PALAEOGEOGRAPHIC EVOLUTION AND MARINE FAUNAS OF THE MID-CRETACEOUS WESTERN PORTUGUESE CARBONATE PLATFORM

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ABSTRACT

The Western Portuguese carbonate platform was one of the large rimmed shelves that bordered the European northern branch of the Tethys realm, during the Mid-Cretaceous interval of accentuated sea-level rise and eustatic highstand. This platform was gradually set up during the Albian and Cenomanian stages, and persisted until the end of Lower Turonian, over large areas of the Western Iberian margin. Presently, its carbonate facies are widely recorded on the onshore sectors of Portuguese Estremadura and Beira Litoral, between the parallels of Lisbon and Aveiro.

In this account are specially focused the Northern and Central of these sectors, with emphasis on the palaeogeographic setting and faunal response to the tectono-sedimentary evolution of the carbonate platform. The maximal development of carbonate sedimentation is associated to a basal Upper Cenomanian onlap, with introduction of fully marine environments and invertebrate faunas, including Tethyan engonoceratid ammonites. This succession is overlain by highly diverse series of carbonate facies, including (1) abundant reef and lagoonal limestones with coral and rudist fringes, (2) nodular limestones with vascoceratid ammonites, and (3) inner shelf and marginal mixed carbonate-siliciclastic sediments with shallow-water associations of tylostomid gastropods, pectinid and exogyrid bivalves, and Hemiasterid echinids.

The Upper Cenomanian is also marked by an important regressive event, associated with subaerial exposure, karst development, and fluvial incision on both onshore domains. After this early uplift episode on the continental margin, the Northern sector sedimentation became active during a short interval, from the middle part of the Lower Turonian onwards. Invertebrate associations included turritelid gastropods, coral-rudist patch-reefs and radiolitid biostromes. Finally, at the end of Lower Turonian occurred a definitive withdraw of the carbonate sedimentation, together with progradation of micaceous alluvial sands over the platform domains.

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INTRODUCTION

The purpose of this paper is to present an overall palaeogeographic synthesis of the Cenomanian-Turonian Western Portuguese carbonate platform (Western Iberian margin), integrated with palaeoecologic and biogeographic data from the marine invertebrate palaeocommunities. This Tethyan carbonate platform was gradually set up during the Albian and Cenomanian stages, and persisted until the end of Early Turonian, over a large area of the Western Iberian margin. The sedimentary setting was mostly centred on the Portuguese onshore sectors of Estremadura and Beira Littoral, where the Lusitanic Basin was active since late Triassic times (Wilson, 1979). The correlative Albian, Cenomanian and Turonian sedimentary successions of these sectors are well documented by many available exposures, and suitable to detailed stratigraphic and palaeogeographic studies (fig. 1).

The deposition of the carbonate series was coincident with the long interval of accentuated sea-level rise and eustatic highstand of mid-Cretaceous (Hancock & Kauffman, 1989), when the emerged lands of West and Southern Europe, and North-Africa were reduced to isolated massifs. In fact, the Western Portuguese carbonate platform can be considered as a typical example of the European and North-African shallow-water rimmed shelves that bordered the northern branch of Tethys, at that time. This palaeogeographic and climatic setting also had obvious implications on the biogeographic patterns of shallow-water marine biotas, with emphasis on the proliferation of hermatypic corals and rudist reefs, one of the most characteristic features of the Tethyan realm.

The settlement and tectono-sedimentary evolution of the Western Portuguese carbonate platform also occurred through a long period of thermal subsidence and tectonic stability within the Western Iberian margin. This period was initiated after the fourth and last rifting phase recorded on the Mesozoic infill of the Lusitanic Basin (Valanginian to Aptian) (Wilson, 1988). It was, above all, a time of considerable change on the geotectonic history of the Western Iberian margin, when a gradual transition from a distensive to a passive margin was in course, before the beginning of the first compressive Alpine events that affected the structure of Iberia (Wilson, 1988; Wilson et al., 1989; Pinheiro et al., 1996; ).

Figure 1: Portuguese sectors of the West Iberian margin. I – Simplified structural setting (A-N – Diapiric anticlines). II – Stratigraphic setting of the onshore (Estremadura and Beira Litoral).
Our interest about the palaeogeography and the palaeoecologic and biogeographic patterns of the biotic communities from the Western Portuguese carbonate platform arises from the fact that:

(1) It is possible, from the study of recent onshore exposures, to establish a comprehensive model of articulated palaeogeographic domains for the carbonate platform, including detailed positions of the ancient coast-lines, and the transition from carbonate to marginal marine siliciclastic environments;

(2) The high faunal diversity and the biotic adaptation to a variety of shallow marine and transition depositional environments (which are a common feature of many Cretaceous carbonate platforms) allow detailed studies on invertebrate palaeoecology, including the synecology of fossil associations, coral-rudist palaeocommunities and ecostratigraphy.

(3) During the Cenomanian-Turonian, the Western Iberian margin was an important axis of faunal change and mixing between the European branch of Northern Tethys, North-Africa and the Temperate Domain of West Europe, with implications on the palaeobiogeographic range of many marine invertebrate species and taxonomic groups recorded in Portugal.

In this account are considered, in particular, the Northern and Central sectors of the carbonate platform, including all the exposures placed between the parallels of Aveiro and Nazaré. This area was previously investigated as the main subject of a doctoral study of regional stratigraphy (Callapez, 1998).

GEOLOGIC SETTING

The mid-Cretaceous post-rifting succession of Western Central Portugal overlies a thick series of almost 5000 meters of upper Triassic, Jurassic and lower Cretaceous sediments, related with the sedimentary and geotectonic evolution of the marginal Atlantic Lusitanic Basin (Soares & Rocha, 1985).

