



# Deep-sea paleoenvironmental evolution in the mid-Cretaceous of the Basque Pyrenees based on microfaunal analysis (Armintza section)

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## ABSTRACT

The mid-Cretaceous Black Flysch Group and Plentzia Formation constitute two key lithostratigraphic units in the evolution of the Pyrenean rift system but many of their paleoenvironmental characteristics are poorly known. In this work, a microfaunal analysis (planktonic and benthic foraminifera and ostracods) of these two units at the Armintza section has been carried out in order to interpret the paleoenvironmental conditions (paleodepth, oxygen level and water masses) in which they deposited, and to relate them to the contemporary tectono-sedimentary settings. Based on the high proportion of planktonic foraminifera with respect to total foraminifera and the assemblages of benthic foraminifera species, a paleodepth of ~600 m is estimated for studied units. During syn-rift deposition of the organic-rich Black Flysch Gp. in middle Albian-early Cenomanian times, the relative abundance of planktonic foraminifera and the proportions of different shell morphotypes suggest the presence of a shallow water mass and the stagnation of deeper waters. Moreover, the presence of abundant hypoxia-tolerant benthic foraminifera species and the occurrence of only rare hypoxia-tolerant platycopid ostracods indicate severe hypoxia conditions (<1.5 ml/l) or even anoxia at the seafloor. A noticeable change is recorded at the contact between the Black Flysch Gp. and the Plentzia Fm. (lower-middle Cenomanian transition). During post-rift deposition of the Plentzia Fm. in earliest middle Cenomanian times, developed microfaunal assemblage shows an important increase in benthic foraminifera species, many of which indicate intermediate waters, and dominance of keeled planktonic foraminifera suggesting the end of water stagnation and the inflow of an intermediate water mass. In addition, the presence of hypoxia-tolerant species of ostracods and benthic foraminifera indicates the development of mild hypoxia conditions at the seafloor during this interval.

## 1. Introduction

The Mesozoic Bay of Biscay-Pyrenean rift system constituted the boundary between Iberian and European plates. In the mid-Cretaceous, the opening of the Bay of Biscay led to an important crustal thinning and stretching in the associated sedimentary basins, causing a significant increase in the activity of their rift structures, subsidence and magmatism. Recent works interpret that hyperextension in the North Pyrenean and Basque-Cantabrian basins culminated with the exhumation of the lithospheric mantle during Albian-Cenomanian times (Jammes et al., 2009; Pedrera et al., 2017; Tugend et al., 2015; among others). These processes would have been recorded by the deposition of the syn-tectonic, deep-water siliciclastic Black Flysch Gp. (middle Albian-lower Cenomanian; Souquet et al., 1985) (Fig. 1A) and postdated by calcareous hemipelagic formations (Upper Cretaceous; Mathey,

1982). Despite the significance of these lithostratigraphic units in the geodynamic evolution of the rift system, little is known about the paleoenvironmental parameters under which they were deposited. In the Basque-Cantabrian Basin (BCB), Rodríguez-Lázaro et al. (1998), based on microfaunal analysis and geochemical data from a deep-water Cenomanian succession, document paleoenvironmental changes and interpret the rocks as deposited in a mesobathyal to infrabathyal seafloor. Other more general works estimate the deposition of the Black Flysch Gp. in the BCB at basinal (Magniez and Rat, 1972) and middle bathyal paleodepths (Castañares et al., 2001; García-Mondéjar et al., 2004).

Microfaunal analysis has been extensively used in the determination of paleoceanographic conditions (paleodepth, seafloor oxygenation, water masses influence, etc.) in which sedimentary rocks were deposited (Brasier, 1980; Murray, 1991). Paleobathymetry estimation is essential

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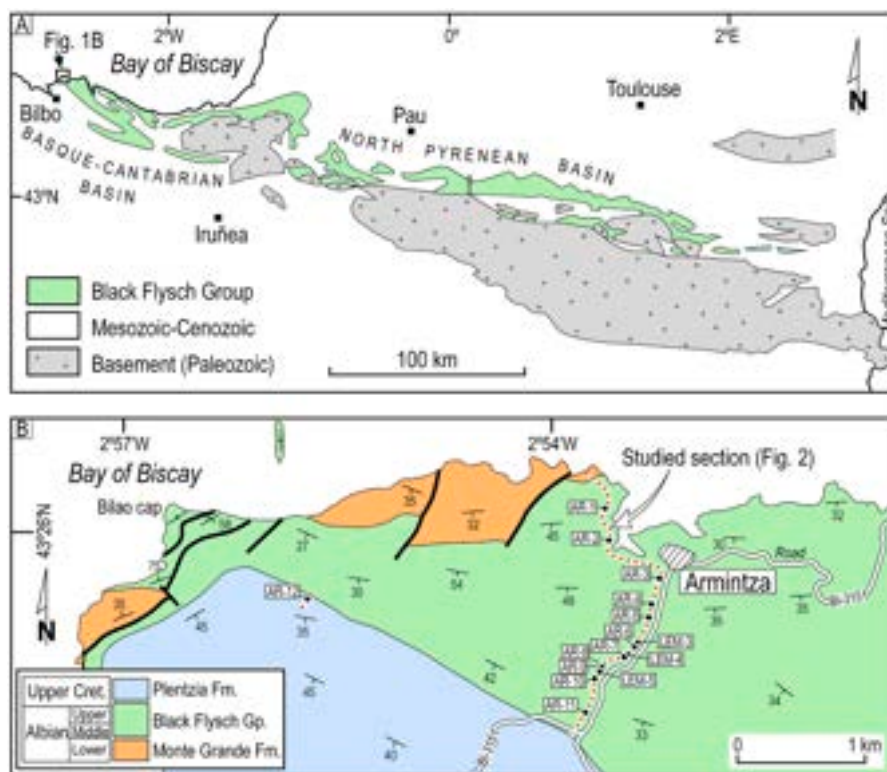


Fig. 1. Distribution of the Black Flysch Gp. outcrops in the Pyrenees with indication of the Armintza locality (Fig. 1B) (modified from Souquet et al., 1985). B) Geological map of the Armintza locality with indication of the studied section and samples.

in basin analysis for calculating subsidence rates (van Hinte, 1978), paleogeographic reconstructions (e.g. Scotese, 2021) and understanding of submarine volcanic processes and products (Cas and Wright, 1988; Fisher and Schmincke, 1984). In this regard, several foraminiferal indices (the ratio between planktonic/benthic foraminifera, test morphology, wall types and species diversity) have been extensively used as paleodepth indicators by comparison with modern analogues (Brasier, 1980; Gibson, 1989; van Morkhoven et al., 1986). The percentage of planktonic foraminifera with respect to the total foraminifera (%P) generally increases with depth (Gibson, 1989). However, van der Zwaan et al. (1990) and van Hinsbergen et al. (2005) noted that oxygen deficiency in poorly oxygenated sea-floors can lead to a decrease in benthic fauna, resulting in an increase in %P. In this case, disregarding infaunal benthic foraminifera in calculating the %P index improves significantly paleodepth estimates (van der Zwaan et al., 1990; van Hinsbergen et al., 2005). Other criteria commonly used for estimating paleodepth is the distribution of benthic foraminifera taxa, which is controlled by a series of depth-related parameters (Holbourn et al., 2001; Sikora and Olsson, 1991; van Morkhoven et al., 1986).

Much information can be also obtained from species and assemblages of benthic foraminifera and ostracods about the paleo-oxygen levels of sea-bottom and the influence of water masses. Many species and assemblages occur in known oxygen requirements and in particular water masses and can therefore be used as proxies for inferring paleo-oxygenation and paleo-circulation of water masses (Murray, 1991; Whatley, 1995). In addition, test morphologies of planktonic foraminifera can be also used as proxies for interpreting the presence of different water masses (Bellier, 1989).

The aim of this study is to infer the paleoenvironmental conditions and their changes during the deposition of the Albian to Cenomanian sediments (Black Flysch Gp. and the lowermost part of the Plentzia Fm.) at the Armintza section (BCB) through analyses of planktonic and benthic foraminifera and ostracods. We also seek to improve the dating of the Armintza section based on planktonic foraminifera.

