Mid-Cenomanian separation of Atlantic and Tethyan domains in Iberia by a land-bridge: The origin of larger foraminifera provinces?

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A B S T R A C T

The Middle and Late Cretaceous shallow-water carbonate platforms widely exposed across the eastern half of the Iberian Peninsula including the Betic Cordillera, the Iberian Ranges and the Pyrenees provides an excellent material for analyzing the origin of two Iberian Late Cretaceous larger foraminifera provinces, the Betic and the Pyrenean: the former corresponds to the Tethyan domain, the latter to the Atlantic domain. The spatiotemporal distribution in the three studied areas of the larger foraminifera k-strategists, the Alveolinaceans, from the latest Albian–Cenomanian time interval suggests that separation of the two faunal provinces started during Early Cenomanian (mid-Cretaceous Global Community Maturation cycle), and the shelves of the Iberian seaway formed the boundaries of the corresponding bioprovinces. This occurred before the Betic–Pyrenean communication near the Middle–Late Cenomanian transition was interrupted by a land-bridge. Therefore, the separation of the two bioprovinces cannot be due to the physical barrier created by the opening or closure of the shallow seaway across the Iberia: here it is attributed to the differences in the ecological gradients. At the end of the Cenomanian, the Cenomanian–Turonian eutrophication event eliminated all the k-strategist larger foraminifera to such a degree that all their essential k-strategy information was lost. The newly arising k-strategist foraminifera needed a considerable time (8–10 m.y.) to recover their lost genetic complexity: this occurred during the Coniacian in the following GCM cycle.

Keywords:
Larger foraminifera
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Middle and late Cretaceous
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1. Introduction

Understanding the geographic distribution of biota in the past and the origin of bioprovinces has been the main ambition of zoologists, botanists and palaeontologists since the XIX Century. From the second half of the last century, with the introduction of the plate-tectonics theory, a revival in palaeobiogeographical studies took place. Many important questions about extinct organisms and their distribution through geological times at least for the last 200 m.y., were answered. Nevertheless, many interpretations remained unclear and are still debated for example, what events cause the provinciality of organisms, how bioprovinces change in range and rank through time, and what is the nature of the barriers limiting these bioprovinces?

The present paper focuses on the origins of the Late Cretaceous larger foraminifera provinces on Iberia, which was placed between the opening Atlantic Ocean and the gradually closing Western Tethys. Iberia has a particularly favourable geographical situation for analysing the separation of two bioprovinces: Betic and Pyrenean (Caus and Hottinger, 1986). The former belongs to the Tethyan domain, the latter to the Atlantic domain. Those bioprovinces respectively developed in the Southern and the Northern continental margins of Iberia, despite their proximity, they were well individualised during the Late Cretaceous because of the palaeogeographic configuration of Iberia in the framework of Europe–Africa convergence. However, during the Cretaceous, both basins were episodically interconnected by a shallow seaway that developed through Iberia via the Iberian intracontinental basin, which could conform an intermittent feature for N–S faunal exchange. This paper endeavours to answer the question: why did separation occur, was it due to palaeogeographical changes, global oceanic circulation and/or ecological gradients?

Larger foraminifera are a group of organisms useful for palaeobiogeographical studies because:

I. They are giant eukaryotic cells (which can reach several cm in diameter), k-strategists organisms, fixing their shape permanently in a calcareous mineralised shell built by successive steps of growing (chambers), that registers the ontogeny of each specimen.
II. The complexity of the shell permits the application of methods of comparative anatomy to differentiate characters linked to evolutionary processes, which can be used for age determining

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in biostratigraphy, as well as the study of functional characters, that can be used for interpreting palaeoenvironments.

III. They are abundant in numerous ecosystems including all recent carbonate and mixed carbonate-siliciclastic platforms from littoral areas to the lower limit of the photic zone (particularly symbiont-bearing foraminifera), the oligotrophic-to-mesotrophic environments of the tropical-to subtropical seas as well as the corresponding ecosystems and environments of past oceans and seas.

IV. The shells of larger foraminifera have diagnostic structures sufficient to be identified, at least at the generic level but frequently at the specific, directly from random sections of rock samples, which is critical for the study of hard rocks or bore-hole material.

Evidence of larger foraminifera exists from the Late Carboniferous to today illustrating the repetitive rise of k-strategist foraminifera during the Earth's history (Hottinger, 1982; 2001) in so-called Global Community Maturation (GCM) cycles. These are periods of continuous and gradual biotic change between two global environmental discontinuities that destroy the respective genetic information necessary to produce k-strategists.

Our study is based on the spatiotemporal distribution of larger foraminifera from the latest Albian to the top of the Cenomanian (mid-Cretaceous GCM cycle), which is separated from the Late Cretaceous GCM cycle, by the Cenomanian–Turonian eutrophication event (Hottinger, 2001). The work was carried out on well developed shallow-water carbonate platforms widely exposed across the eastern half of the Iberian Peninsula, including the Betic Cordillera, the Iberian Range and the Pyrenees (Fig. 1). These areas respectively correspond to the ancient Southern Continental margin of Iberia (or Betic margin), the Pyrenean basin, and the Iberian basin.

Taking into account the previous stratigraphic work carried out by the authors in these zones, three areas have been selected for this study, one in each basin. These are the Jumilla–Yecla region in the Prebetic Zone (in the External Betics), the central-eastern part of the Iberian Ranges, and the Central South-Pyrenean Unit. Additional data from other areas has been also considered.

2. Palaeogeographical setting

In the mid-Cretaceous time, Iberia corresponded to a small and independent plate (the Iberian plate) located between Africa and Eurasia approximately between 25° and 30° North latitude, with a tropical to subtropical climate. Based on paleoclimatic proxies, the average of the surface temperature of the sea for the studied area varies from 24 °C to 31 °C (Pucéat et al., 2003; Steuber et al., 2005).

The mid-Cretaceous was an unusually rapid seafloor spreading on a global scale, producing high mid-ocean ridges, which displaced water out of the ocean basins to cause the largest transgressive episodes since early Palaeozoic times (e. g. Hallam, 1992; Hardenbol et al., 1998). These high mid-Cretaceous sea levels resulted in marine flooding of wide areas across Iberia. In the resulting extensive shallow marine environments oligotrophic regimes rapidly developed that facilitated the onset of carbonate platforms colonised by k-strategist larger foraminifera.

Beyond the global sea-level rise, the palaeogeography of Iberia was influenced by relative movements of the two great contiguous plates: Africa and Eurasia. The Early Cretaceous was characterised by generalised extensional tectonics in relation to the Liguria, Atlantic and Bay of Biscay rifts, and a decrease in relative sinistral motion between Iberia and Africa (Ziegler, 1988). Three main basins (Betic, Iberian and Pyrenean) originated in Triassic and Jurassic times in response to continental break-up were related to Iberia: two of them (Betic and Pyrenean) were placed at the southern and northern margins of the Iberian plate, respectively: the Iberian basin was an intra-continental basin that episodically acted as a shallow seaway allowing direct marine connection between the other two basins.