Like other contemporaneous Mesozoic basins of Western Europe, it was created as a result of the intra-continental rifting that forced the break-up of North America and Europe after the Late Triassic (Hiscott et al., 1990). The basinal area extends northwards over more than 250 km, and is bounded westwards by the basement horsts of Berlengas, already active as a tectonic ridge that isolated the depocentre areas from the adjacent Atlantic offshore basins (Ribeiro et al., 1979).

The stratigraphy of the Lusitanic Basin shows a complex tectonic and sedimentary history, controlled by late Hercynian faults reactivated during the extensional events, and by halokinetic structures associated with Early Jurassic evaporites. Four main rifting phases intercalated with intervals of post-rift thermal subsidence are presently recognized (Wilson, 1979, 1988; Wilson et al., 1989; Cunha & Reis, 1995; Pinheiro et al., 1996; Alves et al., 2003, 2006). After the Aptian, the geotectonic setting evolved to a long interval of thermal detumescence that culminates with the deposition of Albian-Turonian transgressive carbonate series, over the whole basinal areas. During the transgressive peak of the beginning of Early Cenomanian, the carbonate platform reached its maximum geographic extent, matching the landward limits of the basin through an ancient shoreline that crossed the regions of Coimbra, Ourém, Tomar and Setúbal.

The Albian-Turonian carbonate units are organised in two megasequences bounded by unconformities (Cunha, 1992; Cunha & Reis, 1995; Callapez, 1998). The first megasequence (Albian-Upper Cenomanian) shows a relatively scarce carbonate record of Albian age, limited to the region of Lisbon (Beds with *Knemiceras uhligi* and recifal unit with *Polyconites subverneuilli*, sensu Choffat, 1885, 1886). These units record the early stages of development of the Western Portuguese carbonate platform and its transition to a large domain of alluvial plain with coarse siliciclastics. The Lower Cenomanian succession (Beds with *Hymatogyra pseudaficana*) shows a
Pink, fine-bedded, micaceous sandstones and sandy limestones.

Pink, cross-bedded, packstone/grainstone with concentrations of small bioclasts, well sorted and abraded, and mostly of nerineids, rudists and actaeonellids.

White, cross-bedded, grainstone with rudistic concentrations of massive and branched corals, nerineids (*Polyptyxis* spp.), rudists (*Radioites* poroni, *Aegirina longa*), *Actaeonella caucasia gressonii*, and a diverse fauna of small molluscs adapted to hard substrates.

Hardground with *Thalassinoides* burrows.


Yellow dolomitic marls and limestones with *Mytiloides mytiloides* and *M. subbrevicynus*. A few spatangoids, *Tylostoma* moulds, and a single *Vascoerceras durandi*.

White limestone with dissolution cavities and other structures related with subaerial exposure and paleokarst development.

Whiteish-yellow limestone with *Tylostoma ovatum*, *Pymnodonte vesiculare*, *Trigonoceras matheroniense*, *Callicynia* sp. and *Sarcinella* sp. Ammonites are common: *Puzosia* (P.) sp., *Pachydermoceras* sp., *Spahites* (J.) subconcinulatus, *Pseudaspisdiceras* pseudonodosoidea, *Vascoerceras douvillei*, *V. kossmati* and *Eugia catun*. A few *Mytiloides* submytiloides.

Grey marly limestone with abundant spatangoids. *Vascoerceras douvillei*, *V. kossmati*.


First occurrence of *Pseudaspisdiceras* pseudonodosoidea.

Hardground with abundant moulds of vasoceratids. Younger *Euomphaloceras septemseriatum*.

Blue-gray limestone with fragments of branched corals, *Tylostoma ovatum* and *Hemieracticerina* suctiger. Ammonites very rare.

Gray and cream marly limestones with *Tylostoma ovatum*, *Rhynchochostreon suborbidactilum* and *Neithia hispanica*. First *Vascoerceras gamai* near the base. Abundant moulds of vasoceratids and a few *Euomphaloceras septemseriatum* and *Pseudocalycoceras* sp.

White limestone with *Anoplospondylus michelini*, nerineids, massive and branched corals, and *Rhynchochostreon suborbidactilum*. Fragments of *Neolobites* sp. and *Puzosia* sp.

Nodular limestones and marly limestones with *Neolobites vibrinus* and *Calycoceras naviculare*. Abundant *Pymnodonte vesiculare*, *Rhynchochostreon suborbidactilum*, *Hemieracticerina lusitanica* and *Heteroradioldea ouremense*.

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Figure 2: The type section of Salmanha, Figueira da Foz. Upper Cenomanian and Lower Turonian units

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Limestone, *Dolomitic limestone, Marl, Micaeous sandstone, Ammonites, Corals, Exogyriids, Serpulids, Spatangoids, Rudists, Tylostomids, Turritellids, Nerineids, Inoceramids, Actaeonellids*
comparable geographic distribution, but is also present in the exposures of Nazaré (Central sector). However, the Middle Cenomanian (Beds with *Harpagodes incertus*) is marked by an obvious transgressive trend, with the retrogradation of carbonate facies with biostromes of ostreids and exogirinids to north and eastwards, over the northern Estremadura and Beira Litoral.

For the Middle Cenomanian-Lower Turonian interval, the stratigraphic setting of the carbonate platform is based on the ammonite facies of the Northern sector (Costa de Arnes Formation). The most expanded sections of this area (65 m) outcrop near Figueira da Foz, next to the Atlantic coast of Beira Litoral. This Formation shows a set of 14 units, usually designated by the capital letters “B” to “O” (Choffat, 1897, 1898, 1900). Biostratigraphic data from ammonites and microfauna (Soares, 1980; Lauverjat, 1982; Berthou, 1984, Callapez, 1998, 2001, 2004; Callapez & Soares, 2001; Hart et al., 2005) indicate that units “C” and “D” have a basal Upper Cenomanian age, and the first Lower Turonian units of the succession are “K” and “L” (figs. 2, 3).

