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Micropalaeontology and Stratigraphy of the Cenomanian/Turonian boundary in the Lusitanian Basin, Portugal

Micropaleontología y Estratigrafía del límite Cenomaniense/Turoniense en la Cuenca Lusitánica, Portugal

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Abstract

   The mid-Cretaceous carbonate succession exposed along the valley of the Rio Mondego (Lusitanian Basin, Western Portuguese Margin, Portugal) is described and the microfauna documented. This succession records the Cenomanian-Turonian transition within a shallow water environment. The majority of Cenomanian-Turonian boundary sections described in the literature are from deeper-water settings and the unusual benthic foraminifera recorded in this succession are rarely discussed in terms of the latest Cenomanian extinction event. The Rio Mondego succession is discussed in terms of the proposed "ejecta horizon" exposed on the coast at Praia da Vitória, 10 km north of Nazaré.

Keywords: Portugal, Lusitanian Basin, Foraminifera, Cenomanian/Turonian boundary, impact breccia

Resumen

   En este trabajo se describe la sucesión de naturaleza carbonática de edad Cretácico medio expuesta en la región del valle del Río Mondego (Cuenca Lusitánica, Margen Occidental de Iberia, Portugal) y su contenido microfósil. La mayoría de las secciones del límite Cenomaniense-Turoniense descritas en la bibliografía registran facies de ambientes marinos de mayor profundidad, mientras que la sección que se presenta en este trabajo muestra dicha transición en depósitos formados en un ambiente marino de aguas poco profundas. Los escasos foraminíferos bénticos que han sido hallados en esta sucesión no habían sido estudiados en detalle previamente en relación al evento de extinción del final del Cenomaniense. En la sucesión del Río Mondego ha sido analizado también el "horizonte de ejecta", expuesto en el litoral de Praia da Vitória, 10 km al norte de Nazaré.

Palabras clave: Portugal, Cuenca Lusitánica, Foraminíferos, Límite Cenomaniense/Turoniense, brecha de impacto

1. Introduction

   The Lusitanian Basin, in western Central Portugal, is one of the marginal basins associated with the opening of the North Atlantic Ocean (Fig. 1). It extends over 23,000 km², and is exposed along the coastline of Portugal for over 250 km from Lisbon to Aveiro. The northern margin is ill-defined, connecting to off-shore Mesozoic basins that are surrounded by the Porto and Vigo Seamounts and the Galicia Bank. Off-shore basement horsts within

the basin include the Berlengas and Farilhões Islands. Most of the basin fill is Jurassic in age but Upper Triassic sediments are known from a few areas. Lower and Upper Cretaceous sediments are also present, overlain by a cover of Cenozoic sediments. Two episodes of rifting and extension are recorded, the first being in the late Triassic. The later movements, which gave rise to ocean opening, occurred in the latest Jurassic and earliest Cretaceous (Ribeiro *et al.*, 1979; Wilson, 1988: Proença Cunha and Pena dos Reis, 1995). The basin suffered tectonic inversion in the Cenozoic and, as a result, a large part of its pre-, syn-, and post-rift sequences became exposed (Wilson, 1988). The area close to the Nazaré Fault (Fig. 2) has also been affected by salt diapirs (see Proença Cunha and Pena dos Reis, 1995, fig. 3, and Pena dos Reis, 1998, fig.1), the emplacement of which is important in the geological history of the area.

The mid-Cretaceous successions described herein are located along the Rio Mondego inland of Figueira da Foz and at Praia da Vitória (immediately north of Nazaré). As a part of a larger study of the Cenomanian-Turonian boundary our interest in this area arises from the fact that:

(1) there is a well-documented Cenomanian-Turonian succession in relatively shallow-water sediments as compared to the deeper-water successions normally investigated at this level; and

(2) there is a suggestion that an impact ejecta deposit is present within the Praia da Vitoria succession.

2. The Late Cenomanian Extinction Event

The Late Cenomanian extinction event (= Cenomanian-Turonian Boundary Event [CTBE] or Bonarelli Event or OAE 2) was an important biotic crisis in the history of the Cretaceous world-wide. It is one of the extinction events identified by Raup and Sepkoski (1982) in their analysis of periodic extinctions. It is not one of the 'big five' extinction events of the Phanerozoic record as the majority of the faunal changes are at the species level, rather than higher taxonomic levels. In a recent review Hart *et al.* (2002) have discussed the evidence for the 'event' and listed a number of potential causes.

Much of the data on the CTBE come from localities located within the chalk succession of Western Europe (Eastbourne, Folkestone, etc.), the limestone/shale/marl successions of the Western Interior Seaway of the USA or the carbonate/clay successions drilled as part of DSDP/ODP/IPOD programs in the various oceans of the world. A wide range of potential causes has been assembled (see Hart *et al.*, 2002, p. 36) extending from the purely oceanographic to a bolide impact. In the debate over the

potential/probable causes few authors (e.g., Kennedy and Simmons, 1991; Caus *et al.*, 1997) have presented data from a shallow-water, carbonate succession. In the successions from the Lusitanian Basin planktic foraminifera are extremely rare while the larger and smaller benthic taxa are more abundant. The microfaunas are associated with extensive, and well-known, ammonite and rudist faunas first described in detail by Choffat (1885, 1886, 1896, 1897a,b, 1898, 1900). In recent years this original work has been revised by Soares (1966, 1972, 1980), Berthou and Philip (1972), Berthou (1973, 1978, 1984a,b), Berthou *et al.* (1975, 1985), Berthou and Lauverjat (1975, 1976, 1979), Lauverjat (1978, 1982), Lauverjat and Berthou (1973-74), Amédro *et al.* (1980) and Callapez (1998). One of the most accessible reviews (in English) is that of Berthou (1984a) who presented a reinterpretation of Choffat's ammonite stratigraphy of the Cenomanian-Turonian boundary (as well as an overview of the complete Albian-Turonian succession).

Choffat (1900) and Berthou (1984a, fig. 1) identify three regions in the Lusitanian Basin that are characterised, in the Late Cenomanian, by ammonites (north of
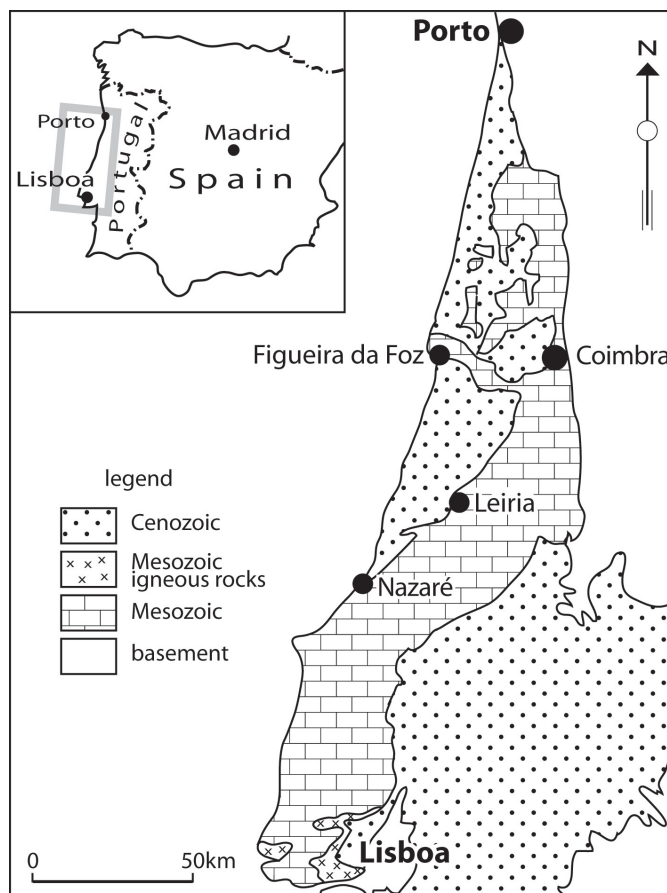

Fig. 1.– Outline geological map of the Lusitanian Basin.
Fig. 1.– Mapa geológico de la Cuenca Lusitánica.

Leiria), rudists (south of Leiria) and echinoderms (east of Leiria). In this account we are considering the foraminifera and biostratigraphy in the area north of Leiria and, in particular, the succession exposed along the Rio Mondego between Figueira da Foz and Coimbra. More recently this area has been investigated by Callapez (1998, 1999) as part of a doctoral study of the region. Callapez (*op. cit.*) has revised the ammonite stratigraphy and provided the framework within which we have investigated the foraminifera.