## 2. Geological setting

The BCB constitute a Mesozoic peri-cratonic rift basin related to the Bay of Biscay opening (Montadert et al., 1974; Rat, 1988) and inverted during Cenozoic compression (e.g. Gómez et al., 2002). During middle Albian-early Cenomanian times, the basin experienced a transtensive rifting phase that induced maximum extension and subsidence rates and magmatism (Cámara, 2017; García-Mondéjar et al., 1996, 2004; Rat, 1988). Recent works interpret this phase as the result of the doming and exhumation of the lithospheric mantle involving large-scale detachment faulting (e.g. Jammes et al., 2009; Pedrera et al., 2017; Tugend et al., 2015). During this phase, high subsidence rates led to the instauration in the central part of the BCB of a N120°-striking deep-water trough in which syn-rift turbidite sediments of the Black Flysch Gp. were deposited (Fig. 1A). These sediments were piled up by numerous northern- and southern-sourced siliciclastic turbidite systems in structurally semi-confined sub-basins, which were controlled by syndepositional transtensive faulting (Agirrezabala, 1996; Agirrezabala and Dinars-Turell, 2013; Agirrezabala and García-Mondéjar, 1994; Agirrezabala et al., 2002; García-Mondéjar et al., 1996) and/or salt tectonics (Poprawski et al., 2014; Roca et al., 2021). Later in a post-rift tectonics phase, middle Cenomanian-Santonian calcareous hemipelagites and minor calciclastic turbidites (Plentzia and Itziar formations) deposited in a relatively wide and unconfined deep-water environment (Mathey, 1987).

The studied Armintza section (Figs. 1 and 2) constitutes one of the most complete succession and with best outcrops of the Black Flysch Gp. and Plentzia Fm. in the BCB. At the Armintza locality, the Black Flysch Gp. shows a thickness of ca. 1200 m, overlies unconformably the deltaic Monte Grande Fm. (lower Albian) and is overlaid unconformably by the Plentzia Fm. This group is mainly composed of interbedded turbidite sandstones, lutites, marls, conglomerates, and minor volcanic rocks (Fig. 3A). Among the fine-grained deposits, lutites dominate in the lower part of the unit while marls and calcareous mudstones dominate in the

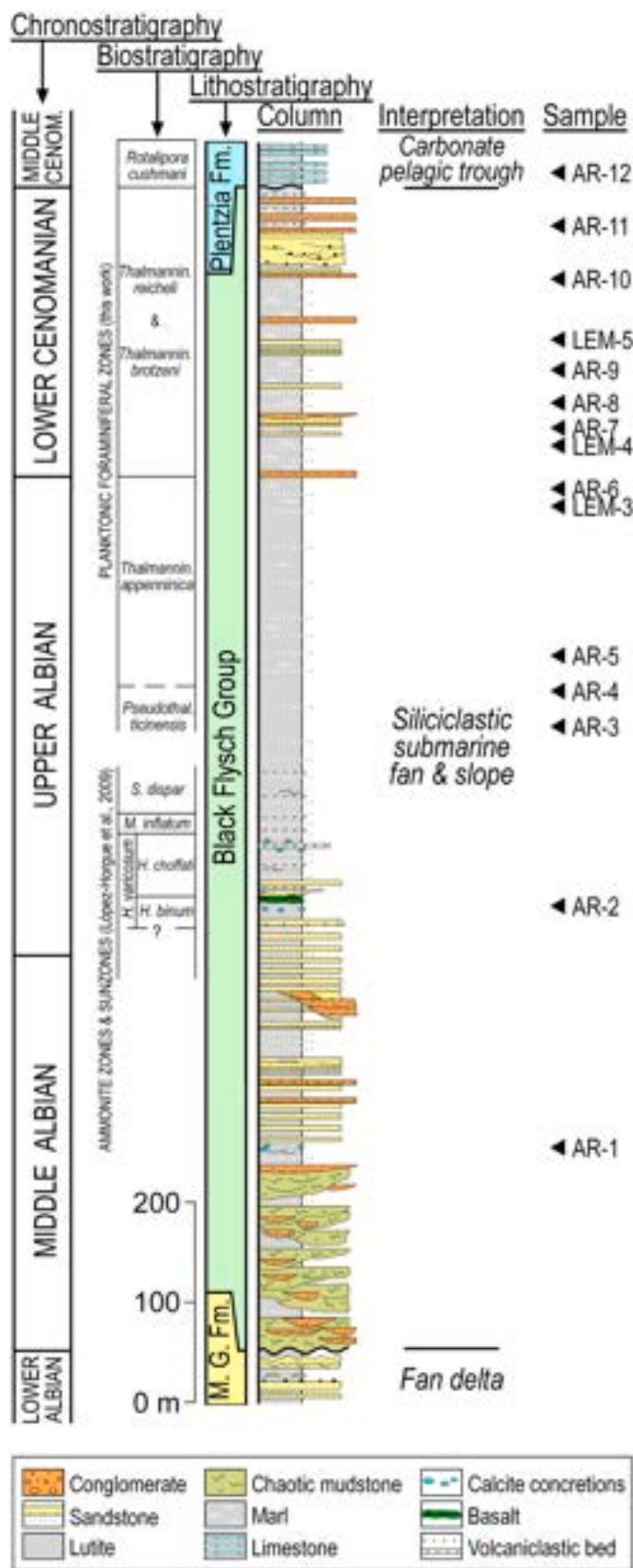


Fig. 2. Stratigraphic succession of Armitntza with indication of chrono-, bio- and lithostratigraphic units, sedimentologic interpretation and samples location. Ammonite zonation after López-Horgue et al. (2009). Planktonic foraminiferal zonation is based on results of this work.

upper part. Lutites exhibit a dark grey colour, are organic-rich (Total Organic Carbon TOC = 1–1.3%) and present abundant vegetal fragments, pyrite and siderite concretions, as well as scattered fossils of dissolved or pyritized ammonites and inoceramids, and belemnites (Fig. 3A–E). These deposits are interpreted as deposited by gravity-driven flows and hemipelagic processes in submarine fan and slope environments (García-Mondéjar and Pujalte, 1985; Robles et al., 1988). Occurrence of abundant siderite concretions and pyrite has been interpreted as formed in early diagenetic suboxic to anoxic conditions at very shallow depth beneath the seafloor in relation to the decomposition of the abundant organic matter (Ábalos and Elorza, 2012; Gil et al., 1986).

The Plentzia Fm. (middle Cenomanian-Santonian) in the Armitntza section overlies unconformably the Black Flysch Gp. and is composed of marls of light grey colour, marly micritic limestones and scarce calcarenitic (bioclastic) turbidites (Fig. 1B, 2, 3F–G). Marls are poor in organic matter (TOC = 0.1%) and pyrite. This unit has been interpreted as deposited in a deep-water, low-relief hemipelagic environment with occasional diluted turbidity currents sourced by adjacent carbonate platforms (Mathey, 1987).

At the Armitntza section, López-Horgue et al. (2009) dated the middle part of the Black Flysch Gp. as early middle Albian-upper Albian (*dispar* Zone) based on ammonites (Fig. 2). Feuillée (1967) dated the upper part of the Black Flysch as Cenomanian based on planktonic foraminifera. However, the vague location of the samples analysed by Feuillée (see his Fig. 11) does not allow their assignment to specific levels of the stratigraphic column.

### 3. Materials and methods

In order to document paleoenvironmental conditions and their changes between the middle Albian and the middle Cenomanian of the Armitntza section, we collected a total of fifteen samples from the north-south oriented outcrop (seacliff and BI-3151 road slope) of the Black Flysch Gp. and lowermost part of the Plentzia Fm. (Fig. 1B). Fourteen samples were collected from the fine-grained intervals (lutites and marls) distributed throughout the Black Flysch (Fig. 2). One sample was collected from the lowermost part (2 m above the base) of the Plentzia Fm. in an outcrop ca. 2 km away from the Armitntza section due to the presence of a fresher outcrop (Fig. 1B and 2). Total organic carbon content (TOC; wt%) was measured by a duplicated analysis of 3 samples (lutites and marls) with a FlashEA 1112 (ThermoFinnigan) elemental analyzer (Thermo Fisher Scientific Co., Waltham, MA, USA) after acid removal of carbonates by using hot (80 °C) hydrochloric acid.

