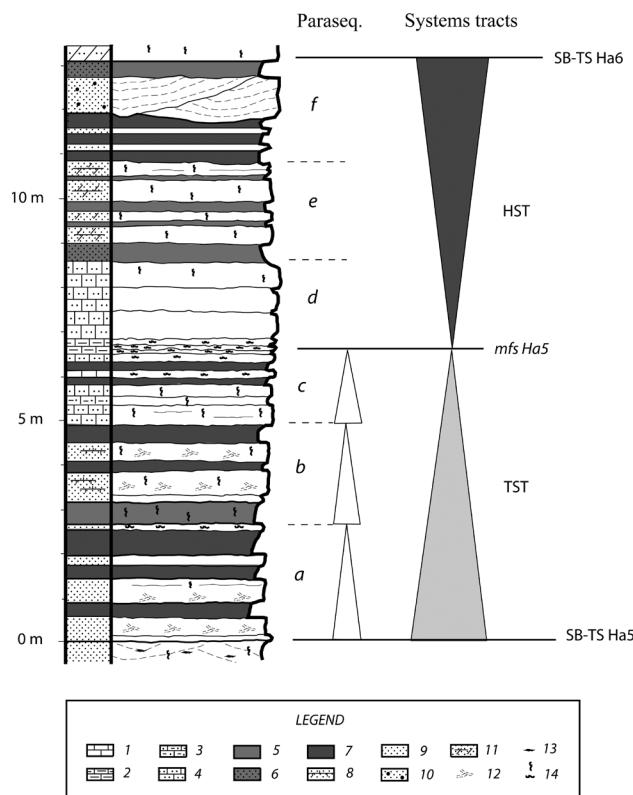


Fig. 53 – Sequence Ha 5 at Os Dois Irmãos: lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: muddy limestone; 3: sandy–muddy limestone; 4: sandy limestone; 5: marl; 6: sandy marl; 7: black clay; 8: calcareous sandstone; 9: fine sandstone; 10: coarse sandstone; 11: sandstone with dolomitic cementation; 12: cross-stratification; 13: lignite; 14: bioturbation.

2.4.3. Sequence Ha 5

Definition

The infilling of the Lusitanian Basin continued with the deposition of sequence Ha 5. The sequence is composed of both siliciclastic and carbonate elements and was deposited in a tidal-flat environment. The sequence is characterized mainly by the high degree of symmetry of its two systems tracts with respect to the evolution of lithological facies as well as to the stratal patterns and bioturbation.

Age

Hauterivian. Lacking good chronological markers, the probable assigning to the late Hauterivian is based on its stratigraphic position and on a comparison with the known depositional sequences in the European sedimentary basins.

Composition (Figs 53–55)

Sequence boundary and transgressive surface:

This discrete boundary is located between a cross-bedded lens of sandstone and a thin horizontal bed of sandstone.

Transgressive system tract:

Three levels are distinguished in this tract, corresponding to three deepening-upwards parasequences:

- level a: horizontal and thickening-upwards beds of fine sandstones with internal cross-bedding, separated by black clays with lignite.

- level b: two horizontal beds of carbonate-cemented sandstones with internal cross-bedding included within grey marls and black clays.

- level c: bioturbated and thinning-upwards sandy limestones, with serpulids, triontiids, and *Choffatella*, interbedded with black marls. The varied bioturbation (*Teichichnus*? and *Planolites*, Fig. 54c and d) increases progressively upwards.

Maximum flooding surface:

The surface is marked by the finest and most bioturbated bed of sandy limestones (Fig. 54a and b).

Highstand system tract:

This tract is composed of three levels with a general shallowing-upwards evolution:

- level c: horizontal and thickening-upwards beds of sandy limestones with decreasing bioturbation.

- level d: fine yellow dolomite-cemented sandstones, arranged in vacuolar and bioturbated beds separated by black clays and grey marls.

- level e: lenses of fine or coarse sandstones, with an eroded base and cross-stratification (channel infilling), covered by black clays with lignite.

Mineralogical analyses of Sequence Ha 5 (at Ericeira)

The following observations can be made (Fig. 55):

- the sequence boundary of Ha 5 is marked by a relative abundance of coarse detrital minerals (quartz and K feldspars).
- approximately 2–3 m above the boundary, there is a significant increase in phyllosilicates, predominantly illite, and a decrease in coarse detrital minerals, probably indicating the presence of a transgressive surface (at the parasequence level).
- around the level of maximum flooding, carbonate fractions are more calcitic and less dolomitic, and a minimum value of detrital minerals occurs 7 m from the base of the section, in samples 16 and 17 (most likely marking the position of the mfs).
- the highstand tract is characterized by a slight increase in coarse detrital minerals and in kaolinite and by a gradual increase in dolomite (denoting a higher-energy environment and a decrease in water depth).