3. Rio Mondego Succession

The Cenomanian-Turonian carbonate succession of the Western Portuguese Margin is part of a larger (?)megasequence that extends (Fig. 3) from the Upper Aptian to the Lower Campanian (Wilson, 1988; Pinheiro *et al.*, 1996). Within this setting there is an extensive carbonate platform of mid-Cenomanian to early Turonian age (Figs. 3, 4). The carbonate platform wedges out towards the basin margin. It is interesting that the maximum stratigraphical extent of this carbonate succession ranges from mid-Cenomanian to mid-Turonian, coincident with the sea-level highstand of the mid-Cretaceous (Hancock, 1989 and references therein). This is significant as it almost certainly indicates a response to global events rather than local tectonic control. In the Northern Sector (Fig. 3) the succession shown is that inland of Figueira da Foz along the valley of the Rio Mondego (Fig. 2). This part of the succession is shown in Figure 4, which also includes the facies changes and stratigraphy along a section from the coast (Figueira da Foz) inland towards Coimbra. The letters (B, C, D, etc.) are the classic units of Choffat (1900), that have been retained by both Berthou (1984a) and Callapez (1998, 1999). The described succession begins in Salmanha Quarry (Lauverjat and Berthou, 1973-74, fig.1; Callapez, 1999, fig.16) and a range of other overgrown quarries and roadside exposures along the valley of the Rio Mondego. The composite succession shown in Figure 4 indicates that, in the vicinity of Salmanha Quarry, Beds B – O are present. The ammonite zonation used in this diagram is the international standard that is in general use in N.W. Europe and the Western Interior Seaway of the U.S.A. The application of this zonation to successions in Spain and Portugal is slightly controversial and we use the evidence presented in Callapez (1998, 1999). In recent years a number of interpretations of the ammonite zonation have been presented: see, for example, Wiedmann (1980, fig. 7), Wiedmann and Kauffman (1978), Meister *et al.* (1992, figs 24-26), Hardenbol *et al.* (1998, chart 5) and Kassab and Obaidalla (2001, table 3)
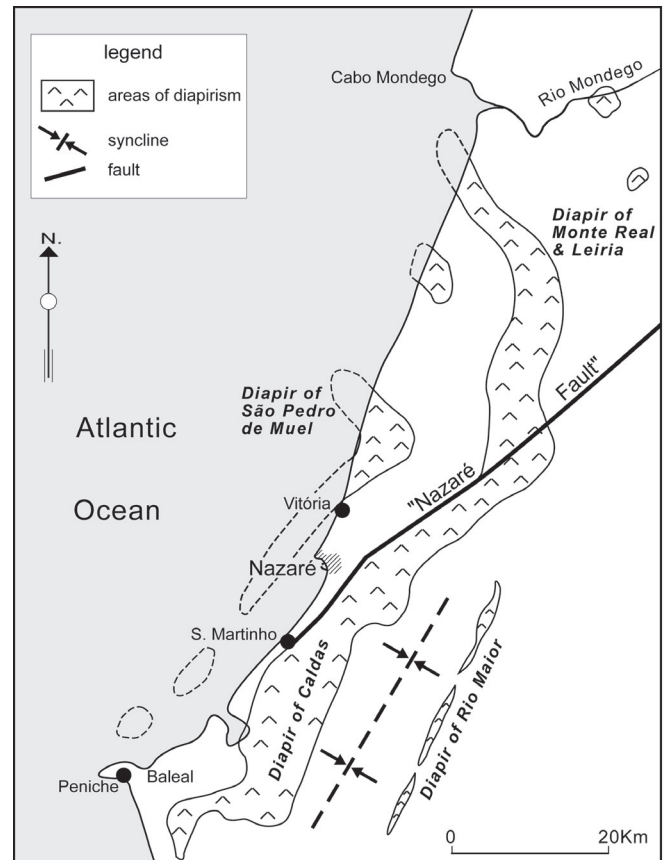

Fig. 2.– Location of Nazaré and the Rio Mondego. The approximate position of salt diapirs associated with the Nazaré–Leiria–Pombal flexure/fault (the Nazaré Fault of Berthou, 1984a) are indicated.
Fig. 2.– Situación de Nazaré y del Río Mondego. Posición aproximada de los diapiros salinos relacionados con la flexión/falla de Nazaré–Leiria–Pombal (Falla de Nazaré, según Berthou, 1984a).

The contemporaneous ammonite assemblages of Northern Spain described by Wiedmann (1980) and Wiedmann and Kauffman (1978) are somewhat different to those in the Lusitanian Basin, except for the common occurrence of *Neolobites* and *Calycoceras* in the basal Upper Cenomanian and the abundance of *Spathites subconciliatus*. The age of the first *Vascoceras* assemblages (a problem Berthou tackled for many years) can be defined as a result of the discovery of *Euomphaloceras septemseriatum* in the same beds. This species is known from assemblages correlative with the Geslinianum Zone. The papers of Kennedy (1984, 1988), Kennedy and Cobban (1991), Kennedy and Juignet (1994) and Kennedy *et al.* (1989) are very helpful in this respect. The hiatus recorded between Beds J and K may be of relatively short duration but is certainly present. The ammonites from the overlying beds are representatives of the middle of the Lower Turonian. *Pseudaspidoceras flexuosum* Zone faunas are not found, despite being typical of many other Tethyan Cenomanian–Turonian boundary successions.
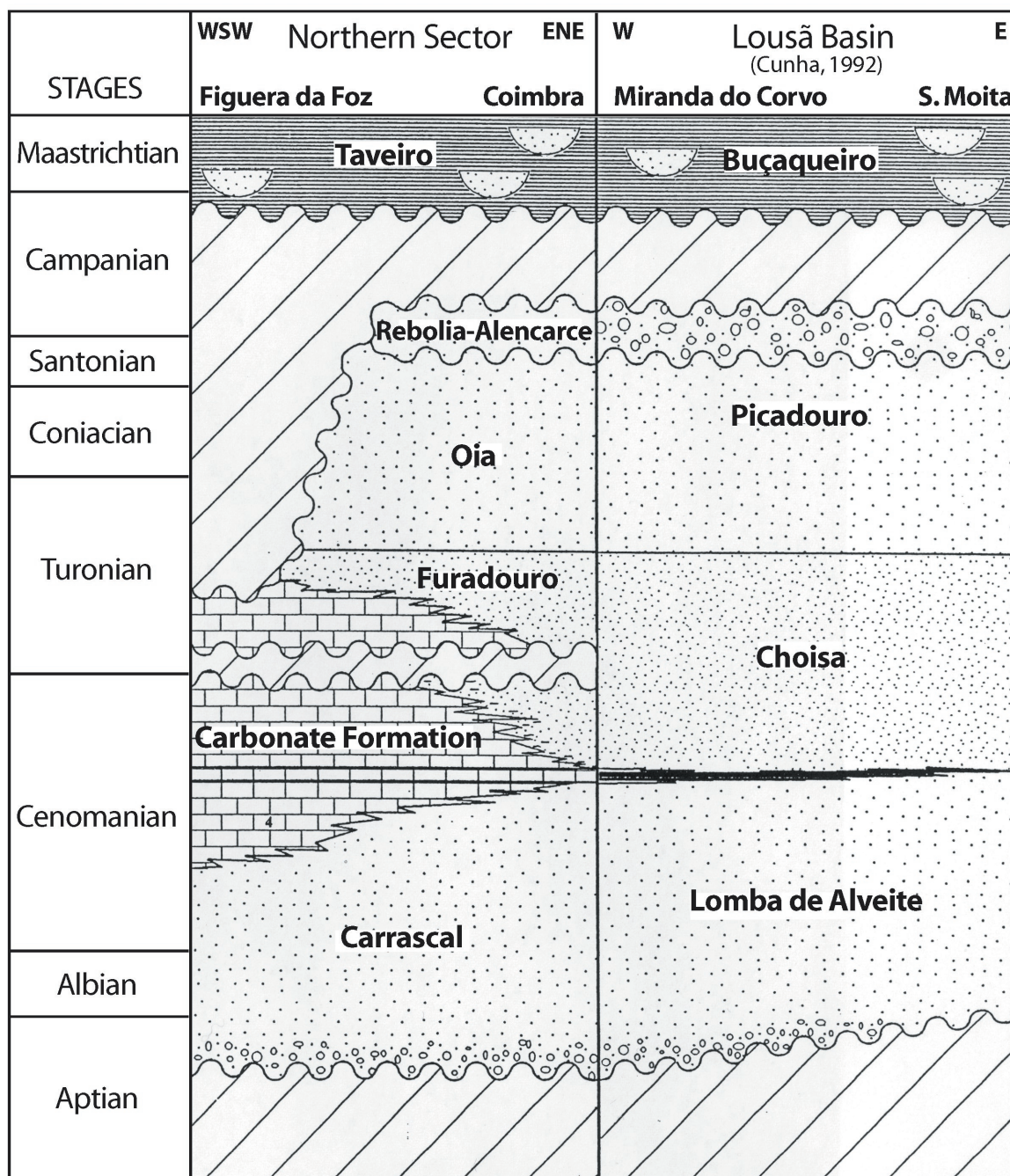
Fig. 3.– Simplified summary of the stratigraphic succession within the Upper Aptian to Lower Campanian 'megasequence' of the Western
    Portugal Margin (modified after Callapez, 1998, 1999).
Fig. 3.– Resumen simplificado de la sucesión estratigráfica correspondiente a la "megasecuencia" Aptiense superior - Campaniense infe-
    rior del Margen occidental de Portugal (modificado de Callapez, 1998, 1999).