The basal Upper Cenomanian starts with a transgressive surface followed by sequences of nodular limestones with *Neolobites, Calycoceras* and abundant alveolinids. The platform carbonate facies reach a maximal geographic range at this time. This succession is overlain by an highly diverse series of carbonate facies, including reef and lagoon limestones and marls, nodular limestones with ammonites, and inner platform mixed carbonate-siliciclastic sediments with shallow-water fossil faunas. A palaeogeographic differentiation in two adjacent sectors is evident:
(a) The Northern sector shows a succession of nodular marly limestones with ammonites and open platform benthic faunas. The lateral changes for mixed and siliciclastic facies of inner platform, lagoon and alluvial plain can be observed following a transect from Figueira da Foz to Coimbra (40 km).

(b) The Central sector shows a correlative succession of calcarenites, boundstones and marls with hermatypic corals, rudists, and associated reef faunas of rimmed platform. After a WSW-ESE transect from Nazaré to Leiria and Ourém (50 km) are recorded sequences of calcarenite shoals with Caprinula, Radiolites, and Durania; bioherms with Caprinula and Chondrodonta; a reef fringe with platy corals (Microsolenidae); and a large open lagoon with exogyrinids and Hemiasterids.

The transition between the two sectors matches with the NE-SW tectonic and diapiric axis of Pombal-Leiria-Pataias and Nazaré, a reactivated tardi-hercynian fault with implications on the gradual uplift of central Estremadura, after the Middle Cenomanian. This megasequence finishes with regressive facies on the top of unit “J” followed by a regional unconformity with subaerial exposure and paleokarst development (Nazaré and Figueira da Foz).

The second megasequence has a Turonian age (units “K” to “O” of the carbonate succession and subsequent siliciclastic beds) and a record centred in the Northern sector of the studied area. At this time, the NE-SW tectonic and diapiric axis of Pombal-Leiria-Pataias and Nazaré acted as a flexure, with uplift and emersion of the Central and Southern sectors of the carbonate platform. Units “K” and “L” are dolomitic marls and platy limestones with middle Lower Turonian ammonites and inoceramids. These sequences are overlain by a succession of calcarenites with small patch-reefs of corals and rudists. The upper part of this succession is strongly regressive, and shows a transition to littoral plain and alluvial micaceous sandstones (Furadouro Formation).

**MATERIAL AND METHODS**

The stratigraphy and the invertebrate paleofaunas of the studied area were reviewed as part of a Doctoral research (Callapez, 1998), and upgraded more recently with additional data, including the palaeosyneology and the ammonite and foraminifera biostratigraphy of the Cenomanian-Turonian transition (Callapez, 1999, 2002, 2003, 2004; Callapez & Soares, 2001; Hart et al., 2005; Rey et al., 2006).

The basic field work procedures were based on the detailed description and correlation of 25 stratigraphic sections from the Northern and Central sectors of the carbonate platform, including facies and taphonomic analysis, and a quantitative evaluation of fossil invertebrates for palaeoecological purposes.

The collections of non-allochtonous fossils with similar taxonomic composition and relative abundance of species were grouped in fossil associations, with the help of grupal analysis. This method is an approach to reveal the structure of the original palaeocommunities, but embiased by the lack of soft-bodied species.

The palaeogeographic representations of the carbonate platform discussed here were based on the spatial distribution of facies, species, and fossil associations. These maps also match with the tectono-sedimentary setting of the Lusitanic Basin, and the contemporaneous geotectonic evolution of the Western Iberian margin.

**RESULTS AND DISCUSSION**

*Palaeogeographic evolution of the Cenomanian-Turonian*

The first palaeogeographic maps of the Western Portuguese carbonate platform were drawn by Choffat (1900, pls. X-XI). These figures have been improved by new synthesis proposed by Soares (1966, 1980), Berthou (1973, 1978, 1984), Crosaz-Galleti (1979), Lauverjat (1982) and Rey et al. (2006). The integration
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Plate 1

Lower Cenomanian (Unit with *Ilymatogyra pseudaficana*)

10km

Atlantic Ocean
Middle Cenomanian
(Unit "B")

Atlantic Ocean
of palaeobiologic data was also achieved by Soares (1968) and Callapez (1998), concerning the Northern and Central sectors of the carbonate platform. Next maps are a reviewed and upgraded adaptation of these previous models, with original field-work data.

**Upper Aptian, Albian and Lower Cenomanian (plate 1)**

After the late Aptian tectonic event that deformed segments of the Western Iberian margin (Pinheiro et al., 1996), the palaeogeographic setting of Beira Litoral, and northern and central Estremadura was dominated by depositional environments with braided fluvial systems, and prograding sequences of coarse siliciclastic sediments interbedded with flood plain reddish clays (Soares, 1966; Diniz, 1999; Diniz et al. 2001). The main direction of drainage and clastic transport was from easterly. The source areas of these sediments were uplifted moderate to high relieves of the Iberian Massif, with Hercinian granitoids and metamorphic rocks.

With the beginning of the transgressive event at the Albian, the alluvial systems retreat, and a coastal plain was gradually set up from the regions of Lisbon and Sintra, towards North and East. In the Lower Cenomanian time, the carbonate sedimentation reached the region of Nazaré, on the southwest periphery of the studied area. The marine incursion was followed by the installation of inner shelf environments with mixed carbonate-clastic sediments. These areas included tidal-flats with biostromes of *Ilymatogyra pseudafricana* and *Ceratostreon flabellatum*.