During mid-Cretaceous times, Iberia moved in a 35-degree counterclockwise rotation relative to Europe in response to sinistral transtensional movements occurring between Africa and Europe (e.g., Savostin et al., 1986; Ziegler, 1988). Seafloor spreading took place along the axes established from Aptian times in the Bay of Biscay and the North Atlantic. Also at this time, convergence between Africa and Iberia had started, as reflected by mid-Cretaceous high pressure metamorphism recorded in the Internal Betics. Related to this geodynamic evolution, some changes in subsidence and basin configuration occurred in Iberia during the mid-Cretaceous. The most relevant occurred during the Middle to Late Cenomanian transition, when a generalised tilt of the Iberian plate towards the NW took place, accompanied by important changes in the configuration of the sedimentary basins (e. g., Martín-Chivelet et al., 2002). Palaeogeographical reconstructions (Fig. 2) show the Iberian intra-continent basin as a seaway connecting the Atlantic Ocean (Bay of Biscay) and the Western Tethys during most of the Early and Middle Cenomanian. However, near the Middle–Upper Cenomanian transition, the flexural behaviour of the Iberian lithosphere caused a relative sea-level fall and a regional episode of subaerial exposure across most Iberian shallow marine areas (Giménez, 1987; Martín-Chivelet and Giménez, 1993). Consequently, the former Pyrenean–Betic communication was interrupted.

During the Late Cenomanian–Turonian, increased subsidence and sea-level rise determined a broad and rapid transgression from the Atlantic that flooded the entire Iberian basin from northwest to

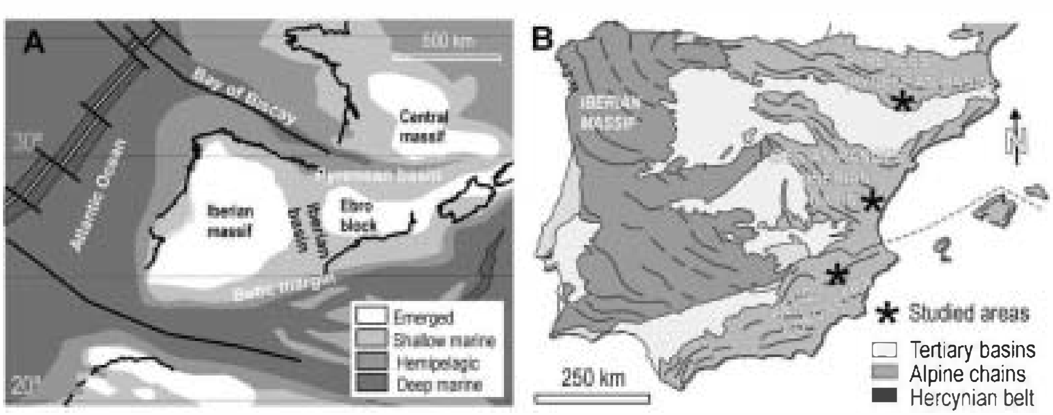


Fig. 1. A. Palaeogeographical map of Iberia and surrounding areas during the Cenomanian (modified from Philip and Floquet, 2000). Note the location of the Pyrenean basin, the Iberian basin, and the Betic margin (or Southern Iberian Continental Margin). B. General map of the Iberian Peninsula showing its main geological units and the location of the studied areas.

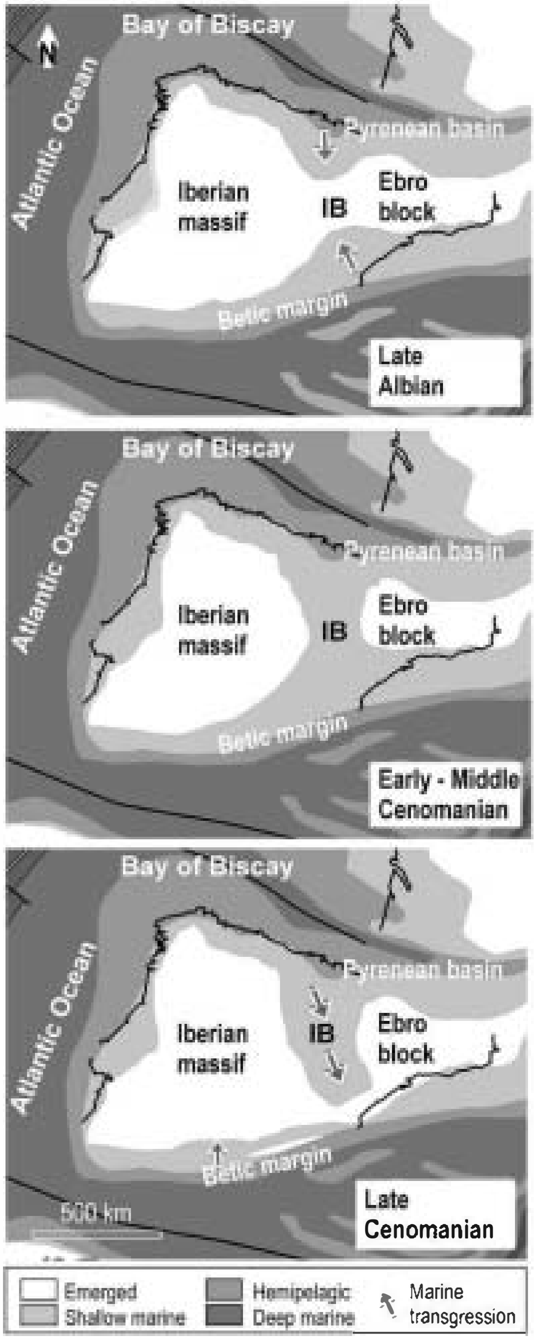


Fig. 2. Palaeogeographic maps for the Late Albian, the Early and Middle Cenomanian, and the Late Cenomanian. Based on Alonso et al. (1993), Martín-Chivelet (1995), Philip and Floquet (2000) and unpublished data.

southeast, with the exception of the southernmost part (García et al., 1993; Alonso et al., 1993). Southwards, the Betic margin experienced a period of regional tectonic activity – related to changes in the intraplate stresses of Iberia – which gave rise to abrupt topographic changes in the basin that may have limited the spatial development of carbonate platforms (Martín-Chivelet, 1995). These small platforms were connected to the open marine conditions of the Tethys towards the southeast. During the Late Cenomanian and Turonian worldwide open marine conditions, the communication between the Betic and Pyrenean basins was interrupted definitively: in the north, the Pyrenean basin penetrated from the open Atlantic far into Western Europe, but closed towards the Western Tethys in the south. The Betic basin opened eastwards to the Tethys.