3.1. Lithological succession and microfauna

Figure 5 shows an outline log of the succession which is based on the work of Callapez (1998, 1999), together with some data on the ranges of important foraminifera. Such information is necessarily incomplete as working with thin section material always means that:

(1)   the fauna recorded for each sample is limited by the number of thin sections studied; and

(2)   many 'smaller' benthic foraminifera are impossible to identify at the species (or even genus) level while 'larger' benthic foraminifera (orbitolinids and alveolinids) tend to display more diagnostic features in thin section.

It is significant that very few planktic foraminifera are recorded, confirming the shallow water environments represented by the greater part of the succession. No deeper-water keeled planktic foraminifera (see, for example, Hart and Bailey, 1979; Hart, 1980, Caron and Homewood, 1983; Hart, 1999) have been found. The only species recorded are *Heterohelix* sp. cf. *H. moremani, Guembelitria cretacea, Hedbergella delrioensis, Whiteinella* spp., and (very rare) *Helvetoglobotruncana praehelvetica.* All of these are (probably) surface dwelling forms (upper 50 m of the water column or less). All of the planktic specimens recorded in the thin sections are very small and are either juveniles or size-limited by the shallow water environment. The benthic foraminifera are probably less diagnostic, although one can suggest that:

(1)   orbitolinids and alveolinids probably hosted algal symbionts (Lee and Anderson, 1991) and, as a result, were probably limited to 25-30 metres of water; and

(2)   abundant milioliids (and little else) almost certainly indicate lagoonal, possibly hypersaline, environments.

Bed B has only been sampled at Tentúgal, inland of Salmanha Quarry. At this locality the sediment is a bivalve-rich rudstone with large macrofossil fragments supported in a lime mudstone matrix. The majority of the fauna comprises turritellid gastropods, bivalves (possibly *Gyrostrea*) and very small planktic foraminifera. Small, indeterminate ostracods are also present.

Bed C is mainly composed of anhedral rhomb-shaped dolomite crystals with rare quartz grains and molluscan fragments. At Tentúgal Bed C is a foraminiferal wackestone with a relatively high diversity fauna that includes *Ammobaculites* spp., *Dorothia* sp., *Marssonella oxycona, Quinqueloculina* spp., *Gavelinella* sp. and planktic forms identified only as *Hedbergella* sp. and *Heterohelix* sp.. Of particular note is the occurrence of *Hemicyclammina sigali, Simplalveolina simplex* (Figs. 6F/G/H and 7A/B) and a form very close to *Thomasinella punica* (*sensu* Arnaud-Vanneau and Prestat, 1984). On many shell fragments (Figs. 6D and 7C) are adherent, agglutinated foraminifera often referred to as "*Placopsilina cenomana*" although this genus does require urgent revision (Hodgkinson, 1992). This assemblage is typical of many mid-Upper Cenomanian successions in shallow-water carbonate-rich environments.
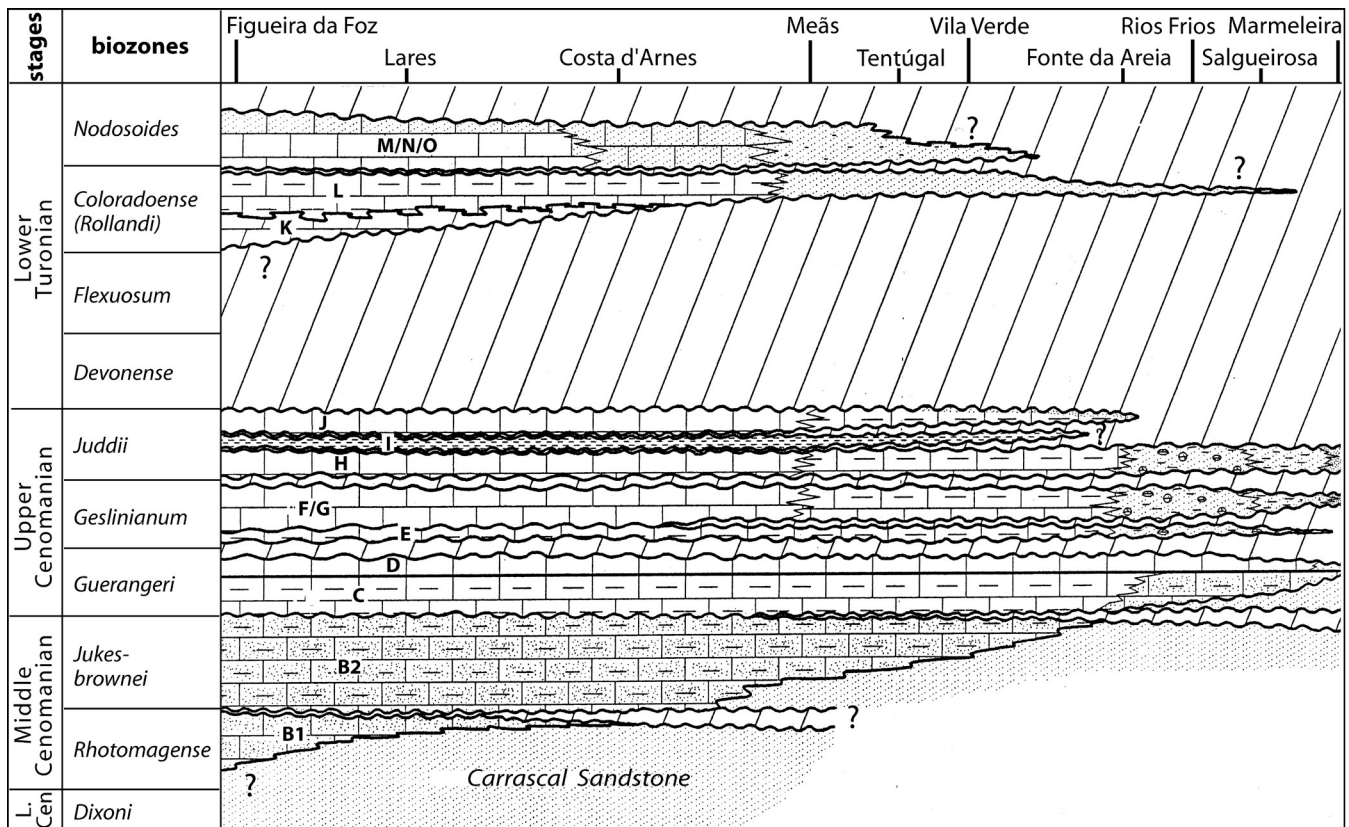

Fig. 4.– Chronostratigraphy and biostratigraphy of the carbonate succession along the Rio Mondego from Figueira da Foz inland towards Tentúgal, Coimbra and Lousã (modified after Callapez, 1998, 1999).

Fig. 4.– Cronoestratigrafía y bioestratigrafía de la sucesión carbonática a lo largo de Río Mondego desde Figueira da Foz hacia el interior por Tentúgal, Coimbra y Lousã (modificado de Callapez, 1998, 1999).

Bed D comprises approximately 2 metres of yellow, marly, limestone. In thin section the rock is a foraminiferal wackestone with a wide range of taxa that includes *Lenticulina* spp., *Marssonella oxycona, Quinqueloculina* spp., *Ovalveolina ovum, Simplalveolina simplex, Hemicyclammina sigali, Nummoloculina* sp., *Pseudocyclammina* sp., *Nummofallotia* sp., *Vidalina* sp., *Trochammina* sp. cf. *T. kugitangensis, Pseudolituonella reicheli* and a few very small specimens of *Hedbergella* and *Heterohelix. Hemicyclammina sigali* is a particularly useful Cenomanian marker in many Tethyan areas (Maync, 1953; Sartorio and Venturini, 1988) and can usually be recognised with little difficulty in thin section. *Trochammina* sp. cf. *T. kugitangensis* was recorded by Lauverjat and Berthou (1973-74) but the form seen in these limestones is much flatter, with sharply angled chambers, than the typically rounded form (holotype) illustrated by Bykova (1947). *Trochammina webbi* Stelck and Wall (1954) and *Trochammina whittingtoni* Tappan (1957) are possible alternative identifications for this taxon, although both are from Northern Canada and Alaska respectively. Unfortunately, neither of these taxa has been illustrated in thin section, but they are much flatter species with a sharply angled periphery. Other bioclasts include molluscan fragments, echinoids, bryozoans, ostracods and fragments of dasycladacean algae. The *Dicyclina schlumbergi* recorded by Lauverjat and Berthou (1973-74, p. 274) has not been encountered during our investigation.