**Middle Cenomanian (plate 2)**

During the Middle Cenomanian time, the sea transgressed far, and the central and northern sectors of the studied area were occupied by a large domain littoral plain with carbonate and mixed carbonate-siliciclastic sediments. The position of shoreline was a few kilometers eastward Ourém, and followed a northerly trend across the vicinities of Pombal and the diapiric anticline of Soure. After that, it followed a northeasterly trend, crossing the Baixo Mondego region a few kilometers halfway Coimbra.

The sedimentation was gradually enriched by carbonates and processed in shallow, intertidal to shallow subtidal environments with tidal flats and sandy shoals drained by tidal channels. These areas were colonized by biostromes with palaeocommunities of oysters (*Gyrostrea ouremensis*), byssate and infaunal bivalves (*Septifer lineatus, Anisocardia orientalis*), and large mesogastropods (*Harpagodes incertus*).

Close to the region of Nazaré, the tidal flat transited into a lagoonal domain with non-restricted environments colonized by benthic communities of *Gyrostrea ouremensis*, together with a rich fauna of vertebrates (Pycnodontidae fishes, crocodiles and turtles). Sedimentation was essentially of shallow sublittoral finely laminated carbonate muds. The synsedimentary instability of the area is evidenced by many slumping structures, within a local tectonic setting influenced by the proximity of the Caldas da Rainha and São Pedro de Muel diapirs.

**Basal Upper Cenomanian (plate 3)**

The beginning of the Upper Cenomanian was a time of generalized flooding and deepening of the sedimentation areas, corresponding to the final set up of a carbonate platform opened to the oceanic influences. The alluvial plain retreated easterly, towards the domains of the Hesperic Massif, and the boundaries of the new inner shelf reached the regions of Mealhada, Coimbra and Condeixa-a-Nova. This episode is correlative with the *Calycoceras guerangeri* standard ammonite zone (Kenney, 1984), when a generalized eustatic rising affected the European and North-African margins of Tethys.

On the studied area, this period of prominent onlapping was characterized by the widespread of nearshore and offshore oxygenated soft-bottoms with carbonate rich deposits. The environmental were
Upper Cenomanian (Units "C/D")
Upper Cenomanian (Unit "G")

Atlantic Ocean
Upper Cenomanian (Unit "J")

Atlantic Ocean
highly favorable to the spreading of palaeocommunities with free-living bivalves (Pycnodonte vesiculare, Rhynchostreon columbum, Ceratostreon flabellatum, Neithea hispanica, N. dutrugei, Plicatula auressensis) and gastropods (Harpagodes incertus. Cimolithium tenouklense, Drepanocheilus olisiponensis), together with a large number of semi-infaunal (Pinna sp.) and infaunal species (Proveniella cordata, Hemiaster lusitanicus, H. scutiger, H. palpebratus) of Tethyan affinities. Ammonites (Neolobites vibraye anus) and nautiloids (Lessoniceras mermeti) were the commonest nektonic groups, and the microfauna was composed by abundant alveolinids and ostracods.

Middle part of Upper Cenomanian (plate 4)

From the middle part of Upper Cenomanian time (units “E”, “F” and “G” – Euomphaloceras septemseriatum ammonite zone) upwards, the Central and Northern sectors of the carbonate platform evolved as separate palaeogeographic units, controlled by reactivated faults and diapiric anticlines, including uplifted structures associated with the tectonic axis of Pombal-Leiria-Pataias. The palaeogeographic domains situated southward this NE-SW structural ridge became part of a large rimmed shelf with coral and rudist buildups, and moderate influx of siliciclastics. On the contrary, the shelf domains from the Northern sector were typical of a nearshore to offshore depositional setting fully opened to marine influences, but affected by a significant influx of clastic sediments from the nearby fluvial systems. This alluvial drainage of fine grained siliciclastic particles acted as a factor of inhibition for the emergence and grow up of reefal palaeocommunities on these areas.

On the northern sector, the transition from the middle to the outer shelf was a domain with subtidal muddy bottoms colonized by dense palaeocommunities of infaunal echinids (Hemiaster scutiger), gastropods (Tylostoma ovatum), exogyrinid and pectinid bivalves, and soft-bodied infaunal polychaetes or crustaceans. Vascoceratid ammonites were common.

(1) A narrow band with well-oxygenated shallow subtidal muddy bottoms, colonized by dense palaeocommunities of infaunal echinids (Hemiaster scutiger), gastropods (Tylostoma ovatum), exogyrinid and pectinid bivalves, and soft-bodied infaunal polychaetes or crustaceans. Vascoceratid ammonites were common.

(2) A shallow subtidal and intertidal flat with muddy limestones and sandy marls. Benthic palaeocommunities were dominated by epifaunal mollusks, including the ubiquitous Tethyan Tylostoma and Rhynchostreon. Ammonites and infaunal echinids were rare.

(3) A barrier area with shoals and tidal flats drained by tidal channels, emplaced over an uplifted tectonic block controlled by NW-SE faults. The tidal sedimentation was of carbonated muds with resedimented rounded blocks of limestone, interbedded with marly sands and tempestite deposits with oriented coquinas. These facies graded to lagoonal deposits situated landwards.

(4) A narrow domain of coastal lagoons with marly and sandy sedimentation, abundant plant remains and euraline bivalve (Rhynchostreon, Curvостrea, Paraesa) and gastropod (Ampullina, Avellana) palaeocommunities.
(5) A domain of littoral plain with micaceous sandy sedimentation.