The micropaleontological analysis of the rock samples was carried out using standard laboratory procedures, including sieving through a 63 µm and drying at 50 °C. A representative split of the >63 µm fraction was used to pick ≥300 planktonic and benthic foraminifera and the ostracods present per sample, to determine their percentages. However, in the sandy samples ARM-3 and ARM-9 only 5 and 4 microfossils could be picked, respectively, and therefore they have not been considered in the analysis. This allowed calculating several paleoceanographic indices: planktonic percentage %P (also known as oceanicity index; Gibson, 1989) expressed as  $P/(P + B) \times 100$  (percentage of planktonic foraminifera with respect to the total foraminiferal population); simple diversity (number of species); percentage of keeled planktonic foraminifera, incipiently keeled and globular in the planktonic foraminifera assemblage. In addition, in the case of the benthic foraminifera, simple diversity (number of species) and test type percentages (agglutinated, hyalines and porcelaneous) were calculated.

The taxonomic classification was based on the systematics of Loeblich and Tappan (1988) as well as Robaszynski et al. (1984), Caron (1985), Jenkins and Murray (1989), Robaszynski and Caron (1995) and Gräfe (2005), among others. Foraminiferal taxonomic names have been updated in WoRMS (Hayward et al., 2022) and <https://www.mikrotax.org/pforams/> (last visited 8 - December 2022). Used biozonation scheme is based on Robaszynski and Caron (1979) and Caron (1985).



**Fig. 3.** Field aspect of the main sedimentary facies of the Black Flysch Gp. (A–E) and Plentzia Fm. (F–G). A) General view of the lower part of the Armitza section showing Black Flysch Gp. deposits (meters 300 to 490 in Fig. 2, approx.) composed mainly of interbedded turbidite sandstones and lutites. B–C) Typical interbedding of sandy turbidites, organic-rich dark lutites and early diagenetic siderite in the Black Flysch. D) Dark lutites with abundant early diagenetic framboidal pyrite. E) Organic-rich lutite enclosing a vegetal fragment. F) Plentzia Fm. deposits constituted by organic-poor, light marls and interbedded limestones. G) Detail of the Plentzia Fm. showing interbedding light grey marls and marly limestones.

Paleobathymetric interpretations of the obtained data were done according to the bathymetric subdivisions of van Morkhoven et al. (1986) and Berggren and Miller (1989): inner neritic (0–30 m), middle neritic (30–100 m), outer neritic (100–200 m), upper bathyal (200–600 m), middle bathyal (600–1000 m), lower bathyal (1000–2000 m), upper abyssal (2000–3000 m), and lower abyssal (>3000 m).

## 4. Results

### 4.1. Biostratigraphy

Fig. 4 shows the distribution of planktonic and benthic foraminifera and ostracods in the Armitza succession (for species counts of benthic foraminifera see Table A.1 in Appendix), and the most representative microfossil taxa are displayed in Fig. 5. Four planktonic foraminiferal biozones have been recognized. In the Black Flysch the *Pseudothalmaninella ticinensis* Zone is characterized by the presence of the index species (middle part of the section). The *Thalmaninella*

*appenninica* Zone contains the index species in addition to *Praeglobotruncana delrioensis* (Plummer). The overlying deposits to this zone yield *Thalmaninella appenninica* (Renz), *Thalmaninella brotzeni* Sigal, *Muricohedbergella delrioensis* (Carsey) and *Muricohedbergella planispira* (Tapan) planktonic species, indicating the *Thalmaninella brotzeni* and/or the *Thalmaninella reicheli* zones. Finally, in the lowermost deposits of the Plentzia Fm. (AR-12 sample) the *Rotalipora cushmani* Zone has been identified, which yields the index species in addition to *Thalmaninella appenninica*, *Praeglobotruncana delrioensis*, *Thalmaninella brotzeni*, *Praeglobotruncana gibba* Klaus, *Thalmaninella greenhornensis* (Morrow), *Praeglobotruncana stephani* (Gandolfi), *Muricohedbergella planispira*, and *Claviohedbergella simplex* (Morrow).

### 4.2. Microfaunal analysis

The microfossils obtained generally show poor test preservation due to strong burial diagenetic processes such as recrystallization and cementation (Fig. 5). In some cases, this makes difficult to identify them

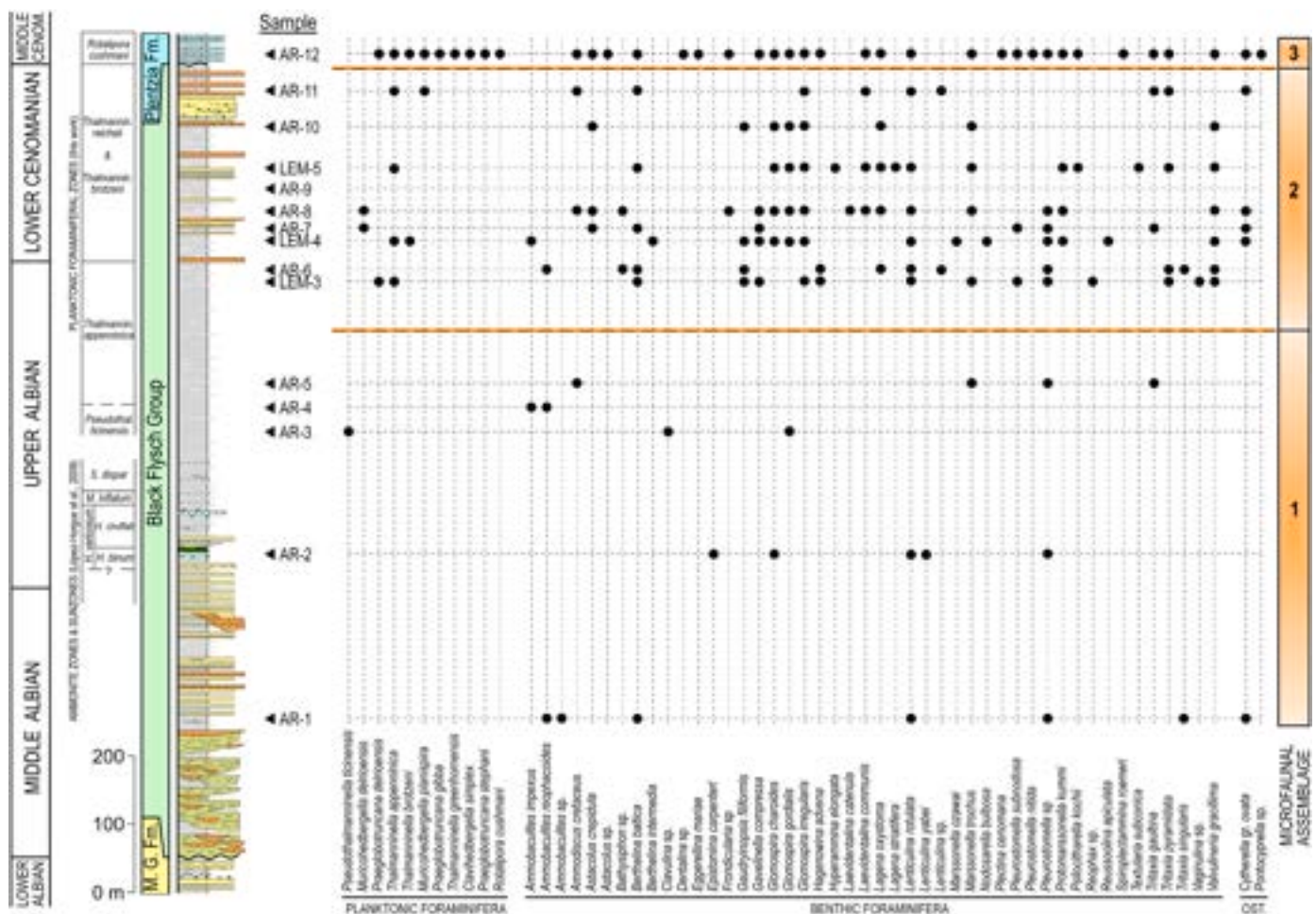


Fig. 4. Distribution of planktonic and benthic foraminifera and ostracods in samples of the Armintza section with indication of the three microfaunal assemblages distinguished (1–3).

at a specific level. However, the microfossil tests are complete and unbroken, and in the case of ostracods, the valves are articulated, suggesting that the microfaunas have not been reworked. This interpretation is also supported by the lack in the microfaunal associations of microfossils of different ages and/or different bathymetric zones (see 5.1. Paleobathymetry section).