Beds C and D record the highest diversity faunas of the succession under discussion. These faunas, and the associated calcareous algae, represent a mid-carbonate ramp assemblage with both shallow water and slightly deeper water environments being represented. This diverse assemblage is also coincident with the "maximum flooding surface" (see Fig. 3) of this part of the succession and appears to conform to the model proposed by Emery and Myers (1996, fig. 6.14). In the Central Oman Mountains Kennedy and Simmons (1991, fig. 4) record a similarly diverse assemblage from the Natih Formation of mid-Late Cenomanian age (including *Hemicyclammina sigali* and *Praealveolina*).

Bed E is a marly nodular limestone. Lauverjat and Berthou (1973-74, p. 275) record the presence of abundant *Exogyra* in these sediments, while Callapez (1998) records an ammonite fauna that contains *Vascoceras gamai* and *Euomphaloceras septemseriatum* that indicate an equivalence with the Western European zone of *Metoicoceras geslinianum*. This is a different interpretation to that presented in Hardenbol *et al.* (1998, chart 5), who indicate that the Gamai Zone fauna overlies the Geslinianum Zone fauna. This particular lithology is difficult to thin section, being on the boundary between being semi-processable by normal methods and having to be sectioned. The fauna recorded is, therefore, probably reduced because of these difficulties. The fauna includes (Fig. 5) *Thomasinella* (?)*punica, Hemicyclammina sigali, Simplalveolina simplex, Trochammina* sp. cf. *T. kugitangensis* and "*Placopsilina cenomana*". Algal fragments (dominated by *Permocalculus*) are abundant, although the layer of transported *Pseudocyclammina* sp. at the top of the bed that was reported by Lauverjat and Berthou (1973-74) was not located.

Bed F is ~2.5 m of beige-coloured grain supported peloidal packstone with a lime mud matrix. The main allochems are foraminifera (Fig. 6A) and peloids/pisoids. Spines from spatangoids are abundant, although the foraminifera dominate the thin sections. The fauna includes *Hemicyclammina sigali, Trochammina* sp. cf. *T. kugitangensis, Ammobaculites* spp., *Quinqueloculina* sp., *Nautiloculina* sp., *Textularia* sp., (?)*Pseudoglandulina* sp., *Gavelinella* sp. and "*Placopsilina cenomana*". Very small *Hedbergella delrioensis* are also present.

Bed G is a grey compact limestone that is approximately 3 m thick. Bivalves, gastropods, echinoids and branching corals are present but foraminifera are less common. "*Placopsilina cenomana*", *Heterohelix* sp. and *Hedbergella delrioensis* are recorded, associated with algal debris (including *Permocalculus*).

Bed H is a bioclastic wackestone with echinoid spines, foraminifera, bryozoan fragments and occasional coral fragments (Fig. 6B). The foraminiferal assemblage is much reduced with only rare, indeterminate, agglutinated taxa and very small *Hedbergella* sp. and *Guembelitria* sp.. It is interesting to note the first appearance, up section, of calcispheres (Hart, 1991; Jarvis *et al.*, 1988; Hart *et al.*, 2002, fig.1; and see Fig. 8). Though not as

Fig. 5.– (opposite page) The Cenomanian-Turonian succession of the valley of the Rio Mondego with notes on the lithology of the limestone succession and the ranges of some characteristic foraminifera. Level 1 marks the disappearance of the majority of the Cenomanian microfauna, and this is almost complete by the top of Bed F. Level 2 marks the appearance of *Helvetoglobotruncana praehelvetica*. Note the distribution of calcispheres between Bed H and Bed J. Hiatuses are marked by a wavy line adjacent to the schematic sedimentary log.