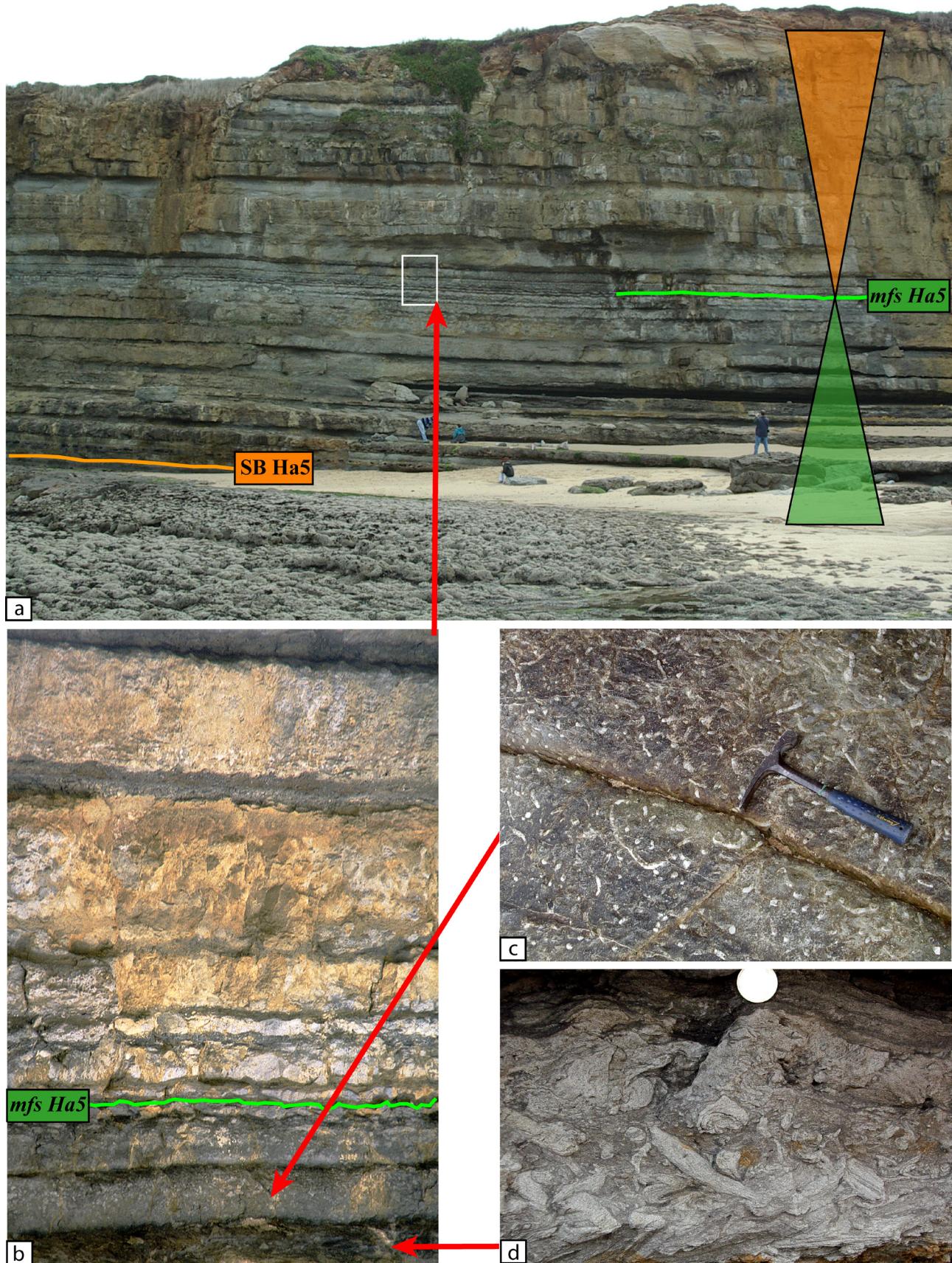


Fig. 54 – Sequence Ha 5 at Os Dois Irmãos. a: general view; b: maximum flooding surface; c: bioturbations (*Planolites*); d: bioturbations (*Teichichnus*?).

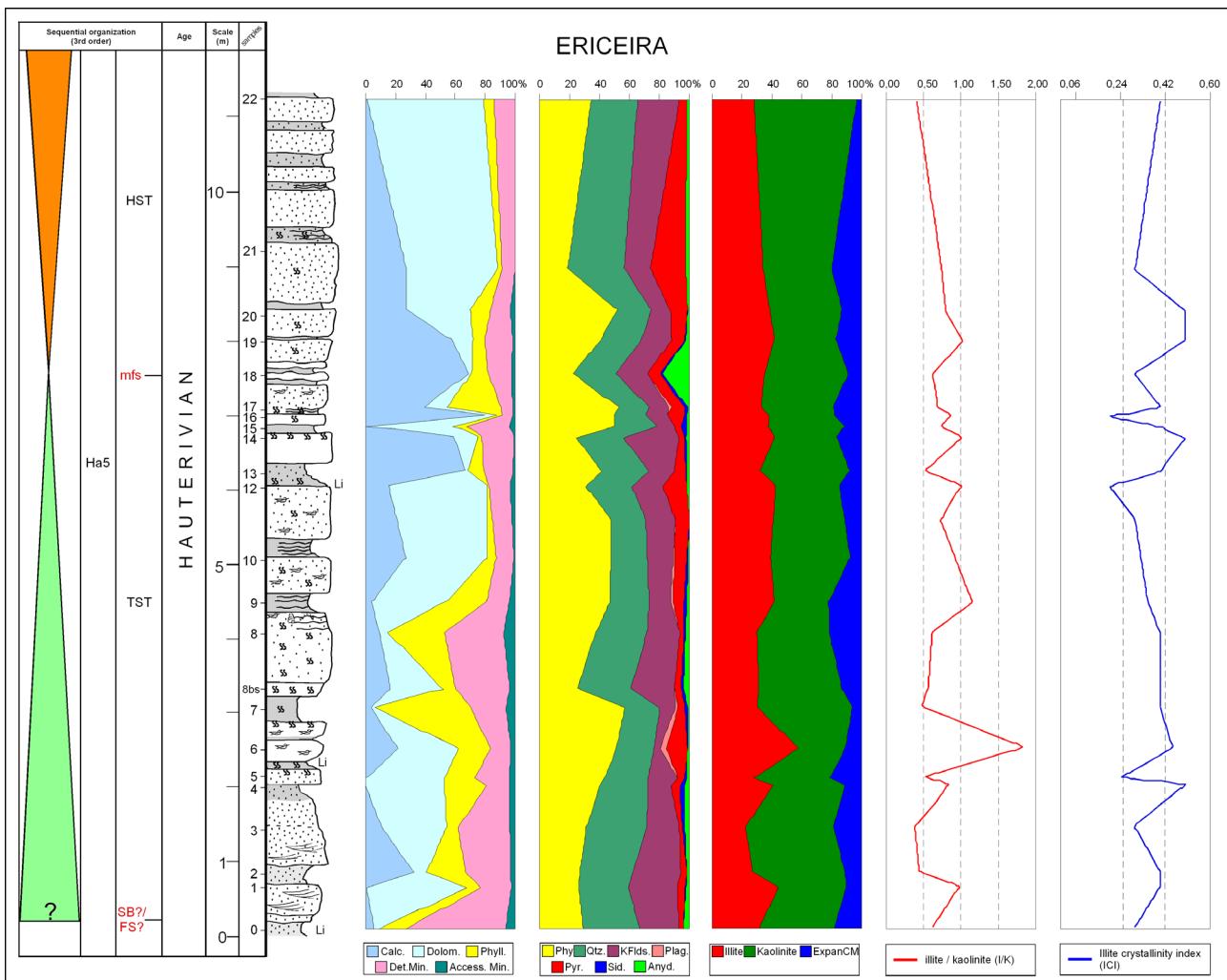


Fig. 55 – Results obtained from the Ericeira section (sequence Ha 5): mineralogical assemblages of the total sample, insoluble residue due, and $<2\text{ }\mu\text{m}$ fraction; illite/kaolinite ratio (I/K); and illite crystallinity (Kubler/Segonzac index – ICI).