At the same interval but southwards the NE-SW Pombal-Leiria-Pataias axis, the carbonate platform was rimmed with fringes of corals and rudists, some of them placed over the diapirc anticlines of Caldas da Rainha, Leiria, Monte Real and São Pedro de Muel. Behind these higher energetic areas, large extensions of calcarenite shoals occupied shallow and more confined environments.

During this first period of reef grow up (units “F” and “G”) the central sector of the carbonate platform was divided in four domains:

(1) A fore-reef slope and transition to outer shelf, recorded in the exposures of Nazaré. Sedimentation was of cross-bedded bioclastic calcarenites with limestone blocks and skeletal debris of ressedimented shells.

(2) A middle shelf with calcarenite shoals, sand bars and scattered buildups of *Caprinula*, *Radiolites*, and *Chondrodonta*. This domain was bounded westwards by the Caldas da Rainha diapirc anticline, and eastwards by the tectonic ridge of Leiria-Porto de Mós.

(3) A reef complex with large and coalescent bioherms of massive and branching corals, including plate-like *Microsolenidae*. This middle shelf area with NW-SE orientation was centered on the region of Leiria-Caranguejeira, and controlled by uplifts of the tectonic axis of Pombal-Leiria-Pataias.

(4) A shallow infralittoral to intertidal lagoon with soft and muddy bottoms colonized by palaeocommunities of *Hemiasterids* and gryphaeid bivalves (*Ceratostreon flabellatum*, *Exogyra olisiponensis*)

*Upper part of the Upper Cenomanian (plate 5)*

During the late Late Cenomanian time (units “H”, “I” and “J – *Pseudaspidoceras pseudonodosoides* ammonite zone) the carbonate platform was affected by significant palaeogeographic and tectonic changes, with emphasis on the gradual uplift and emersion of the Central and Southern sectors.

As a first episode, the complex of bioclastic calcarenite shoals and carbonate sandy bars backstepped landwards, over the previous domains with coral buildups. At this time, reef communities with caprinulids and corals were extensively replaced by radiolitids (*Radiolites lusitanicus* and *Durania arnaudi*) and communities of *Chondrodonta joannae*.

This time of widespread of coarse bioclastic sedimentation, correlative to the accumulation of deeper water carbonates in Figueira da Foz and Montemor-o-Velho, was followed by a period of generalized decrease of the carbonate production and sedimentation of argillaceous carbonate muds (unit “I”). Large extensions of the platform were filled by sublittoral soft muddy bottoms, and colonized by benthic paleocommunities dominated by the infaunal echinoid *Hemiaster scutiger*, together with abundant epifaunal *Tylostoma* and *Pycnodonte*.

The carbonate sedimentation returned at the uppermost Cenomanian (unit “J”), when new domains of shallow calcarenite facies developed over the Central sector of the platform. These banks and bars of bioclastic sands migrated eastwards and northwards, over the lagoonal domains of Ourém and the diapirc anticlines of Monte Real and São Pedro de Muel. Some of these areas were colonized by biostromes with *Durania arnaudi*. In the Baixo Mondego, the sublittoral bottoms were soft and carbonate rich, allowing colonization by communities with infaunal or epifaunal suspension-feeder bivalves (*Trigonarca*, *Callucina*, *Pycnodonte*). The nektonic or nekto-benthic faunas were common and represented essentially by Tethyan vascoceratids.

*Middle Lower Turonian (plate 6)*

The transition to the Turonian was marked by a generalized retreat of the carbonate sedimentation,
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Plate 6

Lower Turonian (Unit "L")
Lower Turonian
(Unit "M")

Atlantic Ocean
followed by emersion of the onshore domains of the carbonate platform. This regressive episode related to the uplift of the continental margin is well documented in both sectors, where an unconformity associated with subaerial exposure and karstification has been recognized.

At the middle part of the Lower Turonian (units “K” and “L” – *Thomasites rollandi* ammonite zone), the carbonate sedimentation returned to the western areas of the Northern sector. A tidal flat with dolomitic sedimentation was gradually set up between Figueira da Foz and Montemor-o-Velho, occupying the distal edge of a large alluvial plain with braided fluvial systems, and influx of micaceous sands drained from the relieves of the Iberian Massif.

With the deepening and increasing of marine influence in the depositional environment, the same areas were colonized by subtidal middle shelf communities of turritellids, with *Tylostoma*, *Hemiaster* and other benthic invertebrates adapted to soft substrates with high carbonate content. Ammonites were represented essentially by vascoceratids (*Vascoceras*, *Fagesia*, *Thomasites*). Easterly Montemor-o-Velho, there was also an inner shelf tidal flat with prograding micaceous sands. The commonest benthic faunas were briozoans, *Tylostomidae* gastropods, and small pectinids;

Over the southeast block of the tectonic axis of Pombal-Leiria-Pataias, the correlative Lower Turonian depositional setting was a tidal flat with marly sedimentation and extensive biostromes of *Radiolites peroni*. These rudist buildups grew up in shallow, moderately agitated water, affected by storm events.

The adjacent sector of Nazaré was a middle shelf slope area of the carbonate platform, with synsedimentary tectonic instability and prograding sedimentary wedges of micaceous carbonates, interbedded with pavements of coarse bioclastic debris of rudists.