Fig. 5.– (página opuesta) Sucesión Cenomaniense-Turoniense del valle del Río Mondego en la que se indica la litología de la sucesión caliza y los rangos de algunos foraminíferos característicos. El Nivel 1 marca la desaparición de la mayoría de la microfauna del Cenomaniense. La desaparición de esta microfauna culmina a techo de la Capa F. El Nivel 2 marca la aparición de *Helvetoglobotruncana praehelvetica*. Adviértase la distribución de calciesferas entre la Capa H y la Capa F. Los hiatos se han marcado mediante una línea ondulada junto a la columna sedimentaria esquemática.
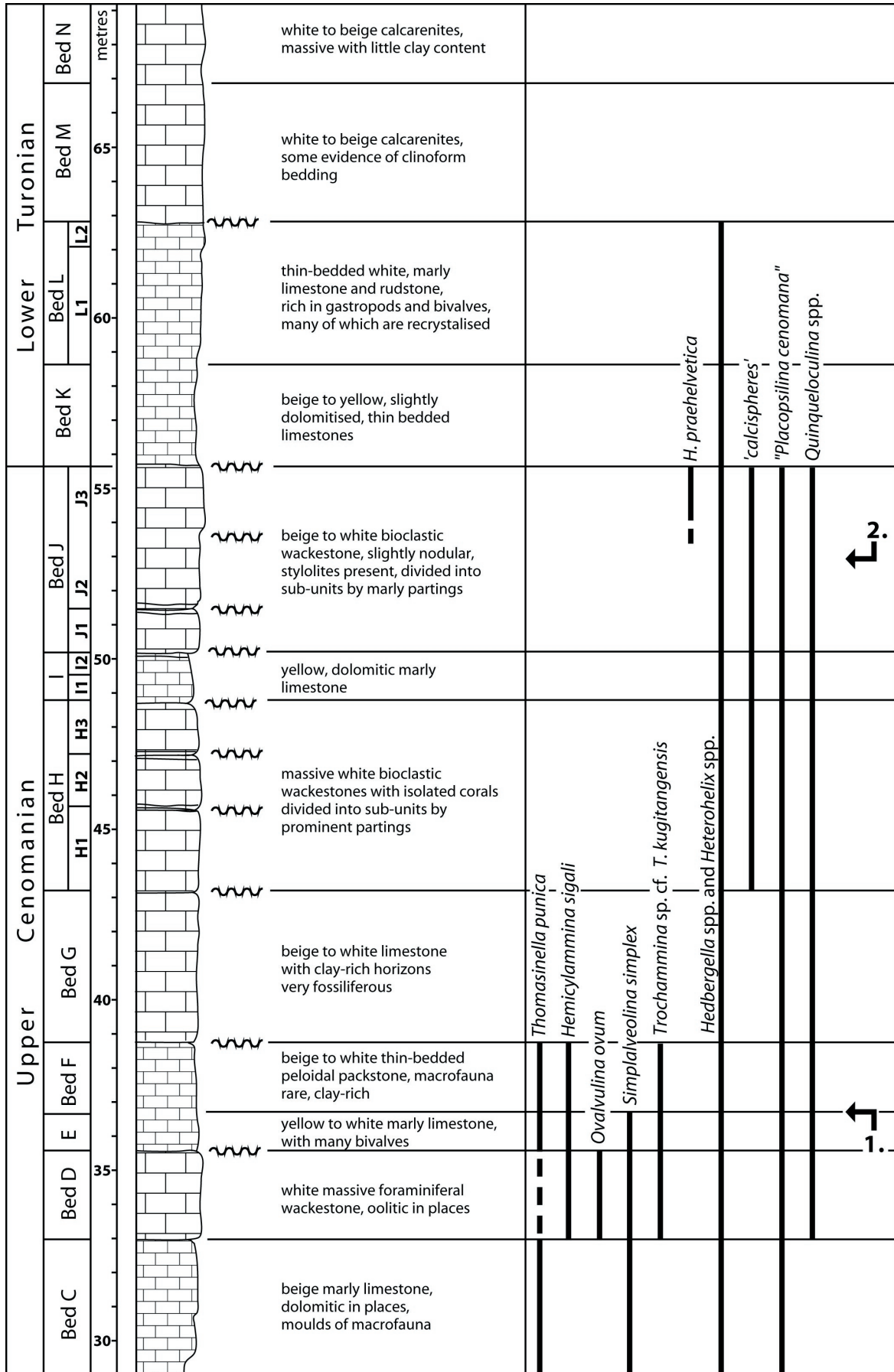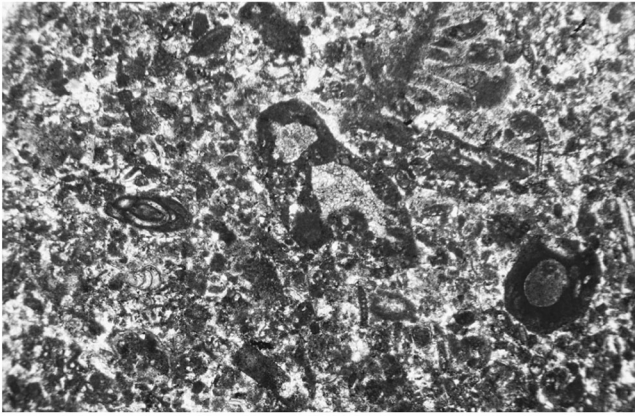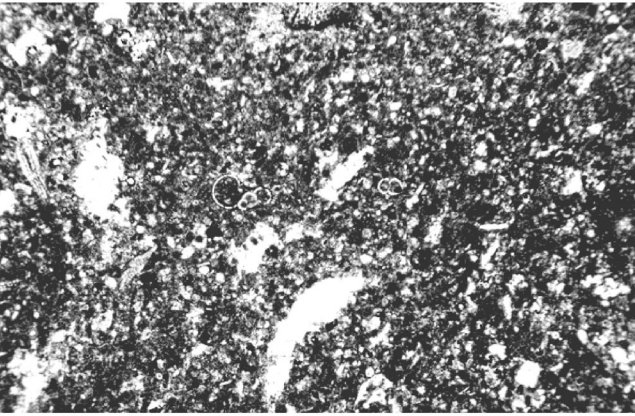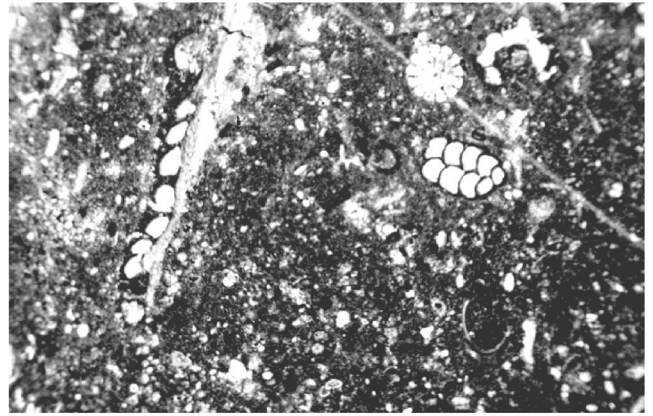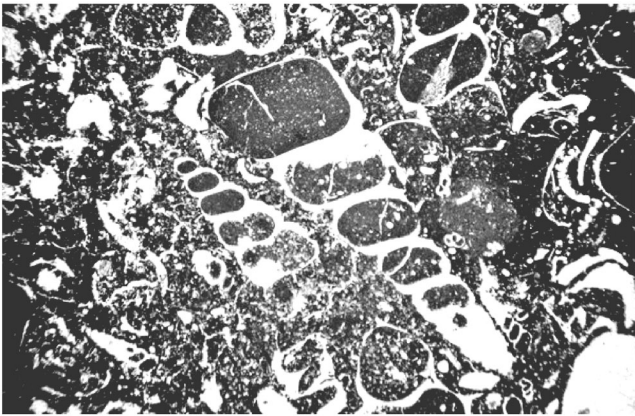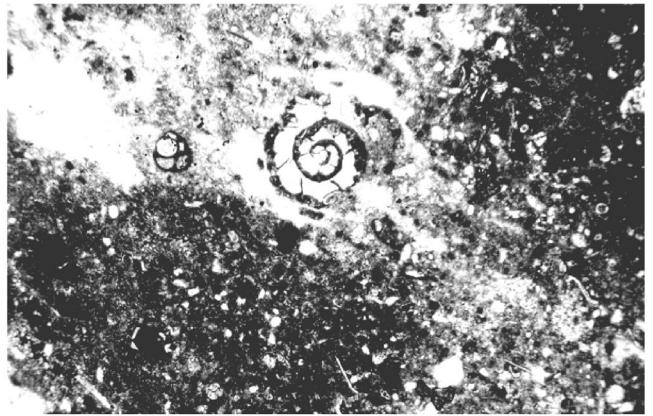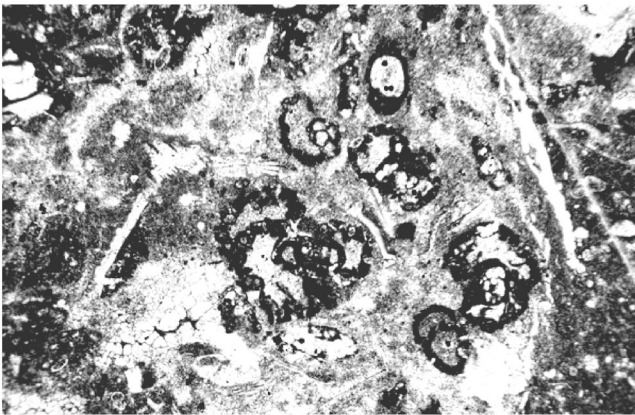
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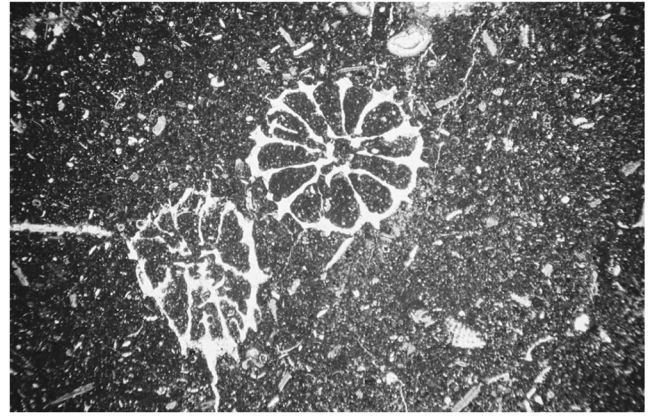
B

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E

F

G

H

abundant as illustrated by Hart (1991, fig.1), Jarvis *et al.* (1988, fig. 4(c, d, g, h)) and Caus *et al.* (1997, pl.1, fig. 4) the occurrence of abundant calcispheres has been related to the extinction events in the latest Cenomanian (Fig. 8). Kennedy and Simmons (1991, fig.4) also record an increase in calcispheres at about this level (listed as *Pithonella ovalis* and *Pithonella spherica*). This latest Cenomanian/earliest Turonian flood of calcispheres is exceptionally widespread in Europe, North Africa and the Middle East and is detected, as in Oman, within quite shallow water environments. Bed H, which is within the Juddii Zone (Fig. 4) lies within the interval (Fig. 8) in which calcispheres would be expected (see also Bed J).

Bed I is a bed of gray marl (Callapez, 1999; Lauverjat and Berthou, 1973-74, p.277) or marl limestone with abundant *Hemiaster scutiger*. This lithology was neither processable for microfossils nor lithified enough for thin sectioning.

Bed J is a white/beige bioclastic wackestone that is quite characteristic in appearance (Figs. 6C and 7D/E/F). The macrofauna includes rare ammonites and bivalves (including *Mytiloides*). In thin section there are abundant echinoid spines and fragmentary bryozoans. Foraminifera are quite rare, including *Marssonella oxycona, Quinqueloculina* sp., *Gyroidinoides* sp*., "Placopsilina cenomana"* and calcispheres. Small specimens of (?)*Helvetoglobotruncana praehelvetica* are also recorded and the association of this species with the occurrence of the calcispheres (see also Kennedy and Simmons, 1991, fig. 4, pl. 7, figs B, E, F) is quite characteristic of the Juddii Zone in many areas (e.g., Eastbourne, Fig. 8). The top surface of Bed J is an important unconformity and is marked by a palaeo-karst. Callapez (1998, 1999, fig. 5) indicates a hiatus between Bed J and Bed K, although Berthou (1984a, fig. 5) only shows this boundary as a gap in the succession.

Bed K is a yellow, marly dolomitic limestone with rare inoceramids (*Mytiloides*) that has not been thin sectioned. Field inspection indicated that the identification of a microfauna would be unlikely, if not impossible.