Based on the stratigraphic distribution of planktonic and benthic foraminifera and ostracod species and microfaunal indicators, three microfaunal assemblages (MA1 to MA3) can be distinguished in the Armintza section (Figs. 4 and 6). MA1 (samples AR-1 to AR-5) ranges from the middle Albian to the uppermost Albian intra-appenninica Zone (lower part of the Black Flysch Gp.) and it is dominated by *Pseudothalmanninella ticinensis* (Gandolfi) and *Thalmaninella appenninica* (Renz) planktonic species and *Ammobaculites reophacoides* Bartenstein benthic species. MA2 (samples LEM-3 to AR-11) extends from the uppermost Albian intra-appenninica Zone to the lower Cenomanian (upper part of the Black Flysch Gp.), and its main planktonic species is *Thalmaninella brotzeni* Sigal, and dominant benthic species are *Glomospira irregularis* (Grzybowski) and *Glomospira gordiales* (Jones & Parker). MA3 (sample AR-12) belongs to the middle Cenomanian (Plentzia Fm.), appears in marly and marly limestone deposits, and it is dominated by *Rotalipora cushmani* (Morrow) planktonic species and *Plectina cenomana* Carter & Hart and *Protomarssonella kummi* (Zedler) benthic species.

4.2.1. Planktonic foraminifera

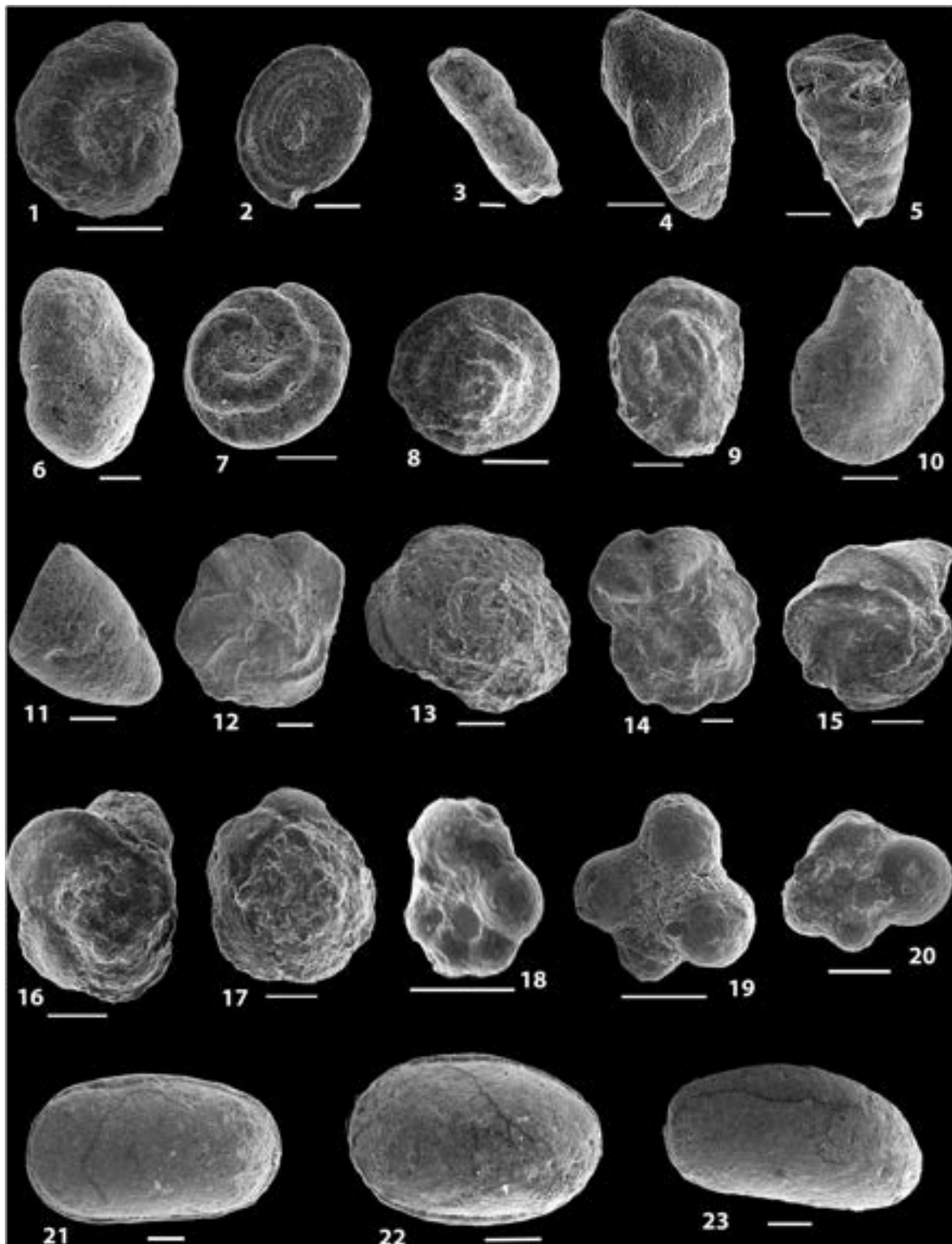
In the studied samples, foraminifera are relatively abundant and the assemblages are dominated by planktonic foraminifera, whereas benthic

counterparts are rare (Figs. 4 and 6 and Table A1). Accordingly, the percentage of planktonic foraminifera in relation to the total foraminifera (%P) in all samples of the section ranges from 91% to 100%. In the MA1 %P is maximum, between 99% and 100%, in the MA2 it ranges from 92% to 100%, and in the MA3 is 91%. A total of 3956 specimens of planktonic foraminifera have been analysed, belonging to 11 species: *Clavhedbergella simplex* (Morrow), *Muricohedbergella debioensis* (Carsey), *Muricohedbergella planispira* (Tappan), *Praeglobotruncana delrioensis* (Plummer), *Praeglobotruncana gibba*, Klaus, *Praeglobotruncana stephani* (Gandolfi), *Pseudothalmanninella ticinensis* (Gandolfi); *Rotalipora cushmani* (Morrow); *Thalmaninella appenninica* (Renz), *Thalmaninella brotzeni*, Sigal; and *Thalmaninella greenhornensis* (Morrow).

Among the planktonic foraminifera, globular morphotypes (*Clavhedbergella*, *Muricohedbergella*) are clearly dominant in the Black Flysch Gp. (MA1 and MA2) with percentages between 91% and 100%, while in the Plentzia Fm. (MA3) the percentage diminishes to 23%, and keeled (*Pseudothalmanninella*, *Rotalipora*, *Thalmaninella*) and incipiently keeled (*Praeglobotruncana*) foraminifera constitute ca. 61% and 16%, respectively (Fig. 6).