*Upper part of the Lower Turonian (plate 7)*

The beginning of the late Lower Turonian (units “M”, “N” and “O” with *Actaeonella caucasica grossouvrei*) was marked by a major regressive trend on the Northern sector, culminating with a final retreat of the sea over the onshore domains of the carbonate platform. During this interval occurred a faster withdraw of the carbonate sedimentation, together with progradation of the micaceous alluvial plain westwards. The sediments accumulated near Figueira da Foz were bioclastic and oolitic inner shelf carbonate sands related to the migration of shoals and sandy bars (unit “M”). These shallow environments were colonized by nerineids (*Polyptyxis*) and actaeonellids (*Actaeonella caucasica grossouvrei*), but also by radiolitids (*Radiolites peroni*) and hermatyipic corals concentrated in small patchreefs. With the progression of the regressive trend, these calcarenitic sands became gradually enriched with micaceous silicilastics, whereas the density of the benthic fauna decreased faster (units “N” and “O”).

On the Central sector of the carbonate platform, the contemporaneous sedimentation areas were almost restricted to the region of Nazaré. The last Lower Turonian sediments recorded were coarse sands with abraded debris of *Radiolites* and *Actaeonella*, suggesting the existence of a shallow littoral domain with prograding alluvial sandy bars.

**CONCLUSIONS**

The Albian-Turonian Western Portuguese carbonate platform overlies the Jurassic and Lower Cretaceous synrift series of the Lusitanic Basin, one of the marginal North Atlantic basins associated with the breakup of Pangaea. This large rimmed shelf was part of the European northern branch of Tethys, but also a significant area for migration and faunal changes with the Temperate Domain, during the Mid-Cretaceous sea-level rise.
The carbonate platform was gradually set up through the Albian and Cenomanian stages, and persisted until the end of Lower Turonian, over large areas of the Western Iberian margin. Most sequences are well documented across the onshore exposures of Portuguese Estremadura and Beira Litoral, from the parallel of Lisbon to the regions of Coimbra, Figueira da Foz and Aveiro. This record makes possible to establish a model of palaeogeographic evolution for the carbonate platform, including detailed positions of the ancient coast-lines, and the transition for marginal marine siliciclastic environments:

(a) From the Albian to the Early Cenomanian the carbonate sedimentation was almost limited to domains of the present offshore, but also reached the regions of Lisbon and Nazaré.

(b) The Middle Cenomanian was a time of gradual enlargement of the platform towards the western boundary of the Iberian Massif. The shallow marine carbonate and mixed environments of the platform were present, for the firs time, in the regions of Beira Litoral and eastern areas of Estremadura.

(c) The maximal increase of carbonate sedimentation occurs after a basal Upper Cenomanian onlap, when fully marine environments were introduced. This succession is overlain by highly diverse series of carbonate facies, including (1) abundant reef and lagoonal limestones with coral and rudist fringes, (2) limestones with Tethyan ammonites and associated benthic faunas, and (3) inner shelf and marginal mixed carbonate-siliciclastic sediments with shallow-water associations of Tethyan mollusks and echinoids.

(d) Near the end of Upper Cenomanian was recorded a regressive event of regional extent, associated with subaerial exposure, karst development, and fluvial incision on both onshore domains. This uplift of the continental margin affected the whole carbonate platform.

(e) From the middle part of the Early Turonian onwards, evidences suggest that the Northern sector of the platform slightly tilted and drowned northwestwards, allowing a temporary return of shallow-marine conditions with carbonate and mixed sedimentation. The contemporaneous benthic faunas included turritelid gastropods, coral-rudist patch reefs and radiolitid biostromes.

(f) The transition to the Upper Turonian is marked by the final withdraw of carbonate sedimentation from the present onshore areas, followed by a fast progradation of micaceous tidal-plain and alluvial sands transported from the adjacent domains of the Iberian Massif.

REFERENCES


Callapez, P. M. (1999). The Cenomanian-Turonian of the western Portuguese Basin, EPA Workshop of Lisbon, field trip 2, 45 PP.


EXPLANATION OF PLATES

Plate 1 - Lower Cenomanian palaeogeographic reconstruction (“Unit with Hylmatogyra pseudaficana”)

A - Depositional areas and sedimentary dynamics:

1- Intertidal and shallow subtidal inner shelf with low diversity invertebrate faunas and exogyridin biostromes;
2- Intertidal and supratidal mixed carbonate-sandy flats;
3- Sandy tidal flats and wetlands;
4- Alluvial plain with braided fluvial systems prograding westwards, and influx of coarse siliciclastic sediments;
5- Approximate position of shoreline;
6- Direction of clastic influx;
7- Direction of marine incursion;

B – Tectonosedimentary setting:

8- Western boundary of the Iberian Massif;
9- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform);

C - Depositional environments:

31- Intertidal and shallow subtidal inner shelf with low diversity invertebrate faunas and exogyridin biostromes;
32- Intertidal and supratidal mixed carbonate-sandy flats;
33- Sandy tidal flats and wetlands;
34- Alluvial plain with braided fluvial systems prograding westwards, and influx of coarse siliciclastic sediments;
35- Approximate position of shoreline;
36- Direction of clastic influx;
37- Direction of marine incursion;

D – Tectonosedimentary setting:

38- Western boundary of the Iberian Massif;
39- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform);
10- Diapiric axis and anticlines with Hettangian evaporites;
11- Diapir associated and late-Hercinian faults reactivated during extensional events of the Lusitanic Basin;

C – Commonest species and palaeocommunities:

12- Biostromes with *Ilymatogyra pseudafricana*, *Ceratostreon flabellatum*, *Septifer* and pholads.