3. Stratigraphical framework

In the three considered basins, regional stratigraphic work carried out during the last decades by the authors and other research teams has shown the existence of two major genetic units for the Late Albian to Cenomanian interval (for details see reviews in Caus et al., 1993; Martín-Chivelet et al., 2002; Vera, 2004). These are respectively uppermost Albian to Middle Cenomanian and Upper Cenomanian in age, and are referred in this paper as the *lower* and the *upper cycle*. The *lower cycle* was deposited during the prolonged sea-level rise that caused a multi-episode transgression in the three basins and that culminated, during the Early (but not earliest) and the Middle Cenomanian, in a well established marine communication between the Pyrenean and the Betic margins via the Iberian basin, which acted as a broad seaway (Fig. 2). The end of that *lower cycle* is defined by a major unconformity that reflect drastic changes in the configuration of the three basins, and that determined the closure of the marine connection through the Iberian seaway. The *upper cycle*, generated during the Late Cenomanian reflects a sedimentation that took place without the former marine connection between the northern and southern continental margins via the Iberia basin. The generalised tilting of Iberia towards the NW and the related regional tectonism determined a relative fall in sea-level the southern part of the Iberian basin and the termination of the previous Pyrenean–Betic marine communication. The cycle reflects a rapid and broad marine transgression coming from the Atlantic in the rapidly subsiding Pyrenean and Iberian basins, and a more limited transgressive event in the Betics, where local tectonic block movements determined the development of narrow carbonate platforms in the areas where accommodation space was favourable.

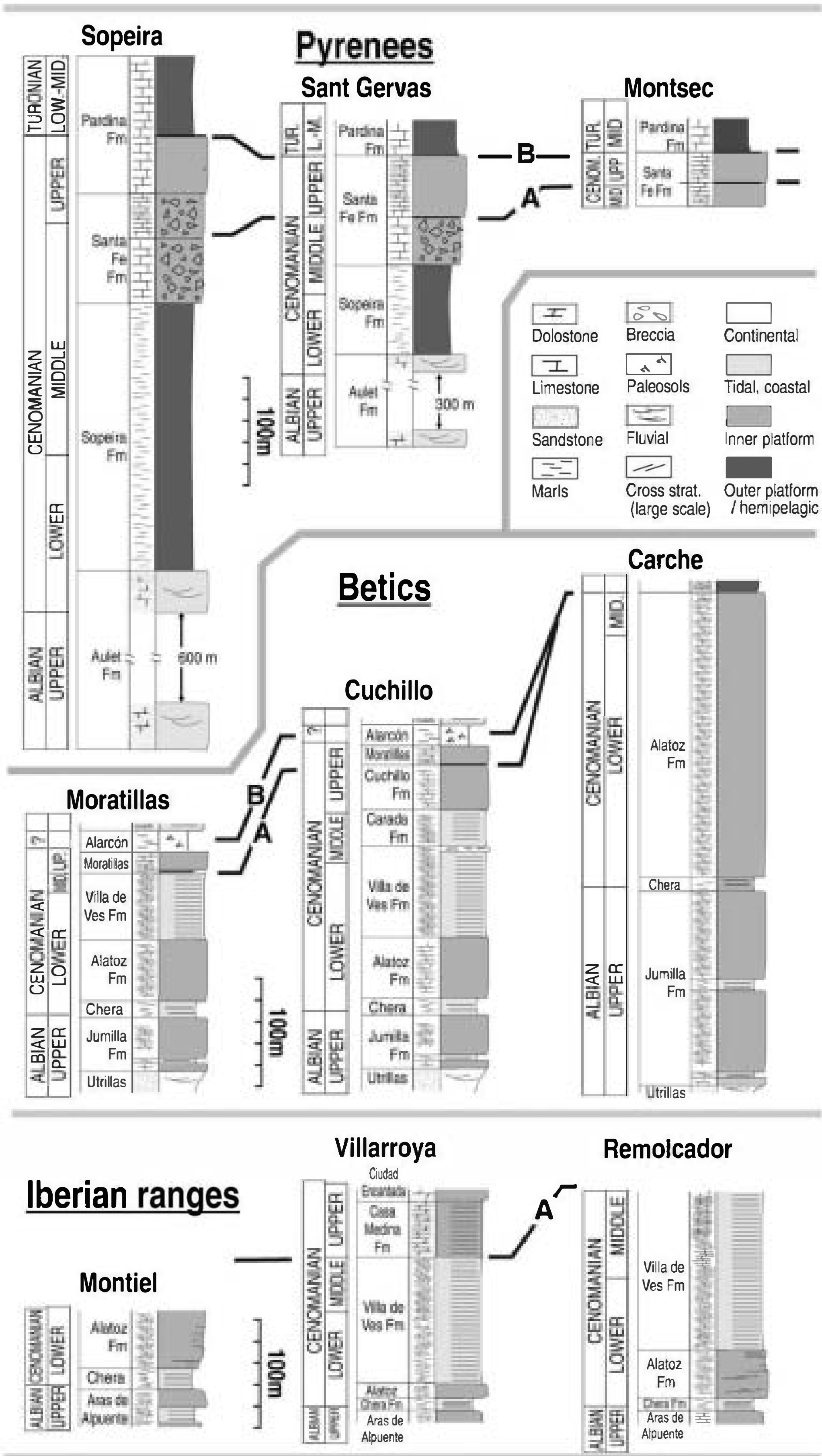
The local stratigraphy and the characteristic benthic foraminifera of each of the studied areas are the following.

3.1. Betic Cordillera

Within the Betics, platform carbonates of the latest Albian–Cenomanian age are only found in the Prebetic Zone, a broad domain that corresponds to the outer portion of the foreland fold-and-thrust belt of the Betic Cordillera. The Prebetic includes a thick para-autochthonous sedimentary cover of the Mesozoic–Cenozoic age, essentially dominated by shallow marine deposits that were generated in the proximal areas of the ancient southern continental margin of Iberia. Fig. 3 shows three sections of those deposits in the Jumilla–Yecla area, which has been chosen as representative of the Prebetic. The palaeontological data summarized in Fig. 4 come from these and other sections of the Prebetic Platform. The *lower cycle* is represented in the area by two successive genetic units bounded by regional unconformities (Martín-Chivelet, 1995; 1996). The first unit includes five formations, from base to top:

I. Utrillas Formation (10–80 m thick). This unit consists of quartz sands and sandstones which show sedimentary structures and architectural elements typical of low sinuosity rivers and low accommodation rate intervals. These fluvial deposits rest unconformably on rocks of ages ranging from Jurassic to Middle Albian. Basinwards and upwards, the sands grade into the heterolithic deposits of the Jumilla Formation. This unit is attributed to the Upper Albian.
II. Jumilla Formation (2–250 m thick). This unit consists of carbonates (often dolomitized), marls and sands. It can be subdivided into three carbonate sub-units separated by two

Fig. 3. Schematic logs of the stratigraphic sections herein considered as the most representative of the studied areas (Pyrenees, Betics and Iberian Ranges). These logs show the main lithostratigraphic units, stratigraphic unconformities and the dominant depositional systems.