4.2.2. Benthic foraminifera

Benthic foraminifera are relatively rare in the studied samples, with only 251 individuals identified, representing ≤1% of the total picked foraminifera (Figs. 4 and 6 and Table A1). In most samples, benthic foraminifera constitute ≤1% of the total foraminifera with the exception of four samples (LEM-3, LEM-4, LEM-5 and AR-12) in which they represent ≤8%. The number of benthic foraminifera specimens per



**Fig. 5.** SEM microphotographs of most characteristic benthic forams (1–11), planktonic forams (12–20) and ostracods (21–23) from this study. Samples are indicated. C, carapace. White bar scale is 100  $\mu$ m. 1. *Gavelinella compressa*; LEM-3. 2. *Ammodiscus cretaceous*; AR-12. 3. *Reophax* sp.; LEM-3. 4. *Tritaxia pyramidata*; AR-6. 5. *Marssonella ozawai*; LEM-4. 6. *Plectina cenomana*; AR-12. 7. *Glomospira charoides*; AR-8. 8. *Glomospira corona*; AR-10. 9. *Glomospira irregularis*; AR-10. 10. *Lenticulina rotulata*; AR-12. 11. *Textularia subconica*; LEM-5. 12. *Thalmaninella appeninica*, dorsal view; LEM-3. 13. *Thalmaninella greenhornensis*, dorsal view; AR-12. 14. *Thalmaninella greenhornensis*, ventral view; AR-12. 15. *Thalmaninella brotzeni*, dorsal view; LEM-4. 16. *Rotalipora cushmani*, dorsal view; AR-12. 17. *Pseudothalmaninella ticinensis*, dorsal view; AR-3. 18. *Muricohedbergella planispira*; AR-11. 19. *Claviohedbergella simplex*; AR-12. 20. *Muricohedbergella delrioensis*; AR-8. 21. *Cytherella* sp. C, left view; AR-12. 22. *Cytherella* sp., C, left view; AR-12. 23. *Pontocyprilla* sp. C, left view; AR-12.

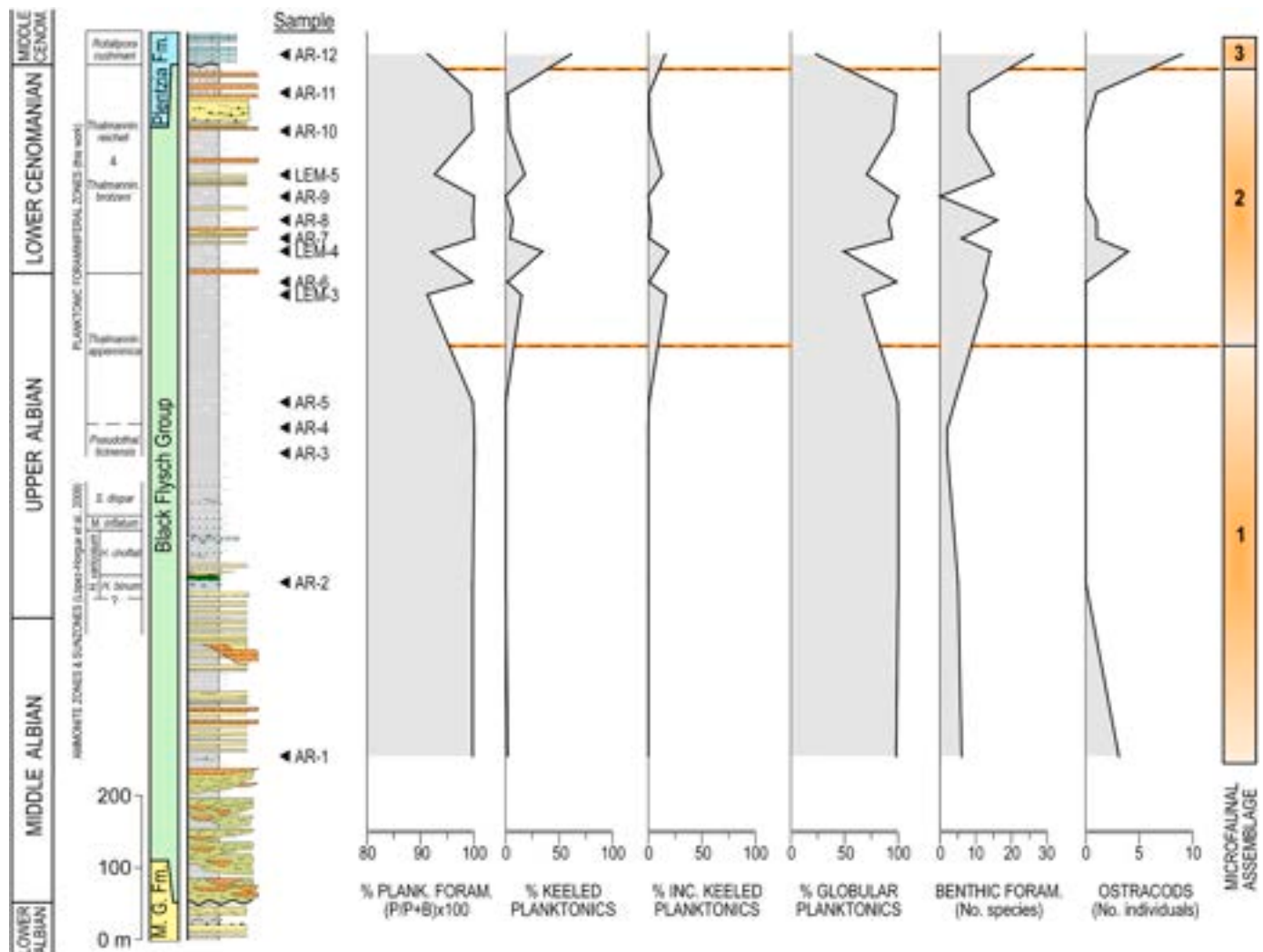


Fig. 6. Relative abundances of paleoenvironmental diagnostic microfaunal taxa in the Armitza section. Distinguished three microfaunal assemblages (1–3) are indicated.

sample ranges from 2 to 65, with no specimens in sample AR-9. Benthic foraminifera are grouped into 46 species of which the most abundant are: *Glomospira gordialis*, *Glomospira irregularis*, *Lenticulina rotulata* and *Pleurostomella* sp. From benthic foraminifera, we recorded 125 agglutinated (*Textulariina*) and 126 hyaline (*Rotaliina*) tests, and no porcelaneous foraminifera (*Milioliina*) have been found.

In the microfaunal assemblage 1 (MA1) dominant species are *Ammobaculites reophacoides* and *Pleurostomella* sp. with fractured and pyritized tests, in addition to *Lenticulina rotulata*. The number of individuals per sample is very low, ranging from 2 to 13, and the number of species is also low (2–6). The proportion of agglutinated shells is 72% on average per sample.

The microfaunal assemblage 2 (MA2) is dominated by the species *Glomospira gordiales*, *Glomospira irregularis*, *Lenticulina rotulata* and *Gavelinella compressa*. The number of both individuals and species are higher than in the MA1 and lower than in the MA3, and in one sample (AR-9) no benthic foraminifera have been found. In benthic foraminifera-containing samples the number of individuals per sample ranges from 38 to 8 (mean = 19), and the number of species per sample ranges from 16 to 6 (mean = 11). Proportion of agglutinated shells (mean = 45%) diminishes with respect to that of MA1 although it is highly variable, ranging between 12% and 65% per sample.

In the microfaunal assemblage 3 (MA3) dominant species are *Plectina cenomana*, *Protomarrsonella kummi*, *Ammodiscus cretaceous*, *Glomospira*

*charoides*, *Pleurostomella* sp. and *Valvulineria gracillima*. The number of benthic foraminifera individuals (65) and number of species (26) augment with respect to MA1 and MA2. In this assemblage, proportions of agglutinated and hyaline shells are similar (49% and 51%, respectively).

#### 4.2.3. Ostracods

Ostracods are very scarce in the collected samples, with a total of 19 individuals in total, belonging to two species, *Cytherella* gr. *ovata* (Roemer, 1840) (16 individuals) and *Pontocyprilla* sp. (3 individuals, all in the sample AR-12) (Figs. 4 and 6). They present complete carapaces with articulated valves. In the samples of the MA1, with the exception of sample AR-1 (3 individuals), no ostracods have been found. In the MA2, the number of ostracod individuals ranges between 0 and 4 per sample and in the MA3 the number is 9.