Bed L is a series of "platy" white rudstones with marl intercalations and an ammonite fauna with *Kamerunoceras* and *Fagesia* which appears to be correlative to the North American Rollandi Zone. In the field, concentrations of *Turritella* form the most obvious feature (Fig. 6E). Other bioclasts include echinoderm spines, rare calcispheres and infrequent ostracods. Foraminifera are also rare, including *Marssonella oxycona, Heterohelix globosa, Heterohelix moremani* and *Hedbergella/Whiteinella* sp. indet.. Benthic foraminifera are generally rare in Lower Turonian successions in NW - Europe (Hart and Bailey, 1979) and Bed L contains a typical assemblage for this stratigraphical level. In Southern England (Hart, 1982) this level in the Turonian would be characterised by the presence of *Helvetoglobotruncana helvetica, Dicarinella imbricata, D. marginata, Praeglobotruncana stephani, P. turbinata,* etc. (see also Caus *et al.*, 1997, fig. 5).

Beds M, N, and O consist of calcarenites with fragmentary corals, radiolitids and acteonellids. Foraminifera are rare and generally indeterminate in thin section. Mica increases in abundance up section and the succession terminates with off-white micaceous sandstones.

At other locations (Montemor-o-Velho, Costa d'Arnes, Tentúgal, Carrasqueira) in this area (Callapez, 1998, 1999) different facies can be studied. At Carrasqueira, for example, Beds 'K' and 'L' are dolomitic and while they contain quite amazing biostromes of *Radiolites peroni* they contain few, if any, stratigraphically useful foraminifera.

Fig. 6.– (opposite page) Thin section micro-photographs of representative lithologies and foraminifera. A. Bed F, peloidal packstone with *Ammobaculites* sp., *Quinqueloculina* sp., *Textularia* sp. and other species of smaller foraminifera. Field of view 6 mm; B. Bed H, bioclastic wackestone with scleractinian corals, echinoid spines and rare small planktic foraminifera. Field of view 6 mm; C. Bed 'J', bioclastic wackestone containing very small planktic foraminifera (*Hedbergella delrioensis* visible in the middle of the slide). Field of view 1.5 mm; D. Bed C, foraminiferal wackestone with "*Placopsilina cenomana*" encrusting a shell fragment. *Dorothia* sp., echinoid spines and small planktic foraminifera are also present. Field of view 1.5 mm; E. Bed L, rudstone with complete and fragmentary *Turritella*. Associated with the turritellids are echinoid spines and small planktic foraminifera. Field of view 6 mm; F. Bed C, foraminiferal wackestone with *Hemicyclammina sigali*. Field of view 6 mm ; G. Bed C, foraminiferal wackestone with *Ammobaculites* sp. and *Hemicyclammina sigali*. Field of view 6 mm ; H. Bed C, foraminiferal wackestone with *Thomasinella* (?)*punica* associated with small planktic foraminifera. Field of view 6 mm.

Fig. 6.– (página opuesta) Fotografías a partir de láminas delgadas de las litologías y foraminíferos más representativos. A. Capa F, *packstone* peloidal con *Ammobaculites* sp., *Quinqueloculina* sp., *Textularia* sp. y otras especies de foraminíferos de menor tamaño. Campo de visión 6 mm; B. Capa H, *wackestone* bioclástico con corales escleractinios, espinas de equinoideos y escasos foraminíferos planctónicos pequeños. Campo de visión 6 mm; C. Capa J, *wackestone* bioclástico con foraminíferos planctónicos de muy pequeño tamaño (*Hedbergella delrioensis* en el medio de la imagen). Campo de visión 1,5 mm; D. Capa C, *wackestone* de foraminíferos con "*Placopsilina cenomana*" incrustando un fragmento de concha, junto con *Dorothia* sp., espinas de equinoideos y pequeños foraminíferos planctónicos. Campo de visión 1,5 mm; E. Capa L, *rudstone* con ejemplares de *Turritella* enteros y fragmentados. Junto con los turritélidos se han observado también espinas de equinoideos y pequeños foraminíferos planctónicos. Campo de visión 6 mm; F. Capa C, *wackestone* de foraminíferos con *Hemicyclammina sigali*. Campo de visión 6 mm ; G. Capa C, *wackestone* de foraminíferos con *Ammobaculites* sp. y *Hemicyclammina sigali*. Campo de visión 6 mm ; H. Capa C, *wackestone* de foraminíferos con *Thomasinella* (?) *punica* junto con pequeños foraminíferos planctónicos. Campo de visión 6 mm.
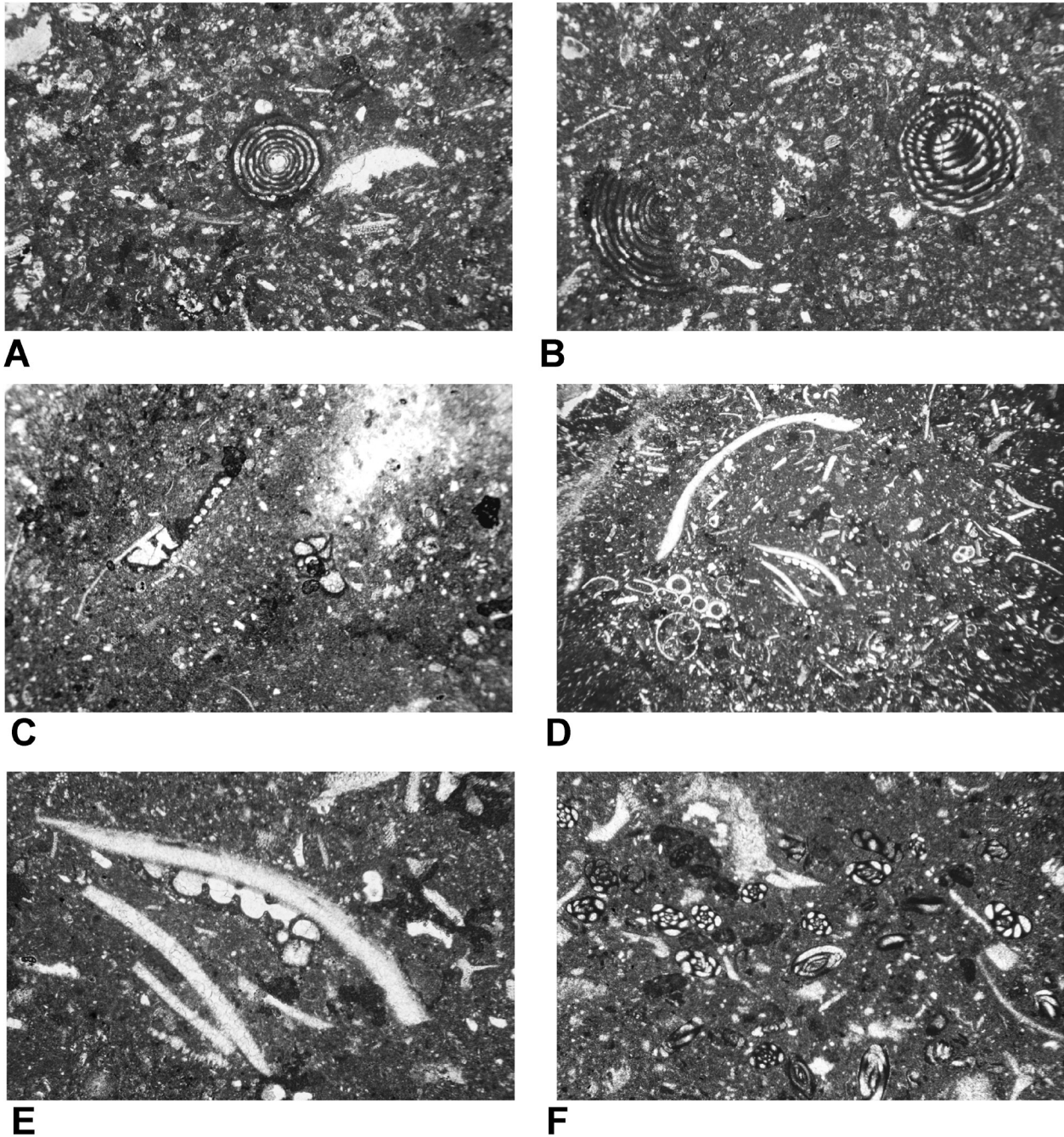
Fig. 7.– Thin section micro-photographs of representative lithologies and foraminifera. A. Bed C, foraminiferal wackestone with *Simplalveolina simplex*. Field of view 6 mm; B. Bed C, foraminiferal wackestone with *Simplalveolina simplex* and *Ovalvulina ovum*. Field of view 6 mm; C. Bed C foraminiferal wackestone with "*Placopsilina cenomana*" overhanging a very small shell fragment. Field of view 6 mm; D. Bed J at Tentúgal. Foraminiferal wackestone with bivalve fragments, serpulids and "*Placopsilina cenomana*". Field of view 6 mm; E. Bed J at Tentúgal. Foraminiferal wackestone with a close-up of the "*Placopsilina cenomana*" visible on the shell fragment in Fig.7E and showing the agglutinated wall structure. Field of view 1.5 mm; F. Bed J at Nazaré. Foraminiferal wackestone with abundant *Quinqueloculina* spp. and *Nautiloculina* spp.. Field of view 1.5 mm.