C. The Lower Cretaceous near Cape Espichel

Location

During the Early Cretaceous, the Serra da Arrábida was located on the southern edge of the Lusitanian Basin (Fig. 7), with siliciclastic and carbonate sedimentation occurring in the prevailing coastal environments. A detailed study of the deposits is possible by following the cliffs along the Atlantic Ocean north of Cape Espichel (Fig. 56), from Praia dos Lagosteiros (Fig. 57) to Foz (Fig. 58). The Lower Cretaceous series is perfectly exposed, with a dip decreasing northwards from 30° to 15° , without gaps.

This fieldtrip focuses on the Valanginian and the lower Hauterivian deposits. The basal part of the succession (Porto da Calada and Vale de Lobos formations, Berriasian–Valanginian *pro parte*) is not described with its third-order sequences because it is poorly dated and made up mostly of fluvial and estuarian siliciclastic deposits. The same applies to the Regatão Formation, which is considered as late

Barremian in age. The Aptian and Albian units crop out west of the triangulation point of Foz, in small and discontinuous outcrops, which are unsuited for sequence-stratigraphic interpretation. The upper Hauterivian and lower Barremian series are too remote for fieldtrip investigation.

2.5. The Vale de Lobos Formation

This formation is composed of white, coarse and fine cross-bedded sandstones with quartz and chert pebbles, grey silts, and purple, green, or white clays with lignite debris (about 40 m thick, Fig. 57). These beds overlie, with a sharp contact, the purbeckian deposits laid down in tidal flats. The formation represents the fluvial environments that existed during the late Berriasian–early Valanginian. Known to occur over large areas of the Lusitanian Basin, these deposits indicate the Neocimmerian crisis that was related to Atlantic events: the beginning of the ultra-slow oceanic accretion in the Tagus sector and the initi-

ation of mantle exhumation in the Iberia sector, as well as the climax of rifting in the northern part of the Iberia sector.

2.5.1. Sequences Va 6 and Va 7

Definition

Above the fluvial sandstones of the Vale de Lobos Formation, these two sequences mark a return to marine environments on the southern edge of the Lusitanian Basin: the beginning of the transgression with the aggrading sequence Va 6, then very rapid sea-level rise with the backstepping sequence Va 7, deposited on a carbonate ramp.

Age

The faunal content (ammonites) of the lower part of sequence Va 7 indicates a late Valanginian age. The maximum flooding surface shows a facies similar to that of the same surface at Cascais and is placed at around the Valanginian–Hauterivian boundary. Therefore, sequence Va 6 is dated late Valanginian and sequence Va 7 latest Valanginian–early Hauterivian.

Composition (Figs 59–60)

Sequence Va 6

At the sequence boundary cutting the Vale de Lobos Formation, this sequence consists of yellow sparite-cemented sandstones arranged in horizontal beds and interbedded with fine sandstones. No clear surface is recognized and the systems tracts are not identified.

Sequence Va 7

Sequence boundary and transgressive surface:

A sudden change of lithology compared with the underlying deposits, comprising sandstones covered by sandy limestones.

Transgressive system tract:

Reddish-brown sandy limestones containing gravel, ferruginous oolite, and grains (decreasing in size upwards) of cracked and limonite-coated quartz, arranged in thick beds separated by more marly interbeds. The fauna is found mainly in the upper part of this system tract: oysters (including *Alectryonia rectangularis*), pectinids, brachiopods, belemnites, ammonites (including *Karakaschiceras biassalense* and *Neocomites neocomiensis*), echinoids (*Phymosoma*, *Heretodiadema*, *Plagiocidaris*, *Rhabdocidaris*, *Pygurus*, *Holectypus*, *Holaster*, and *Toxaster*), *Lenticulina*, and *Trocholina*.

Maximum flooding surface:

The surface corresponds to a conglomerate of isolate corals (*Montlivaltiidae*) in a red marly matrix. These elements are rolled and worn and are associated with belemnites, brachiopods, and various bivalves (oysters and pectinids).

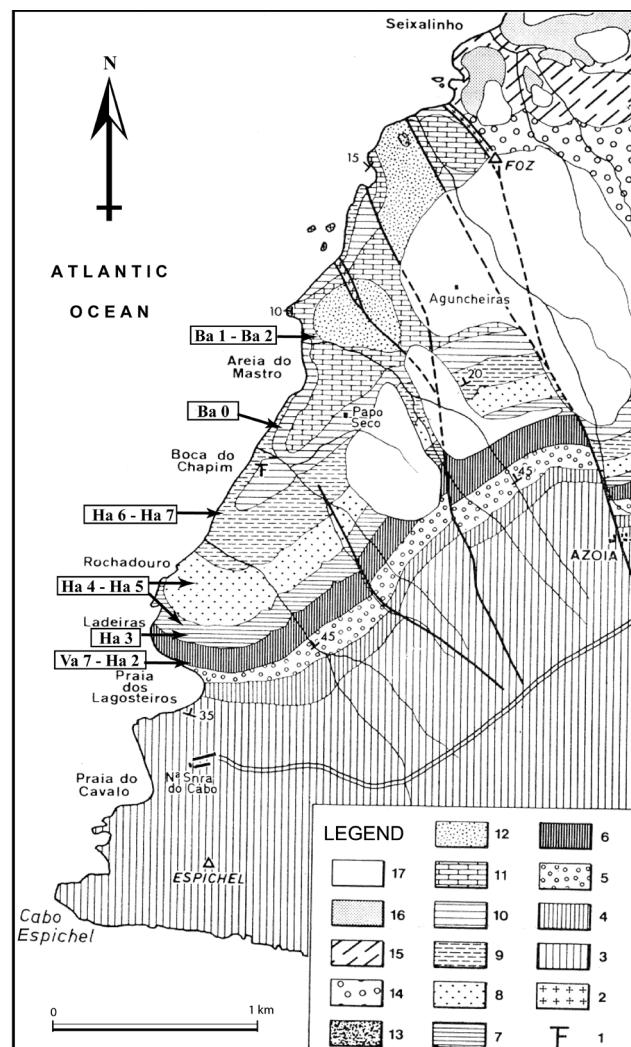


Fig. 56 – Locations of the depositional sequences north of the Cape Espichel (Rey, 2006). 1: site with dinosaur remains; 2: dolerite; 3: Jurassic; 4: Porto da Calada Formation; 5: Vale de Lobos Formation; 6: Guia and Maceira formations; 7: Ladeiras Formation; 8: Rochadouro Formation; 9: Areia do Mastro Formation; 10: Papo Seco Formation; 11: Boca do Chapim Formation; 12: Regatão Formation; 13: Crismina Formation; 14: Rodízio Formation; 15: Galé Formation; 16: Miocene; 17: Quaternary.