## 5. Discussion

### 5.1. Paleobathymetry

Foraminifers may represent a valuable proxy for assessing the paleodepth of sediment deposition (e.g. van Morkhoven et al., 1986). Criteria that can be taken into account when estimating the paleodepth include the proportion of planktonic to total foraminifers (%P index),

the distribution of benthic foraminifera, shell morphology, and wall types (Brasier, 1980; Gibson, 1989). In present-day normal (oxic) marine conditions, the %P generally increases with increasing water depth (Berger and Diester-Haas, 1988; Gibson, 1989; Murray, 1991; Seyve, 1990; van der Zwaan et al., 1990), and this finding has been used for estimating paleodepth in ancient marine successions. However, it should also be noted that the %P index, besides a marker of paleobathymetry, it is an indicator of the oxygen level of bottom waters (van der Zwaan et al., 1990; van Hinsbergen et al., 2005). In the case of oxygen-depleted sea bottoms, stress conditions such as eutrophication and lack of ventilation led to decrease in the abundance and diversity of benthic foraminifera with respect to oxic conditions and therefore an apparent increase of the %P (van der Zwaan et al., 1990; van Hinsbergen et al., 2005). In the studied samples, obtained %P values for the three microfaunal assemblages are >91% and in many samples they are around 98%. Comparing these values with normal marine %P values (Gibson, 1989; Murray, 1991; van der Zwaan et al., 1990) they would indicate a lower bathyal to abyssal paleodepth. However, we interpret that this result overestimates the actual paleodepth of the studied rocks when taking into account that the interpreted hypoxic to anoxic conditions of the seafloor (see section 5.2. Seafloor oxygenation) would have greatly affected the %P.

Alternative criteria to constrain paleodepths are based on the spatial distribution patterns of benthic foraminifera (Holbourn et al., 2001; Sikora and Olsson, 1991; van Morkhoven et al., 1986). The association of benthic foraminifera species of the Armintza section (Fig. 4 and Table A1) indicates a bathyal paleodepth. Most of the Armintza species belong to genera characteristic of upper bathyal depths (200–600 m) such as *Ammobaculites*, *Ammodiscus*, *Bathysiphon*, *Dentalina*, *Gavelinella*, *Glomospira*, *Lenticulina*, *Nodosarella* and *Tritaxia* (Gräfe, 2005; Koutsoukos and Hart, 1990; Sliter and Baker, 1972), and more concretely to the lowermost part of this zone (Kaiho et al., 1993). In addition, species of genera common in middle bathyal depths (600–1000 m) such as *eggerellina*, *Laeidentalina* and *Spiroplectammina* also occur (Kaiho et al., 1993). Based on the above data, a paleodepth of around 600 m (limit between upper and middle bathyal zones) can be estimated for the deposition of Armintza section's rocks. This paleodepth is in agreement with the presence of an intermediate water mass inferred from benthic foraminifera species and shell morphology of planktonic foraminifera (see section 5.3. Water masses). In addition, the absence of porcelaneous foraminifera in this section is congruent with bathyal paleodepths (Boltovskoy, 1965), as well as the high proportion of agglutinated benthic foraminifera (around 50%), which indicates cold bathyal conditions (Murray, 1991).

## 5.2. Sea-floor oxygenation

In the samples of the Armintza section, the low richness of benthic foraminifera (1%–8%; see Fig. 6 and Table A1) considering the estimated paleodepth is interpreted as indicative of low oxygen conditions. Moreover, in these samples benthic foraminifera species that are resistant to conditions of hypoxia are proportionally abundant (Fig. 4 and Table A1), with a total of 20 species (Jarvis et al., 1988; Koutsoukos et al., 1990; Kuhnt, 1992; Rodríguez-Lázaro et al., 1998; Tronchetti and Grosheny, 1990). In the MA1, benthic foraminifera that can live in minimum oxygen conditions reach on average 67% (range between 50% and 100%) and are dominated by *Ammobaculites reophacoides* and *Ammobaculites* sp. (Koutsoukos et al., 1990). This percentage decreases to 59% (range between 25% and 78%) in the MA2, in which dominant species are *Lenticulina rotulata*, *Gavelinella compressa*, *Glomospira irregularis* and *Glomospira gordialis*. In the MA3, the percentage decreases to 33.8% with *Valvulineria gracillima* as dominant species. The high percentages of hypoxia-tolerant benthic foraminifera in the three microfossil assemblages indicate that sea-floor hypoxia conditions maintained during the whole time span of the Armintza succession deposition (e.g. Koutsoukos et al., 1990). Nevertheless, the variation of these

percentages in the three microfaunal assemblages together with the variations in the richness of benthic foraminifera suggest a decrease in the severity of hypoxia conditions from the MA1 to the MA3.

Another hypoxia index is the proportion of different shell types of benthic foraminifera (Koutsoukos et al., 1990; Frontalini et al., 2016). In seafloors with moderate degree of oxygen depletion (0.1–0.5 ml/l) and quasi-anaerobic conditions (0–0.1 ml/l) the proportion of agglutinated foraminifera increases importantly (ca. 10–30% of the total benthic foraminifera or even higher). In the studied samples of the three microfaunal assemblages, the mean proportion of agglutinated shells is >45% which suggests conditions of high hypoxia to quasi-anoxia. It has been previously documented that agglutinated foraminifera are abundant in seafloors with low oxygen, high CO<sub>2</sub>, low pH and slightly negative redox potential (Koutsoukos et al., 1990 and references therein).

The rare ostracod specimens collected in the Armintza section (20 individuals) belong to the platycopid genus *Cytherella* and the cypridacean genus *Pontocyprilla* that can resist low levels of dissolved oxygen and provide evidence for hypoxia (platycopid and Cypridacea “signals”; Whatley, 1995). Whatley et al. (2003) established a negative correlation between platycopid dominance and dissolved oxygen concentration. Following this correlation, the proportion of platycopids (100%) of the MA1 and the MA2 would indicate severe hypoxia conditions with dissolved oxygen concentration <1.5 ml/l, and in the case of the MA3 weakly hypoxia with oxygen concentrations of 2–2.5 ml/l. Moreover, the absence of platycopids and any other ostracods in many samples of the MA1 and the MA2 could indicate that conditions were so strongly hypoxic (anoxic?) that they were unable to inhabit the seabed (Rodríguez-Lázaro et al., 1998). The weakly hypoxic conditions interpreted for the MA3 are in agreement with the increase in benthic foraminifera abundance and taxonomic richness and the occurrence of the cypridacean species *Pontocyprilla* sp., which was interpreted as less tolerant to severe hypoxia than platycopid species (Rodríguez-Lázaro et al., 1998).

## 5.3. Water-masses

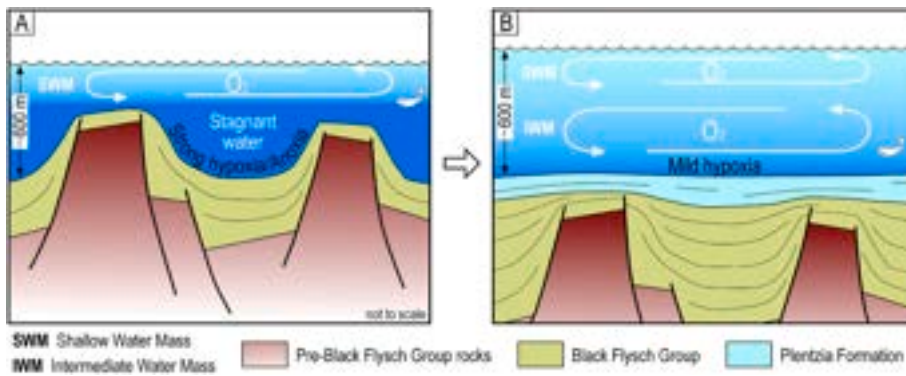
The proportions of the different shell morphotypes of planktonic foraminifera (globular, incipiently keeled and keeled) permit the identification of shallow, intermediate and deep water masses (Jarvis et al., 1988; Bellier, 1989; Crumière, 1989; Tur, 1996; Rodríguez-Lázaro et al., 1998). The proportions of globular planktonic foraminifera in the MA1 and the MA2 (Black Flysch Gp.) are >99% and 50–100%, respectively, with a mean of 90%, indicating the presence of a shallow water mass (Fig. 6 and Table A1). Nevertheless, in the MA2, the samples with lowest proportions (49%–71%) of globular shells would suggest a slight influence of intermediate water masses. Contrary, in the MA3 (Plentzia Fm.) the significant decrease of globular planktonic foraminifera (23%) and increase of keeled individuals (60%), as well as the increment of benthic foraminifera common in intermediate water masses, indicate the apparent presence of an intermediate water mass.