Fig. 7.– Fotografías a partir de láminas delgadas de las litologías y foraminíferos más representativos. A. Capa C, *wackestone* de foraminíferos con *Simplalveolina simplex*. Campo de visión 6 mm; B. Capa C, *wackestone* de foraminíferos con *Simplalveolina simplex* y *Ovalvulina ovum*. Campo de visión 6 mm; C. Capa C, *wackestone* de foraminíferos con "*Placopsilina cenomana*" que resalta sobre un fragmento muy pequeño de concha. Campo de visión 6 mm; D. Capa J en Tentúgal. *Wackestone* de foraminíferos con fragmentos de bivalvo, serpúlidos y "*Placopsilina cenomana*". Campo de visión 6 mm; E. Capa J en Tentúgal. *Wackestone* de foraminíferos en el que se ve un primer plano de "*Placopsilina cenomana*" sobre el fragmento de concha de la Fig.7E en el que se puede apreciar la estructura de su pared aglutinada. Campo de visión 1.5 mm; F. Capa J en Nazaré. *Wackestone* de foraminíferos con abundantes ejemplares de *Quinqueloculina* spp. y *Nautiloculina* spp.. Campo de visión 1.5 mm.

4. The Late Cenomanian Event

4.1. Rio Mondego

As indicated above, the co-occurrence of abundant calcispheres and *Helvetoglobotruncana praehelvetica* stratigraphically above the disappearance of typically Cenomanian foraminifera clearly points to the presence of the latest Cenomanian extinction event. Figure 8 shows the characteristic features of the Upper Cenomanian – Turonian succession at Eastbourne (Sussex, U.K.). The extinction of the *Rotalipora* lineage is quite characteristic of many locations elsewhere in the U.K. (Jarvis *et al.*, 1988) and this has been confirmed by subsequent work (Morel, 1998; Paul *et al.,* 1999; Keller *et al.,* 2001). In the Rio Mondego succession such stratigraphical markers are missing and it is quite difficult to make direct comparisons. *Helvetoglobotruncana helvetica*, which appears just above the base of the Turonian (drawn at the base of the Devonense Zone), is a deep water taxon and would not be expected in such shallow water environments. The main extinction event(s) would be expected to occur at the level of Beds H, I and J. If this is the case, then what is the cause of the hiatus between Beds J and K? Is it, for example, the first signs of basin inversion? In such shallow-water environments the scale of such an event would have been extremely small; creating no more than a hiatus in the sedimentation during the overall global highstand. This event was probably associated with movements along the main diapiric axes, including those of Caldas da Raihna and São Pedro de Muel. The brecciated limestones of the Praia da Vitória succession (see below and Fig. 9) are probably related to movement of the São Pedro de Muel diapir. The uplift across the hiatus (Beds J – K) is more evident in the south, closer to the "Nazaré Fault" (see Fig. 2).

4.2. Nazaré

To the south of Figueira da Foz is the fishing village and holiday centre of Nazaré (Fig. 2). To the immediate north of the main beach and town centre is a major cliff of Cenomanian limestones (Callapez, 1999, fig. 24). Much of this section is quite difficult to access but the uppermost Cenomanian and lowermost Turonian are exposed immediately north of the lighthouse and fort on the headland of Pedro do Guilhim. The upper part of Bed J (Fig. 7D) is exposed at beach level near two small caves. The top surface of Bed J is again represented by an important unconformity/palaeokarst which is, in turn, overlain by Beds L – O, which at this locality are represented by micaceous limestones and yellow cross-bedded sandstones.

These are overlain by grey to white coarse, fluvial/alluvial sandstones of (?) Turonian-Santonian-Campanian age. Though complicated, the Pedra do Guilhim succession provides little new evidence of the Bed J – K hiatus, or the latest Cenomanian extinction event.

4.3. Praia da Vitória

Approximately 10 km north of Nazaré is Praia da Vitória, a long beach backed by a small group of houses and holiday accommodation. One kilometre south along this beach is a major cliff, at the bottom of which is a locality described by Monteiro *et al.* (1998a, b). This succession includes what has been suggested as an "ejecta layer", an iridium anomaly, spherules and a wide range of basement exotics. Of particular note are rounded blocks of fresh basalt up to 85 cm in diameter. The critical horizons are intermittently exposed beneath the active beach sands and the whole area can change in appearance during one tidal cycle. Figure 9 shows a measured section of the key part of the succession. The *in-situ* inner shelfal carbonates are of mid-Late Cenomanian age (Callapez, 1998) on the basis of the macrofauna. The microfauna though not stratigraphically diagnostic by itself, would confirm this dating. The *in-situ* carbonates are sharply overlain by a monomictic breccia, which cross cuts a number of beds in a distinctive manner. The blocks in this monomictic breccia are all local limestones and several contain macrofossils (including some large fragments of Cenomanian *Caprinula*). Within the top metre of this breccia (Fig. 9) is the "ejecta horizon", a complex bed of Lower Jurassic and Cretaceous limestone fragments, cherts, sandstones, assorted metamorphic rocks, iron oxide clasts, diaplectic glass and large (80-85 cm diameter) rounded blocks of fresh olivine basalt. Monteiro *et al.* (1998a, b) have described the glass and other spherules in some detail and have presented a number of geochemical analyses from samples collected from the locality. Of particular interest is the overlying soft grey clay/silt which records a slightly enhanced level of iridium. This clay/silt is overlain by a massive succession of coarse grey sandstones that appear to represent a series of major distributary channel sands. In the base of this sandstone unit is a level of reworked clasts of clay and siltstone. Neither the bed of clay/silt, the reworked sediment clasts nor the sandstones have yielded any microfauna or significant microflora.

No horizon comparable to the "ejecta horizon" is seen at any other locality in the area and this fact, coupled with the nature of the contained blocks, glasses, spherules and the geochemistry led Monteiro *et al.* (1998a, b) to conclude that this could be a potential cause of the latest Cenomanian extinction event; the result of an impact
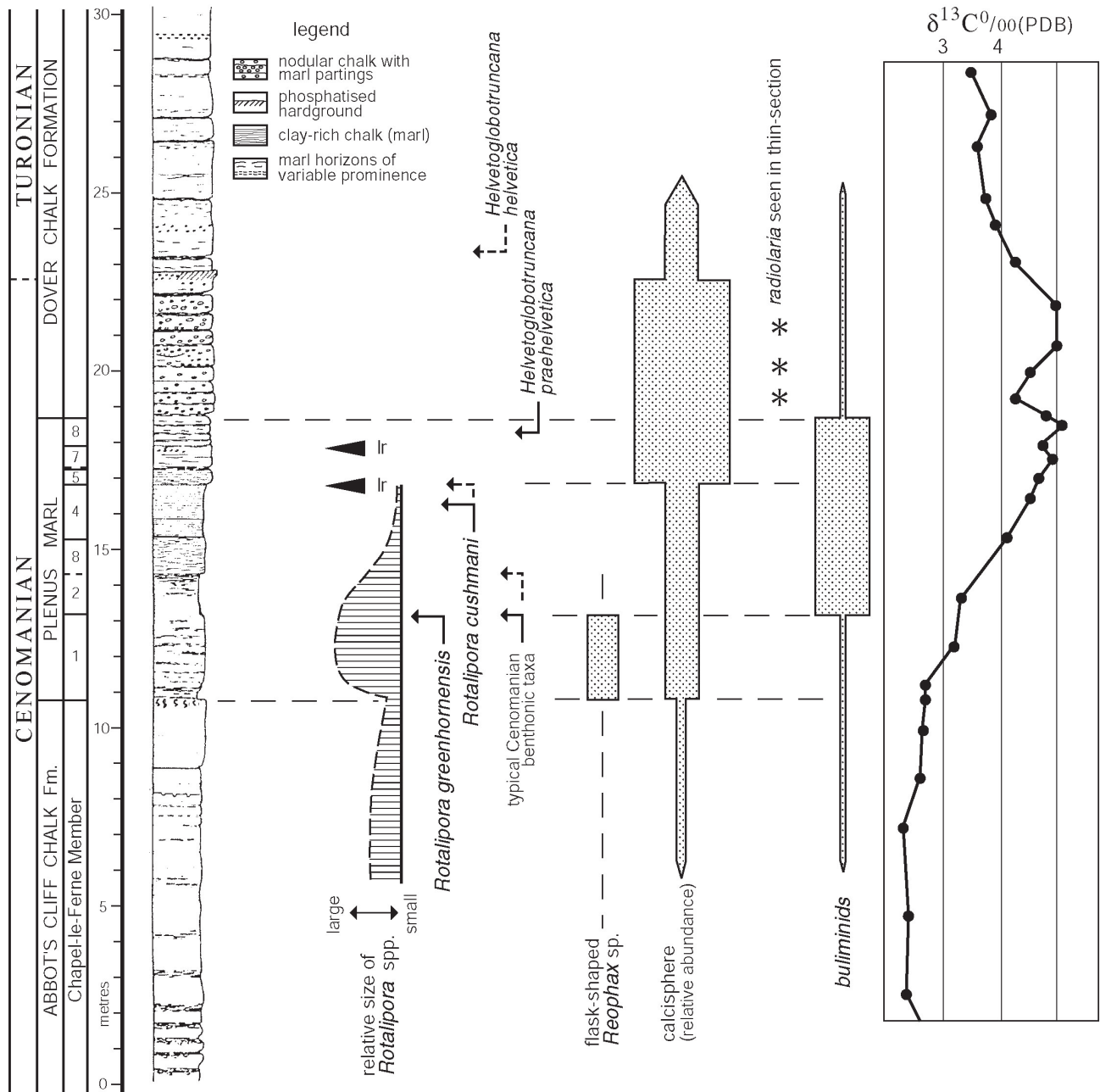
Fig. 8.– Lithostratigraphy, micropalaeontological data and carbon isotope data for the Cenomanian-Turonian boundary succession at Eastbourne, United Kingdom. Figure modified after Hart *et al.* (2002).