Highstand system tract:

This tract comprises five parasequences, each composed of grey marls at the base and bioturbated argillaceous limestones at the top, with spines of echinoids, crinoids, serpulids, ophiuroids, lituolids, and, in the uppermost bed, *Montlivaltiidae*.

2.5.2. Sequence Ha 1

Definition

This fine-grained terrigenous sequence shows, with its sequence arrangement and sedimentary dynamics, significant analogies with the coeval sequence described in the Cascais area. Therefore, this sequence is also characterized by:



Fig. 57 – The Neocomian cliff at Praia dos Lagosteiros.



Fig. 58 – The upper Hauterivian–lower Barremian cliffs between Rochadouro and Areia do Mastro.

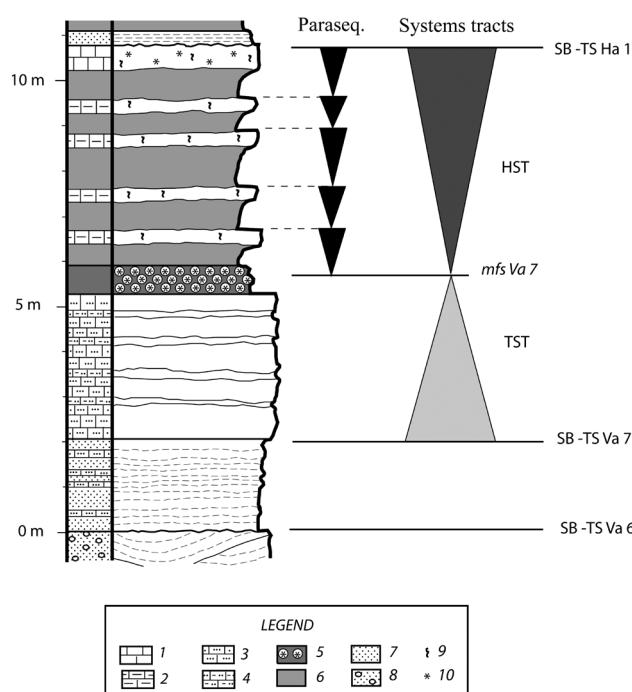


Fig. 59 – Sequences Va 6 and Va 7 at Lagosteiros. Lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: muddy limestone; 3: sandy limestone; 4: sandy-muddy limestone; 5: *Montlivaltiidae* conglomerate; 6: marl; 7: sandstone; 8: pebbly sandstone; 9: bioturbation; 10: *Montlivaltiidae*.

- on the one hand, the presence of a lowstand system tract (shelf-margin wedge), following the well-developed backstepping of the underlying Va 7 sequence.

- on the other hand, the aggrading characteristic of the transgressive system tract and of a large part of the highstand system tract. The sediment supply approximately equalled the sea-level rise, and the environment (ramp) was essentially constant from one system tract to the other. Therefore, the maximum flooding surface is insufficiently characterized. Only the upper part of the highstand system tract presents a shallowing-upwards evolution, associated with the appearance and development of proximal facies.

Age

Early Hauterivian. Lacking good chronological markers, this sequence is dated by its stratigraphic position above the Valanginian–Hauterivian boundary, as well as by sequence correlation with the Cascais Neocomian series.

Composition (Figs 61–62)

Sequence boundary:

Hardground encrusted with oysters on the uppermost limestone bed of sequence Va 7 (Fig. 62a).

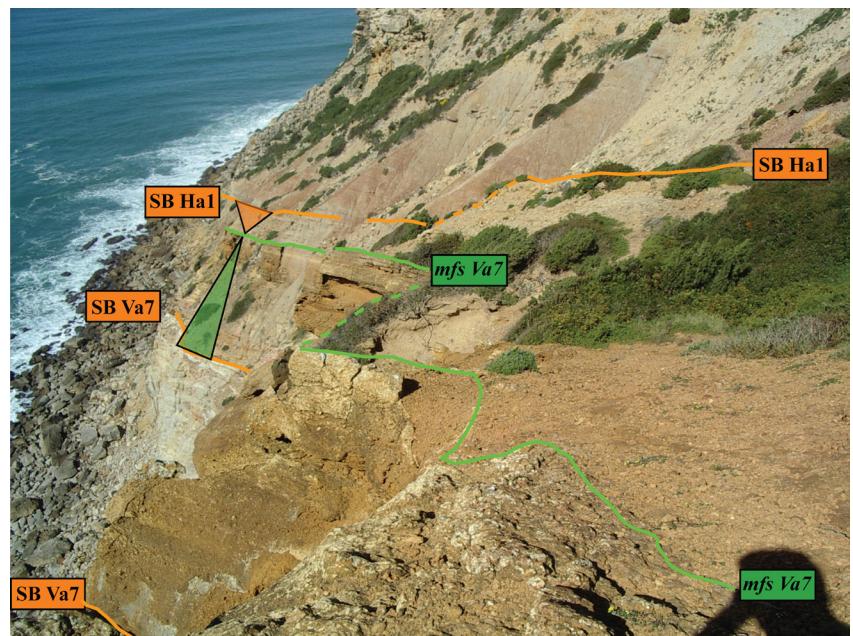


Fig. 60 – Sequence Va 7 at Lagosteiros.

Lowstand system tract:

Grey marls and ochre fine-grained sandstones arranged in a shallowing-upwards parasequence (Fig. 62a).

Transgressive surface:

The oxidized upper surface of a fine sandstone bed, covered by blue marls.

Transgressive system tract:

This tract is composed of blue laminated marls in-

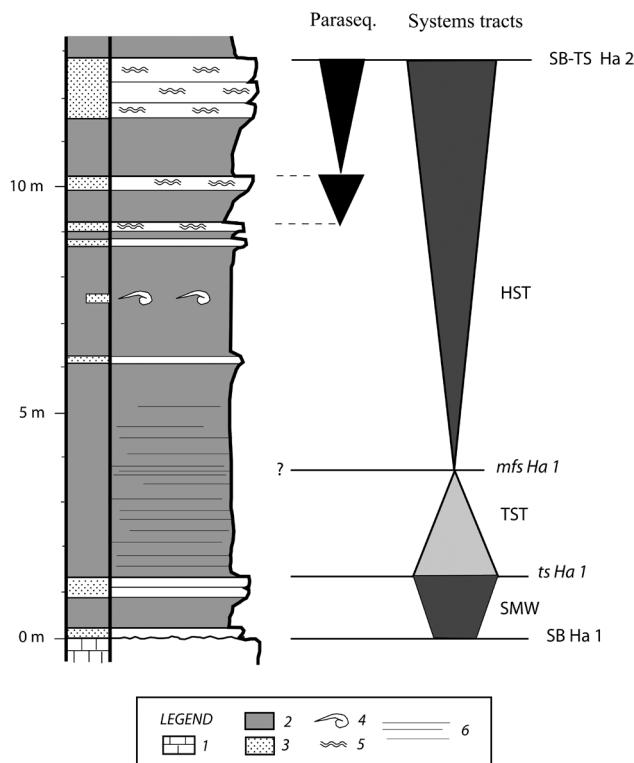


Fig. 61 – Sequence Ha 1 at Lagosteiros. Lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: marl; 3: sandstone; 4: slumps; 5: symmetrical ripples; 6: plates of argillite.