Several of the benthic foraminifera species found in this work also characterise water masses (Paul et al., 1994). There are species characteristics of shallow, intermediate and deep waters, although the highest percentage (13 species) corresponds to intermediate waters (Kaiho et al., 1993; Murray, 1995; Rodríguez-Lázaro et al., 1998; Tur, 1996) (see Fig. 4 and Table A1).

## 5.4. Deep-water basin configuration and evolution

The paleoenvironmental interpretation of the Armintza section, based on the analysis of microfaunal assemblages, is intimately related with the tectono-sedimentary evolution of the northern margin of the BCB during Albian-Cenomanian times. During the deposition of the Black Flysch Gp. in middle Albian-early Cenomanian times, active transtensive rifting led to formation of deep-water, fault-bounded sub-





**Fig. 7.** Cartoons illustrating interpretations of paleoenvironmental conditions and basin configurations during the Albian-Cenomanian in the Armintza area. A) Middle Albian-early Cenomanian. Syn-rift deep-sea (~600 m) deposition of organic-rich Black Flysch sediments with strong morphotectonic control causing stagnation of deep water and strong hypoxia/anoxia conditions on the seafloor. An oxic shallow water mass would circulate freely above submarine structural highs. B) Middle Cenomanian. Post-rift deposition of organic-poor Plentzia Fm. sediments influenced by the inflow of an intermediate water mass. On the wide and smooth seafloor mild hypoxia conditions would dominate.

basins and salt withdrawal minibasins filled with siliciclastic turbiditic deposits (Agirrezabala, 1996; Agirrezabala and García-Mondéjar, 1994; García-Mondéjar et al., 1996; Agirrezabala and Dinarès-Turell, 2013; Poprawski et al., 2014; Roca et al., 2021). As a result, seafloor morphotectonic relief was steep and very irregular with low subsident highs and strongly subsident troughs (Fig. 7A). Southward-directed turbidite fans and slope systems channelized along the deep troughs resulting in organic-rich thick turbidite deposits. In the case of the Armintza trough and based on microfaunal analysis at hand, a paleodepth of around 600 m was presented above. The presence of abundant terrestrial organic matter (TOC ~1–1.3%), early diagenetic siderite and framboidal pyrite in the turbidite deposits indicates suboxic to anoxic conditions near the seafloor, which are corroborated by the microfaunal analysis of the Black Flysch deposits (MA1 and MA2). The steep and irregular submarine physiography would have hindered the circulation of deep waters, leading to water stagnation. In these conditions, the oxidation of part of the abundant organic matter present in the sediments would have led to a decrease in dissolved oxygen levels in water and the development of strong hypoxia to anoxia conditions on the seafloor. These conditions would have been slightly softened during the latest late Albian-early Cenomanian as the MA2 suggests. However, very high proportions of globular planktonic foraminifera in this lithostratigraphic unit indicate the presence of a shallow water mass. The free circulation of oxic shallow waters would have been possible above the submarine structural highs (Fig. 7A).

At the middle Cenomanian, a major tectono-sedimentary change took place in the BCB and syn-rift subsidence was replaced by post-rift subsidence (Ford et al., 2022; Jammes et al., 2009; Pedrera et al., 2017; Tugend et al., 2015). As a result, in the Armintza area during middle Cenomanian-Santonian times organic-poor hemipelagic marls, limestones and calcarenitic turbidites of the Plentzia Fm. were deposited on a deep-water, relatively flat and wide seafloor (Mathey, 1987). Microfaunal analysis of these deposits (MA3) evidences an important increase in both keeled planktonic foraminifera and benthic foraminifera characteristic of intermediate waters suggesting the end of water stagnation and the presence of an intermediate water mass (Fig. 7B). The inflow of the intermediate water mass would have been possible due to the new configuration of the deep seabed in which the absence of submarine sills would have permitted the inflow of deeper waters. The entrance of the intermediate water mass together with the deposition of organic-poor sediment led to partial oxygenation of the seafloor and the development of mild hypoxia conditions (Fig. 7B).

## 6. Conclusions

Albian-Cenomanian microfaunal assemblages (planktonic and benthic foraminifera and ostracods) from the Black Flysch Gp. and Plentzia Fm. at the Armintza section (westernmost Pyrenees) have been studied to determine paleoenvironmental conditions of deposition. Based on the high proportion of planktonic foraminifera and the assemblages of benthic foraminifera species, a paleodepth of ~600 m is estimated for the studied units. During syn-rift deposition of the organic-rich Black Flysch Gp. in middle Albian-early Cenomanian times, the high abundance of planktonic foraminifera (%P between 98% and 91%) most of which are globular species (90%), together with the occurrence of hypoxia-tolerant benthic foraminifera and rare platycopid ostracods indicate the presence of a shallow water mass and the stagnation of deep waters with severe hypoxia conditions (<1.5 ml/l) or even anoxia at the seafloor. During post-rift deposition of the organic-poor Plentzia Fm. in middle Cenomanian times, microfaunal assemblage shows an important increase in benthic foraminifera species, many of which indicate intermediate waters, and dominance of keeled planktonic foraminifera suggesting the end of water stagnation and the inflow of an intermediate water mass. In addition, the presence of hypoxia-tolerant species of ostracods and benthic foraminifera points out the development of mild hypoxia conditions at the seafloor.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luis M. Agirrezabala reports financial support was provided by Eusko Jaurlaritza. Luis M. Agirrezabala reports financial support was provided by Spanish State Research Agency. Ana Pascual reports financial support was provided by Basque Government. Julio Rodriguez-Lazaro reports financial support was provided by Basque Government.

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Table A1 (continued)

ARMINTZA section Benthic foraminifera	Samples												Upper bathyal	Middle bathyal	Lower bathyal	Hypoxic	Shallow-water mass	Middle-water mass	Deep-water mass	
	AR-1	AR-2	AR-3	AR-4	AR-5	LEM-3	AR-6	LEM-4	AR-7	AR-8	AR-9	LEM-5								AR-10
<i>Lenticulina yabei</i> Takayanagi, 1960	1												X	X		X		X		
<i>Lenticulina</i> sp.													X	X		X		X		
<i>Marssonella ozawai</i> Cushman, 1936															2	X		X		
<i>Marssonella trochus</i> (d'Orbigny, 1840)																X		X		
<i>Nodosarella bulbosa</i> Ten Dam, 1950															1				X	
<i>Plectina cenomana</i> Carter & Hart, 1977													6				X			
<i>Pleurostomella subnodosa</i> (Reuss, 1851)															1					
<i>Pleurostomella nitida</i> Morrow, 1934																			2	
<i>Pleurostomella</i> sp.	2	2		1	1	1	1	1	3	3					4					
<i>Protomarssonella kummi</i> (Zedler, 1961)																	X		X	
<i>Psilocitharella kochii</i> (Roemer, 1841)																1			1	
<i>Reophax</i> sp.																		1		
<i>Reussoolina apiculata</i> (Reuss, 1851)															1					
<i>Spiroplectammina roemeri</i> Lalicker, 1935																		2	X	
<i>Textularia subconica</i> Franke, 1928																1			X	
<i>Tritaxia gaultina</i> (Morozova, 1948)																		1	1	X
<i>Tritaxia pyramidata</i> Reuss, 1863																		2	2	
<i>Tritaxia singularis</i> Magniez-Jannin, 1975	1																		1	
<i>Vaginulina</i> sp.																		1		
<i>Valvulineria gracillima</i> Ten Dam, 1947																		1	1	2
No. individuals	13	7	2	2	4	21	13	27	8	38	0	26	16	9	65					
Richness (No. individuals/g of sediment)	12	2	1	1	2	66	3	26	2	11	0	18	2	1	17					
No. species	6	5	2	2	4	13	12	14	6	16	0	15	8	8	26					
No. agglutinated	9	1	2	2	3	7	7	14	1	16	0	17	10	4	32					
No. hyalines	4	6	0	0	1	14	6	13	7	22	0	9	6	5	33					
Agglutinated %	69	14	100	100	75	33	53	51	12	42	0	65	62	44	49					
No. individuals upper bathyal (200–600m)	10	4	1	2	2	13	8	18	3	25	0	16	10	7	27					
No. individuals middle bathyal (600–1000m)	1	4	1	0	0	10	2	15	1	22	0	15	7	5	19					
No. individuals hypoxia	10	4	1	2	2	14	7	21	2	19	0	19	10	6	28					
No. individuals shallow water mass	1	0	0	0	0	9	2	2	2	1	0	1	0	1	13					