**Plate 2 - Middle Cenomanian palaeogeographic reconstruction (Unit “B”)**

A - Depositional areas and sedimentary dynamics:

1- Intertidal and shallow subtidal lagoon with sedimentation of carbonate laminites and an abundant fauna with vertebrates and oysters.
2- Intertidal and shallow subtidal inner shelf with mixed carbonate-sandy sedimentation and low diversity invertebrate faunas, including ostreid and exogyridi biostromes;
3- Coarse sandy tidal flats;
4- Alluvial plain with braided fluvial systems and influx of siliciclastic sands, gradually backstepping to the uplifted domains of the Iberian Massif;
5- Emerged areas or shoals associated with moderate diapiric activity;
6- Direction of clastic influx;
7- Approximate position of shoreline;
8- Direction of marine incursion;

B – Tectonosedimentary setting:

9- Western boundary of the Iberian Massif;
10- Diapiric axis and anticlines with Hettangian evaporites;
11- Diapir associated and late-Hercinian faults reactivated during extensional events of the Lusitanic Basin;
12- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform);

C – Commonest species and palaeocommunities:

13- Areas with abundant shallow marine ostracods.
14- Palaeocommunities with *Anisocardia orientalis* (oxygenated bottoms suitable to infaunal bivalves);
15- Occurrence of reptiles (quelonids and crocodiles);
16- Biostromes and clusters with *Gyrostrea ouremensis*;
17- Pycnodontidae and other related fishes.

**Plate 3 - Early Upper Cenomanian palaeogeographic reconstruction (Units “C”/”D”)**

A - Depositional areas and sedimentary dynamics:

1- Middle to outer shelf with deeper subtidal muddy carbonate sedimentation; Abundant benthic faunas with *Pycnodontinae* bivalves, echinids and ammonites.
2- Middle shelf with subtidal muddy and clastic carbonate sedimentation. Highly diverse faunas of benthic invertebrates, including infaunal echinids; Abundant ammonites and nautiloids.
3- Intertidal and shallow subtidal inner shelf and nearshore with mixed carbonate-sandy sedimentation;
4- Alluvial plain with braided fluvial systems and influx of micaceous sands, backsteeped to the marginal domains of the Iberian Massif;
5- Carbonate shoals associated with diapiric areas;
6- Areas of soft carbonate bottoms with significant colonization by alveolinid foraminifers;
7- Approximate position of shoreline;
8- Direction of clastic influx;

B – Tectonosedimentary setting:

9- Western boundary of the Iberian Massif;
10- Direction of marine incursion;
11- Diapiric axis and anticlines with Hettangian evaporites;
12- Diapir associated and late-Hercinian faults
reactivated during extensional events of the Lusitanic Basin;
13- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform);

C – Commonest species and palaeocommunities:
14- Northern limit of the carbonate muds with dense concentrations of the alveolinid Praealveolina cretacea tenuis;
15- Palaeocommunities with Rhynchostreon columbum and other exogyrid bivalves;
16- Heterodiadema ouremense, H. lybicum and epifaunal echinids;
17- Hemiaster lusitanicus, H. scutiger and associated species of infaunal echinids;
18- Palaeocommunities with the deeper –water Ostreina Pycnodonte vesiculare;
19- Neolobites vibrayeanus (nectobenthonic Tethyan ammonite);
20- Palaeocommunities with the semi-infaunal bivalve Pinna (Pinna) sp.

Plate 4 - Middle Upper Cenomanian palaeogeographic reconstruction (Unit “G”)

A - Depositional areas and sedimentary dynamics:
1- Middle to outer shelf with deep subtidal muddy carbonate sedimentation, Tethyan vascoceratid ammonites and ahermatypic branching corals;
2- Middle shelf with subtidal carbonate muds and locally condensed sedimentation; Abundant vascoceratid ammonites and benthic faunas of Tethyan Tylostomidae, exogyrids and pectinids;
3- Intertidal and shallow subtidal inner shelf with mixed carbonate muddy and micaceous sandy sedimentation;
4- Upper subtidal well oxygenated bottoms with Hemiasterid and crustacean palaeocommunities;
5- Tidal channels;
6- Fault controlled barrier area with instable substrates; Mixed sedimentation of carbonate muds, fine micaceous sands and rounded blocks of resedimented limestone;
7- Coastal lagoons with carbonate muddy bottoms, moderate clastic influx and brackish to marine restricted conditions; Palaeocommunities of ostreids and/or exogyrids;
8- Nearshore tidal flat with micaceous sandy and carbonate sedimentation;
9- Alluvial plain with braided fluvial systems and westwards influx of micaceous sands;
10- Calcarenitic shoals and sand bars with Caprinula and Chondrodonta patch-reefs;
11- Fore-reef slope with skeletal debris and limestone blocks;
12- Reef complex with massive and branching corals, including coalescent bioherms with plate-like Microsolenidae;
13- Shallow infralittoral to intertidal lagoon with mangroves and abundant exogyrids and echinids;
14- Mangroves or coastal tidal wetlands with arborisation.
15- Direction of clastic influx;
16- Direction of marine incursion;
17- (a) Approximate position of shoreline; (b) Barrier;

B – Tectonosedimentary setting:
18- Western boundary of the Iberian Massif;
19- Diapiric axis and anticlines with Hettangian evaporites;
20- Diapir associated and late-Hercinian faults reactivated during extensional events of the Lusitanic Basin;
21- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform);

C - Commonest species and palaeocommunities:
22- Hemiaster scutiger;
23- Deeper water palaeocommunities with
ahermatypic branching corals and serpulids;
24- Vascoceras spp.;
25- Tylostoma ovatum;
26- Rhynchostreon columbun;
27- Ampullina punctata;
28- Radiolites lusitanicus;
29- Ceratostreon flabellatum;
30- Reef palaeocommunities with massive, plate-like and branched hermatypic corals;
31- Reef palaeocommunities with Caprinula boissyi.