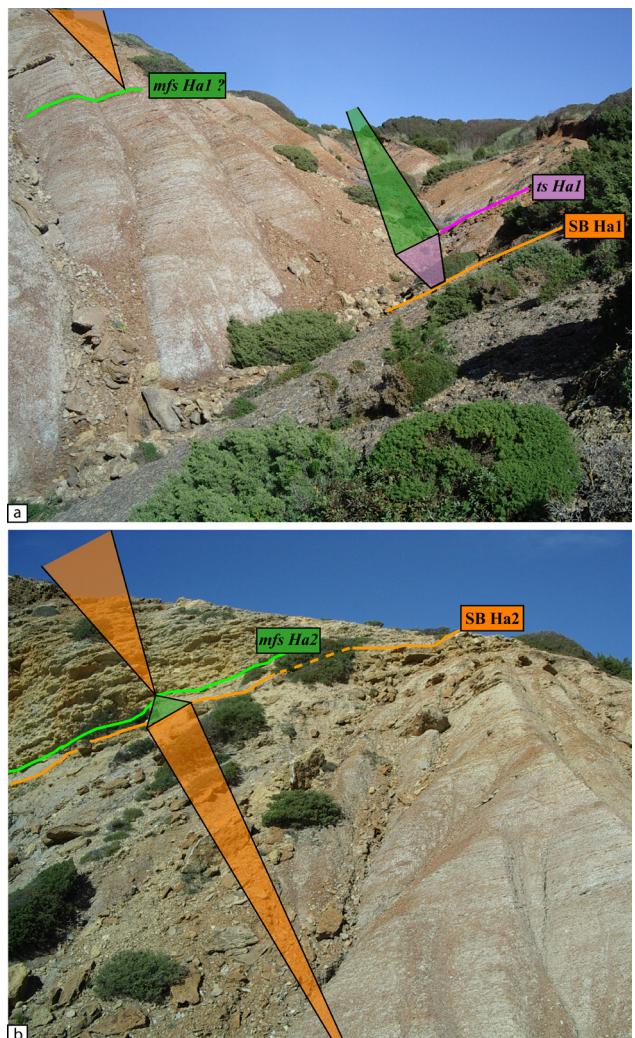


Fig. 62 – Sequence Ha 1 at Lagosteiros. a: basal part; b: upper part and the base of sequence Ha 2.

terbedded with small plates of ochre or reddish densening-upwards argillites, corresponding to hardened and oxidized surfaces. The fauna is scarce and poorly preserved: serpulids, oysters, pectinids, and naticids.

Maximum flooding surface:

This surface is poorly expressed. It is most likely to be located near the maximum density of argillite plates.

Highstand system tract:

This tract consists of blue laminated marls, including small plates of ochre or reddish argillites

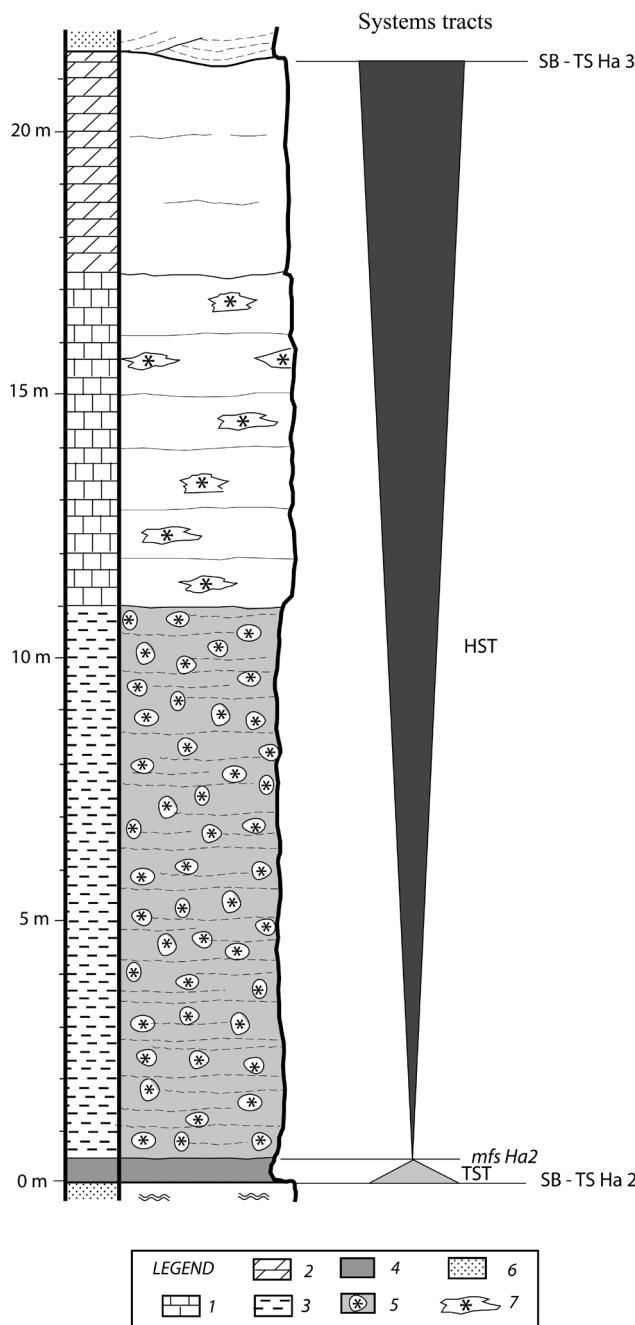


Fig. 63 – The Ha 2 sequence at Lagosteiros. Lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: dolomite; 3: calcareous marl; 4: marl; 5: nodular corals; 6: sandstone; 7: massive corals.

thinning upwards, alternating with beds of fine ochre sandstones that thicken upwards (Fig. 64b). Some lower bodies of sandstones contain slumps, whereas the upper sandstone beds present symmetrical ripples. The very scarce fauna is the same as that in the transgressive system tract.