Pyrenees
Sopeira
Sant Gervas
Montsec
Betics
Carche
Cuchillo
Moratillas
Iberian ranges
Villarroya
Remolcador
Montiel
Dolostone
Breccia
Continental
Limestone
Paleosols
Tidal, coastal
Sandstone
Fluvial
Inner platform
Marls
Cross strat. (large scale)
Outer platform / hemipelagic
TURONIAN
CENOMANIAN
ALBIAN
LOWER
MIDDLE
UPPER
LOW-MID
Pardina Fm
Santa Fe Fm
Sopeira Fm
Aulet Fm
600 m
300 m
100m
A
B
Alarcón
Moratillas
Cuchillo Fm
Canada Fm
Villa de Ves Fm
Alatoz Fm
Chera
Jumilla Fm
Utrillas
Ciudad Encantada
Casa Medina Fm
Chera Fm
Aras de Alpuente

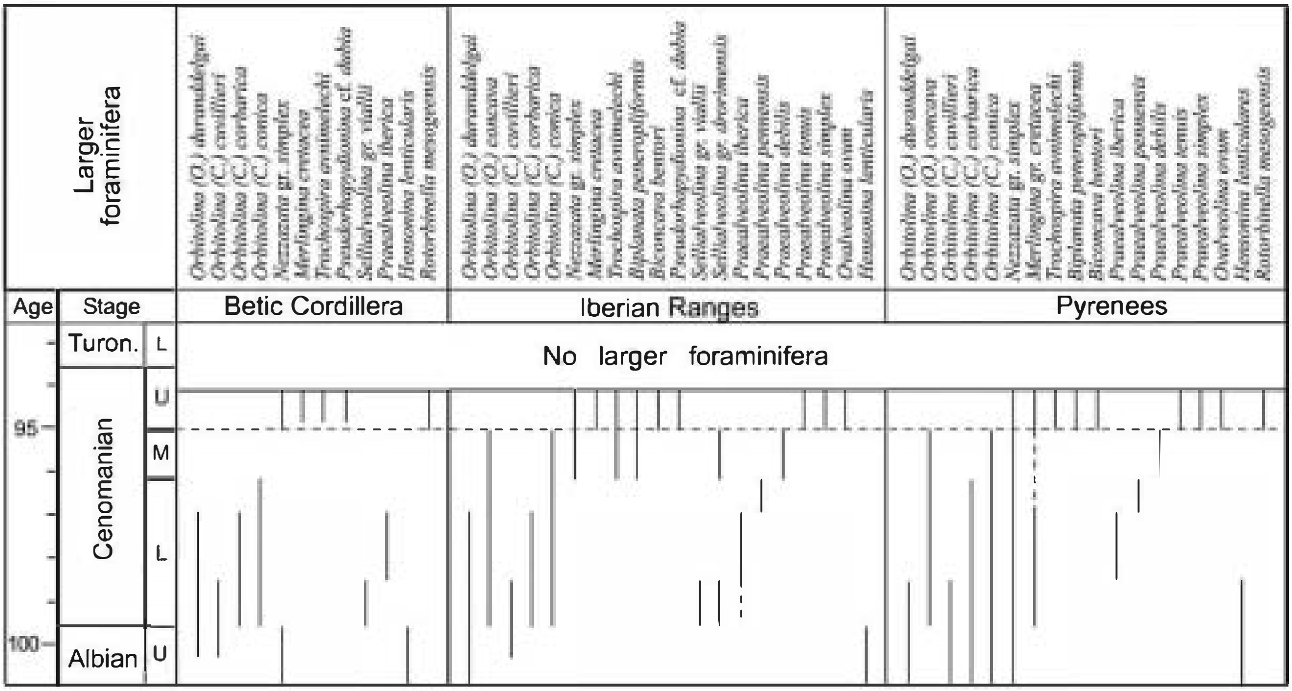


Fig. 4. Distribution of the selected larger foraminifera from the three studied areas.

siliciclastic ones. The carbonate sub-units consists mainly of sandy bioclastic calcarenites, requieniid-rich wackestones and rudist-chondrodont-coral thickets deposited in shallow marine environments of mixed to pure carbonate ramps (Giménez et al., 1993). The siliciclastic sub-units consist of thin-bedded sands, marls, sandy or marly carbonates and stromatolite dolomicrites. They are interpreted as generated in shallow subtidal to supratidal areas. The lower and middle carbonate sub-units yield abundant benthic foraminifers including *Neorbitolinopsis conulus* (Douvillé), *Neoiraquia convexa* Danilova, *Sabaudia minuta* (Hofker), *Hensonina lenticularis* (Henson) and *Nezzazata gr. simplex* Omara, and the "Vraconian" rudist *Caprina choffati* (Martín-Chivelet, 1992). The age of the Jumilla Formation is Upper Albian, and it shows a rapid vertical transition to the overlying Chera Formation.

III. Chera Formation (4–40 m thick). This unit consists of grey to green marls and marly carbonates (usually dolomitized) that were deposited in peritidal to shallow marine environments. They yield a benthic assemblage which includes *Orbitolina (Orbitolina) duranddelgai* Schroeder, *Orbitolina (Conicorbitolina) cuvillieri* (Moullade), *Pseudolituonella reicheli* Marie, *Cuneolina pavonia* D'Orbigny, and *Sellialveolina viallii* Colalongo. The deposits of the Chera Formation preceded the installation of a huge flat-topped, fully aggraded carbonate platform represented by the Alatoz and Villa de Ves Formations. Chera Formation is uppermost Albian to lowermost Cenomanian in age.

IV. Alatoz and Villa de Ves Formations. The Alatoz Formation (10–200 m thick) mainly consists of massive dolostones in which different facies such as mega-crossbedded orbitolinid dolograinstones and dolopackstones and bioturbated dolowackestones can be recognized. They are interpreted as inner-shelf to shelf-edge deposits. The Alatoz Formation (60–120 m thick) deposits grade both vertically and laterally (landward) into the Villa de Ves Formation, which is characteristically formed by peritidal dolomitic facies piled up in m-scale shallowing upwards cycles. In both units, some specimens of Ichthyosarcolitidae can be found. The scarce larger foraminifera are represented by *Praealveolina* cf. *iberica* Reichel, *Orbitolina (Conicorbitolina)* cf. *corbarica* Schroeder, and *Orbitolina* (*C.*) *conica* (D'Archiac). The age of the Alatoz–Villa de Ves ensemble is Lower Cenomanian.