Plate 5 - Late Upper Cenomanian palaeogeographic reconstruction (Unit “J”)

A - Depositional areas and sedimentary dynamics:
1- Middle to outer shelf with subtidal carbonate muds. Abundant Tethyan vascoceratid ammonites and a diverse benthic fauna with Pycnodontinae, arcid and lucinid bivalves.
2- Middle shelf with subtidal carbonate muds and benthic faunas of Tethyan Tylostomidae, exogyrinids and pectinids;
3- Middle to inner shelf with shallow subtidal and intertidal mixed sedimentation of carbonate muds and fine micaceous sands;
4- Alluvial plain with braided fluvial systems and westwards influx of fine micaceous sands;
5- Middle to inner shelf calcarenitic shoals, sand bars and sand flat islands with scattered patch-reefs of radiolitid rudists and abundant nerineid gastropods;
6- Middle shelf carbonate muds with large areas colonised by rudist biostromes of Durania arnaudi;
7- Direction of clastic influx;
8- Approximate position of shoreline;
9- Basinward progradation of coarse carbonate debris, eroded from the uplifted reef front.
10- Landward backstepping of calcarenitic sandy shoals;
11- Direction of marine incursion;
12- Western boundary of the Iberian Massif;
13- Diapiric axis and anticlines with Hettangian evaporites;
14- Diapir associated and late-Hercinian faults reactivated during extensional events of the Lusitanic Basin;
15- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform);

C – Commonest species and palaeocommunities:
16- Syncyclonema ?simplicia;
17- Trigonarca matheroniana;
18- Polyptyxis requieni/schiosensis;
19- Trochactaeon giganteum;
20- Pycnodonte vesiculare;
21- Callucina sp.;
22- Vascoceras sp.;
23- Biostromes and patch-reefs with Radiolites lusitanicus;
24(a)- Biostromes with Durania arnaudi, (b) Tylostoma ovatum;
25- Sandy bottom palaeocommunities with Decapod crustaceans.

Plate 6 - Middle Lower Turonian palaeogeographic reconstruction (Unit “L”)

A - Depositional areas and sedimentary dynamics:
1- Open middle shelf with carbonate muds and storm concentrations of coquinas with oriented turritellid gastropods; Abundant Tethyan vascoceratid ammonites and Tylostomidae gastropods;
2- Inner shelf tidal flat with prograding micaceous sands; Benthic faunas with briozoans, Tylostomidae gastropods and small pectinids;
3- Middle shelf fault controlled slope with micaceous sands and carbonate muds interbedded with ressedimented intraclasts of micaceous limestone and rudist debris;
4- Middle shelf shoals and flats with large biostromes of radiolitids oriented on the dependence of the tectonic axis of Pombal-Leiria-Pataias, and the diapiric anticline of Caldas da Rainha; 
5- Alluvial plain with braided fluvial systems and westwards influx of micaceous sands; 
6- Shoal or low relief emerged area; 
7- Approximate position of shoreline; 
8- Direction of coarse bioclastic influx from the adjacent front-reef with biostromes of \textit{Radiolites peroni}; 
9- Direction of clastic influx; 
10- Direction of marine incursion; 

B – Tectonosedimentary setting: 

9- Western boundary of the Iberian Massif; 
10- Diapiric axis and anticlines with Hettangian evaporites; 
11- Diapir associated and late-Hercinian faults reactivated during extensional events of the Lusitanic Basin. 
12- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform); 

C – Commonest species and palaeocommunities: 

15- Biostromes with \textit{Radiolites peroni}; 
16- Low-diversity palaeocommunities with \textit{Turritella (Haustator) uchauxensis}; 
17- Sandy bottom palaeocommunities with \textit{Syncyclonema ?simplicia}. 

\textbf{Plate 7 - Late Lower Turonian palaeogeographic reconstruction (Unit “M”)} 

A - Depositional areas and sedimentary dynamics: 

1- Middle shelf sandy shoals with coral-rudist patch-reefs and calcarenitic sands with nerineid and actaeonellid gastropods; 
2- Inner shelf with shallow subtidal and intertidal mixed sedimentation of muddy carbonate and fine grained micaceous sands; Abundant concentrations of erected briozoans; 
3- Tidal flat and nearshore environments with fine grained micaceous sediments and epifaunal benthic colonization of small pectinids, serpulids, and decapods; 
4- Fast prograding alluvial plain with braided fluvial systems and westwards influx of micaceous sands; 
5- Nearshore environment with siliciclastic coarse sandy bars and interbedded concentrations of ressedimented limestone debris, including rudist fragments from the middle Lower Turonian biostromes with \textit{Radiolites peroni}. 
6- Uplifted area of erosion or coarse grained siliciclastic sedimentation, situated on the dependence of the tectonic axis of Pombal-Leiria-Pataias and the diapiric anticline of Caldas da Rainha. 
7- Shoal or low relief emerged area; 
8- Approximate position of shoreline; 
9- Direction of clastic influx; 
10- Local influx of coarse grained siliciclastic sediments with carbonate intraclasts and biosclasts. 

B – Tectonosedimentary setting: 

11- Western boundary of the Iberian Massif; 
12- Diapiric axis and anticlines with Hettangian evaporites; 
13- Diapir associated and late-Hercinian faults reactivated during extensional events of the Lusitanic Basin. 
14- Tectonic axis of Pombal-Leiria-Pataias (boundary between the Northern and Central sectors of the carbonate platform); 

C – Commonest species and palaeocommunities: 

15- Patch-reef palaeocommunities with hermatipic massive and branching corals; 
16- Low-diversity palaeocommunities with branched briozoans;
17- Biostromes and patch-reefs with *Radiolites peroni* (Figueira da Foz area);
18- *Actaeonella caucasica grossouvrei*;
19- Palaeocommunities with *Polyptyxis requieni* and *P. schiosensis* from high energy environments.

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