2.5.3. Sequence Ha 2

Definition

This aggrading carbonate sequence is characterized mainly by a very thin transgressive system tract and a very thick highstand system tract with the development of coral buildups (coeval with the Cabo Raso Formation), and, therefore, the installation of a rimmed shelf. The great thickness of the highstand system tract in a reefal context shows that accommodation space was continuing to be created by sea-level rise. The sequence represents the maximum extent of the Hauterivian Sea in the Lusitanian Basin (Fig. 6).

Age

The sequence is Hauterivian, as indicated by the presence of *Pygopyrina incisa*. The probable early Hauterivian age is deduced from sequence correlation.

Composition (Figs 63–64)

Sequence boundary and transgressive surface:

A ferruginous crust on the upper surface of the uppermost sandstone bed of sequence Ha 1.

Transgressive system tract:

This tract is composed of a thin level of pale blue marls (Fig. 64b), with small foraminifers (*Textulariidae*, *Lenticulina*, and miliolids).

Maximum flooding surface:

This surface is located at the top of the marly level.

Highstand system tract:

More than 20 m thick, this tract consists of three parts:

- a lower part of joined nodules of limestone in white marls (Fig. 64b and c). These nodules are formed mainly by colonial corals, along with oncoids (*Lithocodium*–*Bacinella*). In addition, there are brachiopods and echinoids (*Echinotriara*, *Pygopyrina*, and *Cidaris* spines).

- a middle part of pale-grey massive limestones (“packstone”), locally microbrecciated, with colonies of corals and stromatoporoids, large nerineas, and oncoids (Fig. 64a).

- an upper part of karstified and strongly weathered sparry dolomite (Fig. 66d). The dolomitization *per descensum* was most likely to have been created

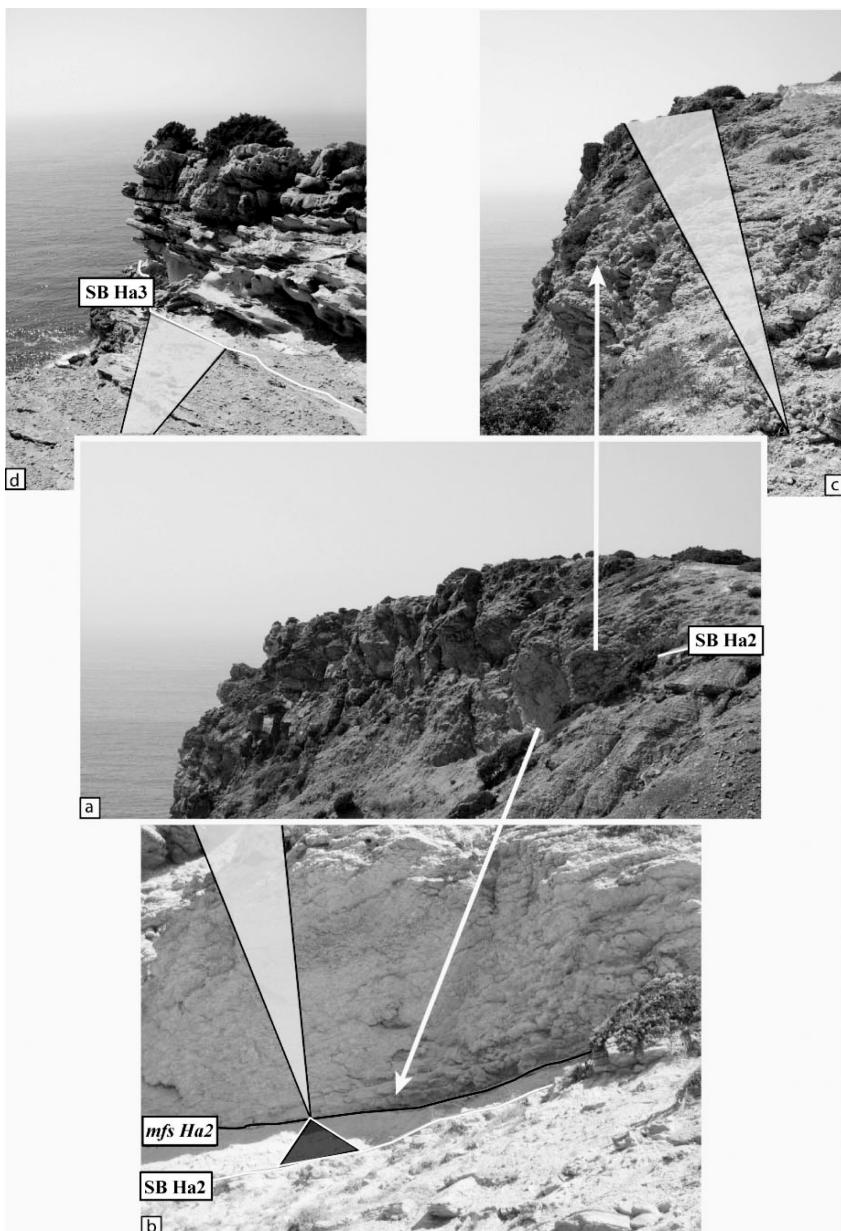


Fig. 64 – Sequence Ha 2 at Lagosteiros. a: general view; b: base of the sequence; c: lower part of the highstand system tract; d: top of the sequence.

by a mixture of marine and interstitial waters, and therefore related to the sea-level fall following the deposition of this sequence.

2.5.3. Sequence Ha 3

Definition

Sequence Ha 3 was deposited in proximal environments of the inner platform and corresponds to a shallowing-upwards infilling sequence that represents the beginning of the long-term regressive evolution of the second cycle of the Valanginian–early Barremian.

Age

The age assigned is Hauterivian. Lacking good chronological markers, this sequence is dated Hauterivian (probably early) on the basis of its strati-

graphic position and by comparison with the chart of depositional sequences in the European sedimentary basins.

Composition (Figs 65–66)

Sequence boundary:

An erosive surface cut into the dolomites of the underlying sequence (Figs 64b and 66a).

Lowstand system tract:

This tract comprises cross-bedded lenses of white fine-grained sandstones (Figs 64b and 66a). This deposit may correspond to the filling of an incised valley. However, the possibility that this detrital body represents the basal part of a transgressive system tract cannot be ruled out.

Transgressive surface:

A surface between cross-bedded sandstones and horizontal beds of sandy limestone (Fig. 64b).