The second unit is much thinner than the first and consists of only two formations, both dolomitic in nature, respectively named the Carada and Cuchillo Formations. Contrary to the lower unit, which has a wide areal distribution, this middle unit has a limited distribution, and was deposited only in differentially subsiding areas, usually adjacent to listric faults (Martín-Chivelet, 1995). The main characteristics of the formations are:

I. Carada Formation. This unit is 15–35 m thick and consists of a well stratified succession of peritidal carbonates that strongly resemble those of the Villa de Ves Formation. Dolomitization, however, is less intense than in that unit and original facies can be recognized more easily. This formation does not show well developed supratidal features and the vertical succession of facies indicates a progressive upward deepening. Subtidal facies show numerous small rudists. This unit is attributed to the Middle Cenomanian (Martín-Chivelet et al, 1990). It grades both laterally and vertically into the Cuchillo Formation.

II. Cuchillo Formation. This unit comprises 20–45 m of massive or bad-stratified black dolostones. Original sedimentary structures and biological remains have almost been destroyed by dolomitization, although bioclasts ghosts, rare and diffuse cross-bedding and bioturbation traces suggest subtidal environments. Because of relative stratigraphic position and its lateral change into the Carada Fm, this unit can be considered as Middle Cenomanian.

The *upper cycle* consists of two formations (Moratillas and Alarcón). The regional distribution of this unit is tectonically controlled and restricted to a narrow WSW–ENE trough limited by two elevated areas. Complex spatial and vertical accommodation patters determined the deposition of facies ranging from outer platform carbonates to palaeosols. The main characteristics of the formations are the following:

I. Moratillas Formation. It consists of 10–40 m of white limestones and characteristically shows the following vertical facies succession, from base to top: the unit starts with a decimetre-scale level formed by outer platform facies which include biomicrites with planktonic foraminifera such as *Guembelitria cenomana* (Keller), *Hedbergella delrioensis* (Carsey), *Whiteinella* cf. *aprica* (Loeblich and Tappan) and *Praeglobotruncana*, calcisphaeres and bryozoa (Martín-Chivelet et al., 1990). This initial bed is followed by a 10–15 m thick carbonate body consisting of bioclastic grainstones and rudists thickets that yield *Peneroplis parvus* De Castro, *Merlingina cretacea* Hamaoui and Saint Marc, *Trochospira avnimelechi* Hamaoui and Saint Marc, *Dicyclina schlumbergeri* Munier-Chalmas, *Pseudorhapidionina* cf. *dubia* De Castro and *Rotorbinella mesogeensis* (Tronchetti). Finally, towards the top, rudist beds grade into very shallow-water pelbiomicrites, rare stromatolite beds which often show evidences of subaerial exposure. These beds mark the transition into the overlying Alarcon Formation, which is gradual but usually rapid. The age of the unit is Upper Cenomanian.

II. Alarcón Formation. This unit is 4 to 15 m thick and consists of a condensed succession of pelbiomicrites and palaeosols. Pelbiomicrites contain green algae, miliolids and small hyaline foraminifera interpreted as deposited in very-shallow, hyposaline waters. This unit grades vertically from the Moratillas Formation, and has usually been attributed to the Turonian (e.g., Martín-Chivelet, 1992). It should be noted, however, that the basal levels of the unit have yielded the Cenomanian species *Chrysalidina gradata* D'Orbigny in the Albacete area (Giménez, 1987).

3.2. Iberian Ranges

Shallow marine carbonates of middle Cretaceous age that were widely deposited in the Iberian intracontinental basin, which formed a broad, SE–NW elongated trough, geographically connected to the Betic margin towards the south and with the Pyrenean–Cantabrian margin towards the north. These carbonate rocks extensively crop out today throughout the Iberian Ranges. In this study, the stratigraphic sections chosen for the analysis come mainly from eastern part of the Iberian Ranges (Maestrazgo area), but also from its neighbouring areas: the Catalan Ranges and the Southern Iberian Ranges.

As in the Betics and the Pyrenees, the Iberian carbonate platforms outline two sedimentary cycles separated by a major regional unconformity (Fig. 3). Interestingly, the platforms developed in the considered sectors of the Iberian basin during the lower cycle (during the Late Albian to Middle Cenomanian interval) deepened to the southeast and were opened towards the Tethyan domain. On the contrary, the platforms of the upper cycle formed in response to a marine transgression that came from the North, and were opened to the Atlantic domain.

Mid-Cretaceous platform distribution and evolution in the Iberian basin depended on thermal and tectonic subsidence on the basin and global sea-level changes. During the Late Albian, two independent platforms developed in the northern and the southern areas of the basin respectively. As sea-levels rose, the carbonate platforms retrograded towards the central part of Iberia, a process that culminated in the Early Cenomanian when marine connection between Tethys and Atlantic was established (Alonso et al., 1993; Floquet, 1998). During the onset of the Late Cenomanian, the generalized tilting of the Iberian plate towards the NE determined a rapid and strong change in the subsidence patterns of the Iberian basin. Mimetically with the plate, the intraplate basin tilted towards the NE. This caused a rapid increase in the subsidence of the northern and central parts of the basin (the "Castilian ramp" of Floquet, 1991) and a rapid marine transgression. Towards the south and the east, these changes in subsidence were much more moderate, but enough to allow the development of a new carbonate platform connected to the rest of the basin and the Bay of Biscay (Fig. 2). In the southeasternmost part of the basin, however, the consequences of the plate tilting were the opposite and the area experienced very low subsidence or even uplift. The resulting elevated fringe outlined at this stage the separation of the Iberian and Betic basins during the Late Cenomanian–Turonian interval (Martín-Chivelet and Giménez, 1993).

The *lower cycle*, which regionally shows quite homogeneous biostratigraphic and lithostratigraphic characteristics, is characterized by the following formations:

I. Aras de Alpuente Formation. This unit is 50 to 110 m thick and consists of brown bioclastic limestones with fragmented bivalves, mainly rudists, gastropods and larger foraminifera including *Orbitolina (Conicorbitolina) cuvillieri* (Moullade), *Orbitolina (Orbitolina)* cf. *sefini* Henson, *Carinoconus casterasi* Cherchi and Schroeder, and *Hensonina lenticularis* (Henson) deposited in a high-energy carbonate platform with terrigenous influence. The age is uppermost Albian. This formation is equivalent to the Jumilla Formation and grades to the northern margin of the basin to the sands and sandstones of the Utrillas Formation, from the Betic Cordillera.

II. Chera Formation (5–25 m). As in the Betics, this formation consists of green marls with some intercalated oyster banks and limestone beds rich in larger foraminifera such as *Cuneolina pavonia* D'Orbigny, *Orbitolina (Conicorbitolina)* cf. *cuvillieri* Moullade, *Orbitolina (C.) corbarica* Schroeder, *Orbitolina (Orbitolina)* cf. *sefini* Henson, *Sellialveolina* cf. *viallii* Colalongo, *Orbitolina? maccagnoae* De Castro, and *Peneroplis parvus* De Castro interpreted as deposits in a flat, low-energy and shallow lagoon of the uppermost Albian to lowermost Cenomanian.