Fig. 8.– Litoestratigrafía, datos micropalentológicos y de los isótopos de carbono de la sucesión que incluye el límite Cenomaniense-Turoniense en Eastbourne, Reino Unido. Figura modificada de Hart *et al.* (2002).

in the vicinity of the Tore Sea Mount (Laughton *et al.*, 1975). The *in-situ* carbonates are dipping towards the SE with the strike direction SW/NE. It was this direction – pointing almost directly towards the Tore Sea Mount – that led Monteiro *et al.* (1998a, b) to propose that location as the potential impact site.

Immediately to the north of the succession shown in Figure 9 is a complex outcrop of evaporites, yellow to grey limestones and dark shales. The limestones and shales are reminiscent of the local Hettangian succession and we have interpreted this anomalous outcrop as being the edge of a salt diapir (see Fig. 2). Intra-Cenomanian movements of a salt diapir might explain the disturbance of the strata seen in the monomictic breccia but could not fully explain the "ejecta horizon". The basalt boulders and other exotics are all rounded and appear to have been

water transported. The size of the basalt boulders also implies a relatively close source (certainly not the distance to the Tore Sea Mount). There are Late Cretaceous volcanics in the Lisbon area and there are two isolated outcrops of olivine-rich basalt at Nazaré. As these basalts cut Turonian sediments (Callapez, 1999) they must be younger in age. There are, however, other olivine basalts of Late Jurassic or Early Cretaceous age in a number of areas onshore that are associated with the second rifting phase within the basin. Some of these may have been exposed at this time as a result of diapiric movements in the basin. While of great interest, the "ejecta horizon" does not appear to be evidence of a latest Cenomanian impact and the cause of the extinction event. In their work on the structure of the Lusitanian Basin, Proença Cunha and Pena dos Reis (1995, fig. 3) indicate the presence of salt diapirism in the mid-Aptian, mid-Turonian and early Maastrichtian (associated with movements on the "Nazaré Fault"). They also show that, in the Late Campanian to Maastrichtian, there was both intrusive and extrusive volcanism in the area. At the present time we do not have the biostratigraphic control to relate the Praia da Vitória monomictic breccia to a specific diapirism event and have no radiometric age information on the basalts contained within the "ejecta horizon".

Further work on the Praia da Vitória succession is in progress, though the microfaunas recovered from the limestones give little evidence for a precise dating for the succession. The sandstones above the grey clay/silt layer have also yielded very poor, non-diagnostic, palynofloras and no calcareous microfossils.

How the Praia da Vitória events relate to the hiatus in the Rio Mondego succession is also unclear. Is the Bed J – Bed K hiatus the result of diapirism in that area? Proença Cunha and Pena dos Reis (1995) do not record any movements at that level, although the mid-Turonian dating for some of their events may be within their stratigraphical resolution. If one compares the Rio Mondego succession to that in the Western Interior Seaway of North America the problem is even more challenging. In a detailed analysis, West *et al.* (1998, figs 2 and 8) indicate that the Devonense Zone was a 3rd–Order highstand. One would, therefore, have expected either deposition of some sediments during that interval or the presence of an erosive surface indicative of a transgressive event. The Rio Mondego succession, with an eroded surface and palaeo-karst is suggestive of a regressive event. The Bed J – K hiatus appears, therefore, to be a local event, even though the overall Upper Aptian to Lower Campanian "megasequence" implies a response to global sea level change.
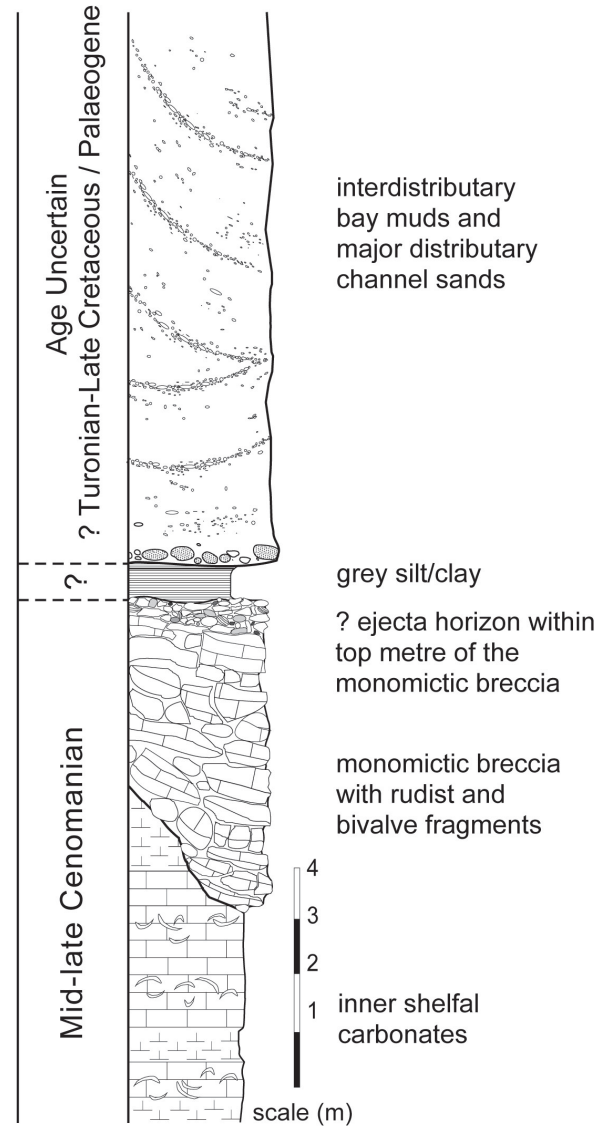

Fig. 9.– Sedimentary log of part of the succession at Praia da Vitória showing the monomictic breccia, the "ejecta horizon" and the overlying bed of grey silt/clay and the coarse sandstones. The sands above the clay layer are most probably a local equivalent of the Oiã Sandstone Formation (of Late Turonian to Coniacian age) shown in Figure 3. The monomictic breccia contains fragments of Beds B, C, D, G and H (see Figure 5).

Fig. 9.– Corte de parte de la sucesión en Praia da Vitória que muestra la brecha monomíctica, el "horizonte de ejecta" y la capa suprayacente de limos/arcillas grises y areniscas gruesas. Las arenas por encima de la capa de arcillas son probablemente un equivalente local de la Formación de Arenas de Oiã (Turoniense superior – Coniaciense) mostrada en la Figura 3. La brecha monomíctica contiene fragmentos de las Capas B, C, D, G y H (ver Figura 5).

5. Conclusions

The Cenomanian-Turonian carbonate succession of the Western Portuguese Margin preserves a shallow water record of the latest Cenomanian extinction event. Few descriptions are available of such a succession through this

interval as most workers on this event have concentrated on localities with open shelf to open oceanic sequences that are rich in planktic microfaunas and microfloras, and which often contain organic rich sediments. In the Rio Mondego succession, none of the normal foraminiferal marker species are present and, instead, there is a record of a wide range of benthic taxa. The 'calcisphere' event appears to be present, but the neobuliminids and gavelinellids used by other authors at this level (West *et al.,* 1998) are not recorded. How the microfaunal events described from the Rio Mondego succession relate to the unusual succession at Praia da Vitória remains to be determined.

Acknowledgements

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