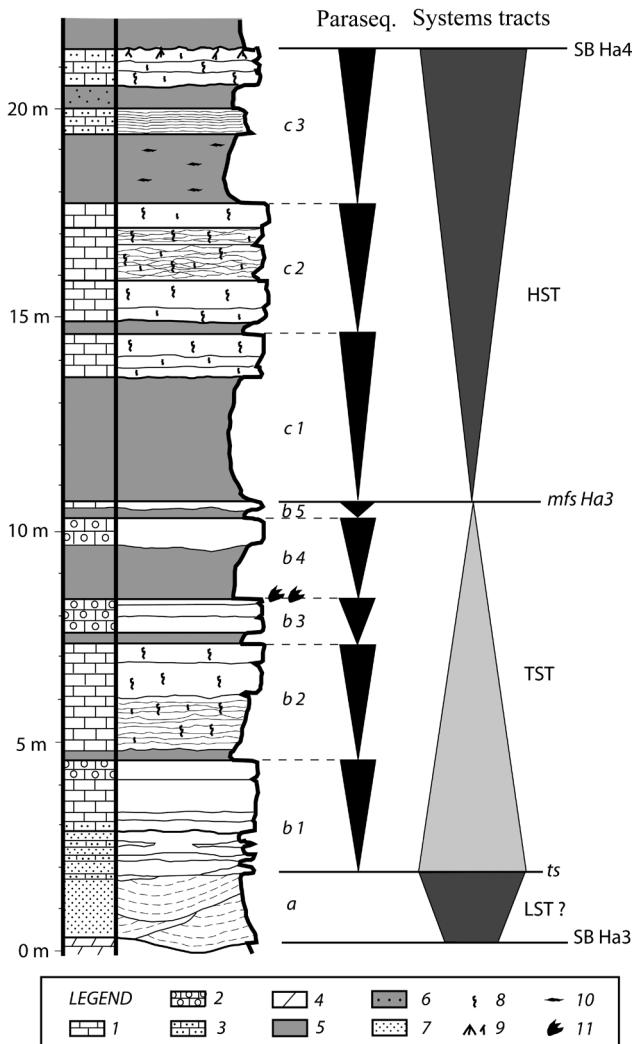


Fig. 65 – Sequence Ha 3 at Lagosteiros and Ladeiras. Lithology, stratonomy, and sequence arrangement (Rey, 2006). 1: limestone; 2: grainstone; 3: sandy limestone; 4: dolomite; 5: marl; 6: sandy marl; 7: sandstone; 8: bioturbation; 9: root prints; 10: lignite; 11: dinosaur footprints

Transgressive system tract:

This tract comprises five parasequences:

- the first one is a backstepping parasequence. It begins with alternating horizontal beds of sandy limestones and fine sandstones, overlain by limestones (wackestone–packstone, then grainstone) (level *b1*).

- the four others are shallowing-upwards parasequences containing green marls and thinning-upwards bioturbated beds of argillaceous limestones and grainstone (levels *b2* to *b5*). The fauna consists of rare colonies of corals and stromatoporoids, large nerineas, brachiopods, echinoids (*Goniopygus* and *Magnosia*), and oysters. The upper surface of the second parasequence is an oxidized hardground with many dinosaur footprints (including *Iguanodon*, *Megalosauropus*, and *Neosauropus*; Antunes, 1976;

Fig. 67b and c).

Maximum flooding surface:

Hardground on a thin calcareous bed.

Highstand system tract:

This tract is composed of three shallowing-upwards parasequences, each comprising a lower unit of clays or marls with lignite and an upper unit of bioturbated limestones (wackestone) with naticids, nerineas, and oysters. The uppermost parasequence contains a large amount of detrital quartz, and the uppermost bed of oyster-rich sandy limestone is bored by rhizoconcretions.

Mineralogical analyses of Sequence Ha 3 (at Cape Espichel)

The following observations can be made (Fig. 67):

- above the sandstone level that occurs around the sequence boundary, in the lower part of the TST, siliciclastic minerals, particularly quartz, K feldspars, and phyllosilicates, continue to be abundant, and the presence of anhydrite is noteworthy. The top of the TST has more carbonate and a lower proportion of detrital grains.
- the maximum flooding of the sequence is marked by a marked increase in phyllosilicates and detrital minerals.
- the mineralogical assemblages of the HST show similar compositions to those from the TST.
- the I/K ratio curve shows an evolutionary trend that correlates with the evolution of parasequences. In each parasequence, the I/K ratio evolution curve starts by displaying lower values (i.e., relatively high kaolinite), then, at the top, or near the top, high peak values are observed (i.e., relatively high illite). The values of each of these high peaks increases until the maximum value is reached ($I/K = 2.78$), which coincides with the maximum flooding surface, above which the value decreases the top of the sequence is reached. These illite maxima correspond to the highest ICI values (illites with low crystallinity).