III. Alatoz Formation. This unit is 10 to 30 m thick and consists of calcarenitic shoals, nodular thin-bedded to massive limestones, and marly limestones. It yields abundant bivalves, gastropods, ostracods and larger foraminifera mainly *Cuneolina pavonia* D'Orbigny, *Orbitolina (Orbitolina) concava* (Lamarck), *Orbitolina (O.) duranddelgai* Schroeder, *Charentia cuvillieri* Neumann, *Daxia cenomana* Cuvillier and Szakall, *Chrysalidina gradata* D'Orbigny, *Praealveolina iberica* Reichel and *Praealveolina pennensis* Reichel that were deposited on a shallow wide platform. The age is Lower Cenomanian.

IV. Villa de Ves Formation (9 to 90 m). This formation consists of thin-bedded to massive limestones intercalated with marly limestones passing upwards into dolomitic limestones and finally to dolomites. The limestone record is rich in fossils such as bivalves, gastropods, ostracods and larger foraminifera including *Orbitolina (C.) conica* (D'Archiac), *Orbitolina (O).* cf. *sefini* Henson, *Charentia cuvillieri* Neumann, *Dictyopsella libanica* Saint-Marc, *Nezzazata* gr. *simplex* Omara, *Trochospira avnimelechi* Hamaoui and Saint-Marc, *Biplanata peneropliformis* Hamaoui and Saint-Marc, *Biconcava bentori* Hamaoui and Saint-Marc, *Merlingina cretacea* Hamaoui and Saint-Marc, *Praealveolina debilis* Reichel, and *Sellialveolina* aff. *drorimensis* Reiss, Hamaoui and Ecker. These sediments were deposited in a shallow wide platform. The age is Lower and Middle Cenomanian. The Carada and Cuchillo Formations from the Betic Cordillera are contemporaneous with the upper part of this unit.

The *upper cycle* is notably more heterogeneous than the former (recording the palaeogeographical changes that occurred in the basin) and composed of the following formations:

I. Casa Medina Formation. This unit is 8 to 35 m thick and consists of nodular limestones showing a rich fauna of larger foraminifera including *Dictyopsella libanica* Saint-Marc, *Chrysalidina gradata* D'Orbigny, *Nezzazata* gr. *simplex* Omara, *Biconcava bentori* Hamaoui and Saint-Marc, *Praealveolina tenuis* Reichel, *Praealveolina simplex* Reichel, *Ovalveolina ovum* (D'Orbigny), and *Pseudorhapidionina* cf. *dubia* (De Castro) and bivalves with interbedded dolomitic levels that pass upwards to thin-bedded limestones alternating with massive dolomites deposited in a shallow-water carbonate platform. The age of this unit is Upper Cenomanian (Calonge et al., 2002).

II. Ciudad Encantada Formation (up to 60 m). This unit is composed of massive dolostone featuring large scale cross-bedding, where local clinoforms developed. The Casa Medina and Ciudad Encantada Formations are equivalent to the Moratillas Formation and maybe the lowermost part of the Alarcón Formation.

The overlying deposits consist of thin-bedded limestones rich in calcispheres and some planktonic foraminifera deposited on an open marine platform.

3.3. Pyrenees

Within the Pyrenees, the studied deposits belong to the southern margin of the Pyrenean Basin where shallow and wide carbonate platforms developed. Nowadays, as a result of the Alpine Orogeny, the materials deposited in these platforms are deformed, fragmented, detached from their substrate and displaced southwards, forming several tectonic units. In this scenario, the Sopeira basin in the South Central Pyrenean unit is the most representative area of the latest Albian–Cenomanian interval (Fig. 3). Its particular geometry — a small extensional basin with high subsidence and a continuous record of sedimentation from the Late Albian to the Cenomanian — allowed the correlation between sediments from the basin (Sopeira section) to basin-margin (Sant Gervàs section) and inner platform (Montsec section). Therefore, shallow benthic foraminifera can be directly correlated with pelagic biozones (planktonic foraminifera and ammonites, Caus et al., 1993). In the other Pyrenean areas the Cenomanian sediments rest unconformably on Lower Cretaceous or Jurassic deposits, with the exception of the Montgrí Thrust Sheet (Calonge et al., 2002), where Albian–Cenomanian sedimentation took place continuously. The palaeontological data summarised in Fig. 4 are from the ensemble of the Pyrenees. The latest Albian–Cenomanian interval is represented by two cycles. The *lower cycle* comprises:

I. Aulet Formation (up to 630 m thick). A complex unit that consists of quartz calcarenites, ferruginous bioclastic limestones and argillaceous limestones rich in orbitolinids including *Orbitolina (Orbitolina) duranddelgai* Schroeder, *Orbitolina (O.) concava* (Lamarck), *Orbitolina (Conicorbitolina) conica* (d'Archiac), *Orbitolina (C.)* cf. *cuvillieri* Moullade, *Orbitolina (C.) corbarica* Schroeder, which is interpreted as being deposited in deltaic and mixed shelf environments. The age is Upper Albian–Lower Cenomanian.

II. Sopeira Formation (up to 347 m thick). This includes open platform to basinal grey marls alternating with thin-bedded nodular marly limestones rich in planktonic foraminifera, ammonoids and calcispheres. The planktonic foraminiferal assemblages belong to the *Rotalipora brotzeni* and *Rotalipora cushmanni* (lower part) zones (Caus et al., 1993), whereas the ammonite assemblages correspond to the *Mantelliceras mantelli* and *Acanthoceras rothomagense* zones (Martinez 1982). Both indicate an age from Lower to Middle Cenomanian.

III. Lower Santa Fe Breccia Formation (up to 39 m thick). This consists of grey marls mixed with blocks of cemented slope — calcisphere limestones — and platform — larger foraminifera limestones — sediments indicating the progradation of the platform and the upper slope into the basin. The planktonic foraminifera contained in the marls are attributed to the Middle Cenomanian (Caus et al., 1993), whereas the larger foraminifera occurring within the resedimented material have an earlier age (Lower Cenomanian).

IV. Lower Santa Fe Formation (9–15 m thick). This unit overlays Lower Cretaceous or older sediments and consists of grey, well-bedded nodular limestones, heavily bioturbated, with a rich fauna of larger foraminifera, dasycladacean "algae" and some rudist fragments, deposited in an inner, relatively flat and shallow platform. The larger foraminifera, including *Orbitolina (Orbitolina) concava* (Lamarck), *Charentia cuvillieri* Neumann, *Cuneolina pavonia* D'Orbigny, *Daxia cenomana* Cuvillier and Szakall, *Nezzazata* gr. *simplex* Omara, *Merlingina cretacea* Hamaoui and Saint-Marc, and *Praealveolina debilis* Reichel indicate a Middle Cenomanian age.

The Aulet, Sopeira and Lower Santa Fe Breccia Formations are represented only in the basin, slope and platform margin areas, whereas the Lower Santa Formation is represented in all the inner platform areas. The top of this lower cycle is marked in the platform by subaerial exposure.

The *upper cycle* comprises:

I. Upper Santa Fe Breccia Formation (up to 32 m thick). This unit only present in the Sopeira section consists of basinal calcisphaerid limestones interbedded with redeposited shallow-water limestones, that grade upwards to the overlying unit (Pardina Formation). The scarce planktonic foraminifera indicate an age of Middle–Upper Cenomanian. Some ammonites from the *Calycoceras naviculare* zone cited by Bilotte and Souquet (1972) in the upper part of the unit indicate an Upper Cenomanian age.

II. Upper Santa Fe Formation (23–160 m thick). This unit, linked to an important sea level rise, covers the previously exposed surface (top of the Lower Santa Fe Formation). In the platform margin (Sant Gervàs section) it consists of massive to well-bedded rudist-coral boundstones capped at the top by karstic dissolution pipes and caves filled by calcisphere limestones (Pardina Formation). In the inner platform (Montsec section) this unit consists of grey, well-bedded nodular limestones with abundant bivalves and larger foraminifera, including *Cuneolina pavonia* D'Orbigny, *Dicyclina schlumbergeri* Munier-Chalmas, *Charentia cuvillieri* Neumann, *Chrysalidina gradata* D'Orbigny, *Coxites zubairensi* Smout, *Merlingina cretacea* Hamaoui and Saint-Marc, *Biconcava bentori* Hamaoui and Saint-Marc, *Biplanata peneropliformis* Hamaoui and Saint-Marc, *Praealveolina tenuis* Reichel, *Praealveolina simplex* Reichel, *Ovalveolina ovum* (D'Orbigny), and *Rotorbinella mesogeensis* (Tronchetti). The age is Upper Cenomanian.

III. Pardina Formation (20–87 m thick). In the Sopeira section, where the contact is concordant this unit overlays the Upper Santa Fe Breccia and it consists of three packages: a) the lower package with a thickness of 19 m consists of calcisphere-rich limestones with planktonic foraminifera from the upper part of the *Rotalipora cushmani* zone; b) the middle package, 14 m thick, consists of calcisphere limestones with nodular black cherts and sinsedimentary contoured beds with abundant large *Whiteinella archaeocretacea*; the Cenomanian/Turonian boundary falls within this package (Caus et al., 1993); c) the upper package of 16 m thick is lithologically similar to the lower package, but is characterised by planktonic foraminifera belonging to the successive *Helvetoglobotruncana helvetica* and *Marginotruncana sigali/schneegansi* zones. In all of the platform margin and inner platform sections, the open marine deposits of the Pardina Formation overlays the Upper Santa Fe Formation, and the boundary between the two units is marked by a sharp surface and a gap in the sedimentation, which represents the uppermost Cenomanian and the lowermost Turonian. This hiatus is said to be due to the eutrophication event (Caus et al., 1997) and the deposition under open marine conditions as a drowning unconformity (Drzewiecki and Simó, 1997; 2000).

4. The distribution of larger foraminifera

4.1. Mid-Cretaceous GCM cycle

In Iberia, the shallow carbonate deposits of the *lower cycle* (latest uppermost Albian–Middle Cenomanian) contains, in the three areas studied (Fig. 4), a rich association of small spherical to slightly elongate alveolinids like *Praealveolina iberica*, *Praealveolina pennensis* or *Praealveolina debilis* (which replaced each other over time) and agglutinated foraminifera, mainly orbitolinids and dicyclinids, some nezzazatids, and the perforate-lamellar Hensonina (Fig. 5/3). However, the rhapydioninids represented by the small primitive *Sellialveolina* gr. *viallii* (Fig. 5/2) in the Lower Cenomanian and the complex, axially compressed *Sellialveolina* aff. *drorimensis* (Fig. 5/1) (which replaced *S.* gr. *viallii* at the earliest Middle Cenomanian) apparently reached only the northern margin of the Iberian seaway, in spite of almost continuous communication between the Tethyan and Atlantic domains.

In the *upper cycle* (late Cenomanian), the Iberian shallow-water platforms that open to the Atlantic Ocean are dominated by large elongate *Praealveolina tenuis* (Fig. 5/4) associated with spherical *Praealveolina simplex* and *Ovalveolina ovum*, whereas in those open to the Tethyan Sea, the Upper Cenomanian sediments are strongly dolomitised and the fauna is poorly represented; where dolomitisation is week praealveolines and ovalveolines have been identified. In both areas, alveolinids are associated with the same agglutinated foraminifera, nezzazatids and the smaller rotaliid *Rotorbinella mesogeensis*.

From Italy to Iran and the northern Africa — see list in Schroeder and Neumann (1985) — the genus *Sellialveolina* is quite common in all the Cenomanian shallow, restricted areas of the isolated and pericontinental Tethyan carbonate platforms. Nevertheless, the exact range of these foraminifera as given by Schroeder and Neumann (1985) is questionable.

Deloffre and Hamaoui (1979) found evidence of *Pseudedomia drorimensis* in a well in southwest France (Aquitania Basin).The figures given by Fourcade and Hamaoui (also reproduced by Schroeder and Neumann, 1985, plate 67, figures 1–3) show specimens comparable to the *Sellialveolina drorimensis* from the Upper Cenomanian of Israel (Drorim valley, Negev, Israel, Reiss et al., 1964). However, they have never been found in outcrops or other wells along the wide Cenomanian platforms on both sides of the Pyrenean Basin (extending from the Atlantic coast of southwest France to the area around Marseille in the southeast, and from south of the Cantabrian Mountains to the Mediterranean Sea). Therefore, the occurrence of the *Sellialveolina* in the Pyrenean basin remains questionable, and further studies need to be done.

The *Merlingina cretacea* and *Praealveolina tenuis* faunas have also been identified along the Atlantic shelves from île Madame in western France to Alcantara in Lisbon, Portugal, (Reichel, 1936–1937) and the north of Africa (Goharbandt, 1966), which suggests that the interruption of the seaway through the Iberian subcontinent had no effect on the delimitation of the *Praealveolina* populations during the Late Cenomanian. In the Tethys from Italy to the Middle East, *Praealveolina* and *Ovalveolina* are accompanied by two other Alveolinidae