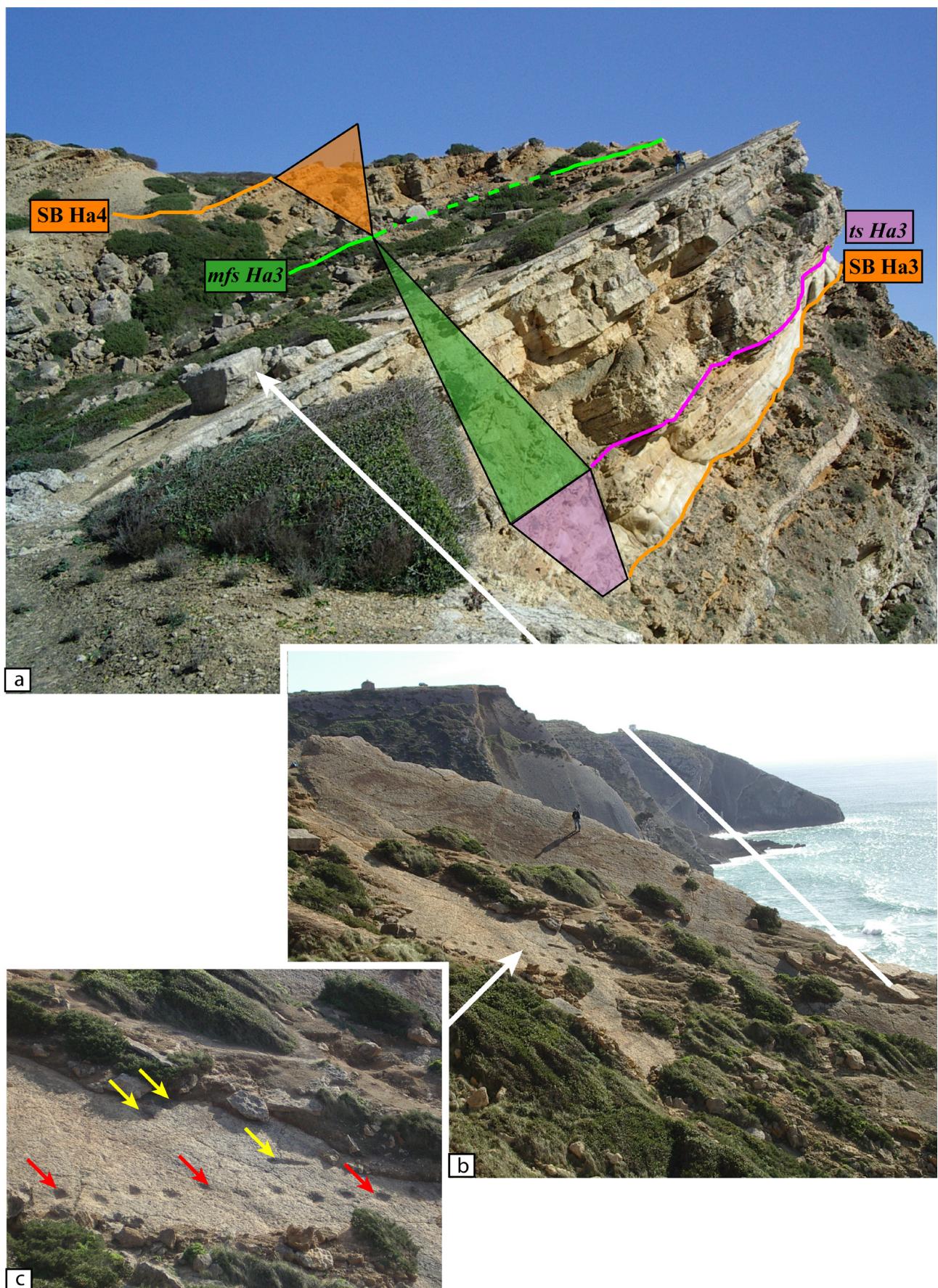


Fig. 66 – Sequence Ha 3 at Lagosteiros and Ladeiras. a: general view; b: transgressive surface with dinosaur footprints; c: details of footprints of tetrapods (red arrows) and *Iguanodon* (yellow arrows)

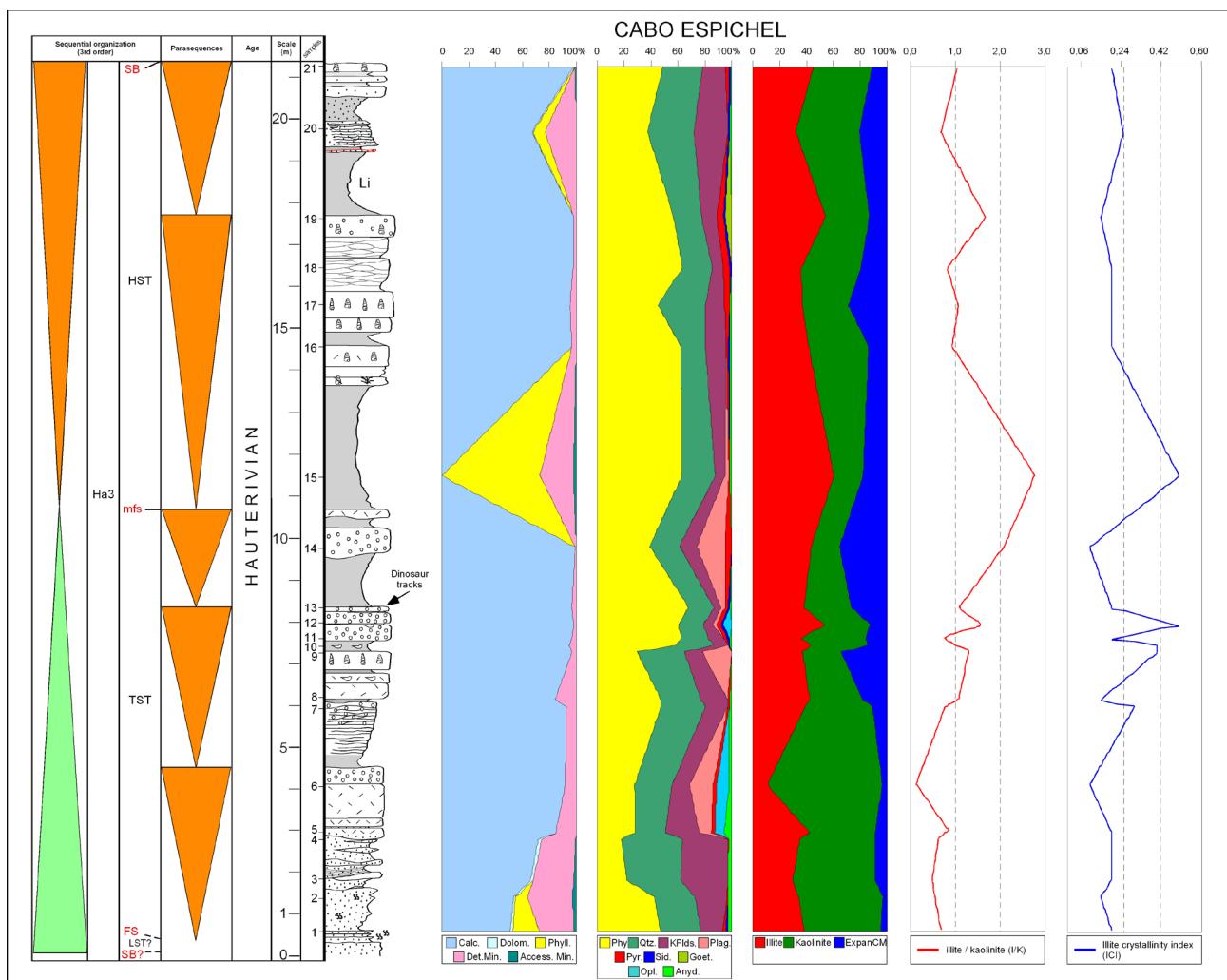


Fig. 67 – Results obtained from the Cape Espichel section (sequence Ha 3): mineralogical assemblages of the total sample, insoluble residue, and $<2\text{ }\mu\text{m}$ fraction; illite/kaolinite ratio (I/K); and illite crystallinity (Kubler/Segonzac index – ICI).

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