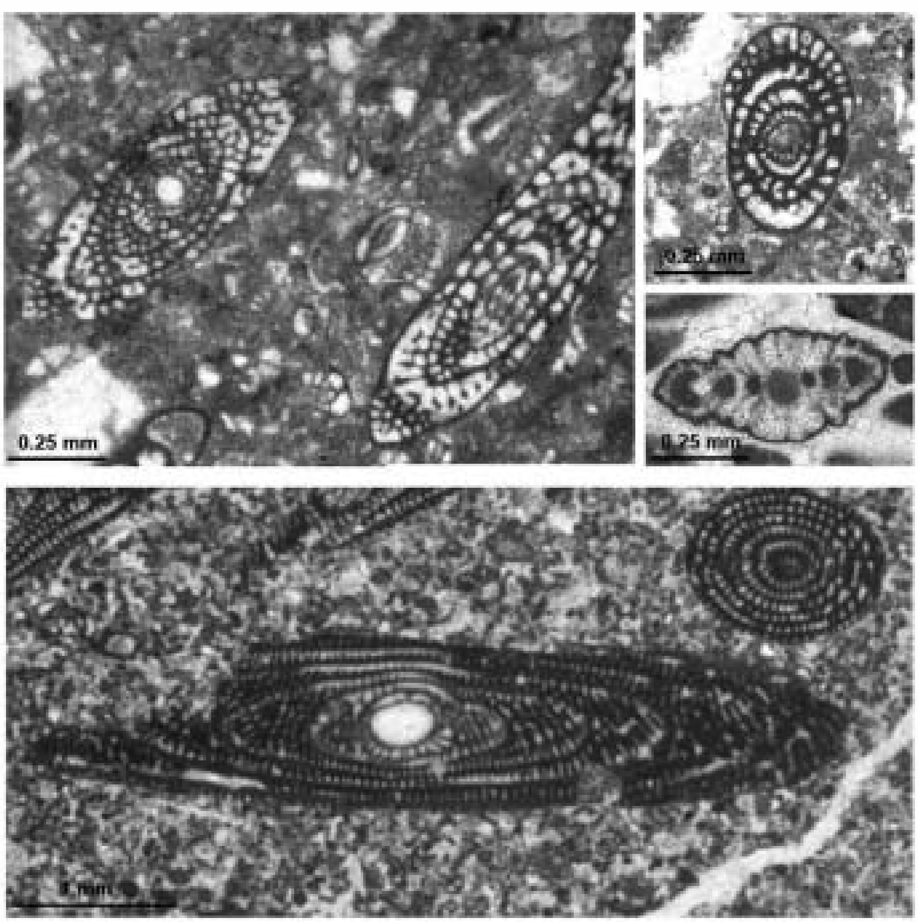


Fig. 5. 1. *Sellialveolina gr drorimenis* Reiss, Hamaoui and Ecker from the Villa de Ves Fm, Middle Cenomanian. 2. *Sellialveolina* gr. *viallii* Colalongo from the Chera Fm, Lower Cenomanian, 3. *Hensonina lenticularis* (Henson) from the Aras de Alpuente Fm, Upper Albian. 4. *Praealveolina tenuis* Reichel from the uppermost part of the Santa Fe Fm. Upper Cenomanian.

genera, *Cisalveolina* and *Multispirina*, which have never been recorded in the Iberian Peninsula. *Cisalveolina* has been found from Italy to the Middle East — see Schroeder and Neumann (1985). This genus has also been identified in Portugal (Berthou, 1973), although it is probable that the figures given by the author are oblique sections of elongated *Praealveolina*.

Near the Cenomanian–Turonian boundary, all of the alveolinacean genera disappeared in Iberia, which coincides with other areas of the Tethyan realm (Philip et al., 1995; Parente et al., 2008).

4.2. Late Cretaceous GCM cycle

The data used here to characterize the Late Cretaceous GCM cycle comes from the previous studies (see literature referenced below), and are used to establish the differences between the two successive cycles.

After the Turonian crisis, the newly arising porcelaneous k-strategists foraminifera living in the upper part of the photic zone produced more or less endemic species in each province. In the Betic province, the family Rhapydionidae, and in particularly its genus *Murciella* indicates the westward extension of the Tethyan domain (Vicedo, 2008). In the Pyrenean province three genera of Alveolinidae, the spherical *Hellenalveolina* (Lower Santonian), the slightly axially compressed *Fabalveolina* and the elongate *Subalveolina* (Upper Santonian) settled on shallow platforms (Vicedo et al., 2009). The large Santonian and Campanian meandropsinids such as *Palandrosina*, *Spirapertolina*, *Larrazetia* and *Fallotia* are restricted to the Pyrenean province (Hottinger and Caus, 2009). Representatives of the Cretaceous Fabulariidae, the *Lacazina* species, are found in both provinces, although they are much more diversified in the Pyrenean domain (Hottinger et al., 1989).

The larger agglutinated foraminiferal groups such as dicyclinids and cyclolinids living in similarly shallow environments are common in both provinces, but there are also a number of agglutinated genera such as *Spirocyclina*, *Montsechiana*, *Calveziconus* or *Ilerdorbis* that are restricted to the Late Cretaceous GMC cycle. Concerning the lamellar-perforate foraminifera, the rotaliids, the primitive genus *Rotorbinella* that seems to be the origin of the Rotaliidae family (Boix et al., 2009), appeared in both provinces.

4.3. Discussion

Taking account of the larger foraminifera distribution in Iberia it seems that the Rhapydioninids characterized the Betic (Tethyan) bioprovince in both GCM cycles: Mid and Late Cretaceous, but they are absent in the Pyrenean (Atlantic) bioprovince. Moreover, as indicated by the temporal distribution of the genus *Sellialveolina* such a separation of the two bioprovinces started during the Early–Middle Cenomanian before the definitive closure of the communication between the two domains by a land-bridge.

Therefore, the cause of the delimitation of the two bioprovinces cannot be attributed to a barrier (land-bridge) cutting off the propagation of the individual offspring. It probably corresponds instead to accelerated gradients of ecologically limiting conditions that did not allow the build-up of populations of the *Sellialveolina* in the northern shelves of the Iberia, which could be due to the circulation patterns of ocean surface waters.

5. Conclusion

The Late Albian to Late Cenomanian epoch represents a Global Community Maturation (GCM) cycle in which agglutinated larger foraminifera, in particular the orbitolinids, were successively replaced by larger porcelaneous foraminifera, the alveolinaceans, for the first time in Earth's history. The alveolinaceans dominated the shallow-water assemblages in the Tethys until the eutrophication event at the Cenomanian–Turonian boundary, which eliminated them to such a degree that all their essential k-strategy information was lost. It took considerable time (between of 8–10 m. y.) to recreate their genetic complexity during the following GCM cycle arising in the Coniacian.

Within the mid-Cretaceous GCM cycle, Iberia exhibits two faunal provinces at the boundary between the Atlantic and Tethyan realms: the Betic and Pyrenean, respectively. Their separation is attributed here to the differences of ecological conditions from north to south along the Atlantic and Tethyan shelves, not by the palaeogeography that is dominated by the opening or closing of the shallow seaway across Iberia.

Therefore, the mid-Cretaceous distribution of the larger foraminiferal k-strategists in space and time document faunal provinces that are not conditioned by the seaway across Iberia: the provinces were different before the interruption of the seaway and delimited after its recovery across the platform extending along its southeastern coasts of the seaway.

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