(continued on next page)



- northwest europe. *Cretac. Res.* 15, 707–738. <https://doi.org/10.1006/cres.1994.1039>.
- Pedraza, A., García-Senz, J., Ayala, C., Ruiz-Constán, A., Rodríguez-Fernández, L.R., Robador, A., González-Menéndez, L., 2017. Reconstruction of the exhumed mantle across the North-Iberian margin by crustal-scale 3D gravity inversion and geological cross section. *Tectonics* 36, 3155–3177. <https://doi.org/10.1002/2017TC004716>.
- Poprawski, Y., Basile, C., Agirrezabala, L.M., Jaillard, E., Gaudin, M., Jacquin, T., 2014. Sedimentary and structural record of the Albian growth of the Bakio diapir (the Basque Country, northern Spain). *Basin Res.* 26, 746–766. <https://doi.org/10.1111/bre.12062>.
- Rat, P., 1988. The Basque-Cantabrian basin between the Iberian and European plates. Some fact but still many problems. *Rev. Soc. Geol. Esp.* 1, 327–348.
- Robaszynski, F., Caron, M., Gonzalez Donoso, J.M., Wonders, A.A.H., 1984. Atlas of late cretaceous globotruncanids. *Rev. Micropaleontol.* 26, 145–305.
- & European working group on planktonic foraminifera. In: Robaszynski, F., Caron, M. (Eds.), 1979. Atlas of Mid Cretaceous Planktonic Foraminifera (Boreal Sea and Tethys). Parts 1–2. *Cahiers Micropaléontol.*, pp. 1–366.
- Robaszynski, F., Caron, M., 1995. Foraminifères planctoniques du Crétacé: commentaire de la zonation Europe-Méditerranée. *Bull. Soc. Geol. Fr.* 166, 681–692.
- Robles, S., Pujalte, V., García-Mondéjar, J., 1988. Evolución de los sistemas sedimentarios del margen continental cantábrico durante el Albiense y Cenomaniense, en la transversal del litoral vizcaíno. *Rev. Soc. Geol. Esp.* 1, 409–441.
- Roca, E., Ferrer, O., Rowan, M.G., Muñoz, J.A., Butillé, M., Giles, K.A., Arbués, P., Matteis, M., 2021. Salt tectonics and controls on halokinetic-sequence development of an exposed Deepwater diapir: the Bakio Diapir, Basque-Cantabrian Basin, Pyrenees. *Mar. Petrol. Geol.* 123, 104770 <https://doi.org/10.1016/j.marpetgeo.2020.104770>.
- Rodríguez-Lázaro, J., Pascual, A., Elorza, J., 1998. Cenomanian events in the deep western Basque Basin: the Leioa section. *Cretac. Res.* 19, 673–700. <https://doi.org/10.1006/cres.1998.0125>.
- Scotese, C.R., 2021. An atlas of phanerozoic paleogeographic maps: the seas come in and the seas go out. *Annu. Rev. Earth Planet Sci.* 49, 679–728. <https://doi.org/10.1146/annurev-earth-081320-064052>.
- Seyve, C., 1990. *Introdução à Micropaleontologia*. Universidade A. Neto, Elf Aquitaine, Angola.
- Sikora, P.J., Olsson, R.K., 1991. A paleoslope model of late Albian to early Turonian foraminifera of the western Atlantic margin and North Atlantic basin. *Mar. Micropaleontol.* 18, 25–72. [https://doi.org/10.1016/0377-8398\(91\)90005-Q](https://doi.org/10.1016/0377-8398(91)90005-Q).
- Sliter, W.V., Baker, R.A., 1972. Cretaceous bathymetric distribution of benthic foraminifera. *J. Foraminif. Res.* 2, 167–183. <https://doi.org/10.2113/gsjfr.2.4.167>.
- Souquet, P., Debroas, E.-J., Boirie, J.-M., Pons, P., Fixari, G., Roux, J.-C., Dol, J., Thieuloy, J.-P., Bonnemaïson, M., Manivit, H., Peybernes, B., 1985. Le groupe du Flysch noir (Albo-Cenomaniens) dans les Pyrénées. *Bull. Centr. Rech. Expl. Prod. Elf Aquitaine* 9, 183–252.
- Tronchetti, G., Grosheny, D., 1990. Les assemblages de foraminifères benthiques au passage Cénomaniens-Turonien à Vergons, S-E France Benthic foraminiferal assemblages from the Cenomanian-Turonian boundary transition at vergons. *S.E. France. Geobios* 24, 13–31. [https://doi.org/10.1016/0016-6995\(91\)80032-U](https://doi.org/10.1016/0016-6995(91)80032-U).
- Tugend, J., Manatschal, G., Kusznir, N.J., 2015. Spatial and temporal evolution of hyperextended rift systems: implication for the nature, kinematics, and timing of the Iberian-European plate boundary. *Geology* 43, 15–18. <https://doi.org/10.1130/G36072.1>.
- Tur, N.A., 1996. Planktonic foraminifera recovery from the Cenomanian-Turonian mass extinction event, northeastern Caucasus. *Geol. Soc. Spec. Publ.* 102, 259–264. <https://doi.org/10.1144/GSL.SP.1996.001.01.19>.
- van der Zwaan, G.J., Jorissen, F.J., De Stigter, H.C., 1990. The depth dependency of planktonic/benthic foraminiferal ratios: constraints and applications. *Mar. Geol.* 95, 1–16. [https://doi.org/10.1016/0025-3227\(90\)90016-D](https://doi.org/10.1016/0025-3227(90)90016-D).
- van Hinsbergen, D.J.J., Kouwenhoven, T.J., van der Zwaan, G.J., 2005. Palaeobathymetry in the backstripping procedure: correction for oxygenation effects on depth estimates. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 221, 245–265. <https://doi.org/10.1016/j.palaeo.2005.02.013>.
- van Hinte, J.E., 1978. Geohistory analysis—application of micropaleontology in exploration. *Geology. Bull. Am. Assoc. Petrol. Geol.* 62, 201–222, 10.1306.
- van Morkhoven, F.P.C.M., Berggren, W.A., Edwards, A.S., 1986. Cenozoic cosmopolitan deep-water benthic foraminifera. *Bull. Centr. Rech. Expl. Prod. Elf Aquitaine* 11, 1–421.
- Whatley, R.C., 1995. Ostracoda and oceanic palaeoxygen levels. *Mitt. Hambg. Zool. Mus. Inst.* 92, 337–353.
- Whatley, R.C., Pyne, R.S., Wilkinson, I.P., 2003. Ostracoda and palaeo-oxygen levels, with particular reference to the upper cretaceous of east anglia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 194, 355–386. [https://doi.org/10.1016/S0031-0182\(03\)00333-X](https://doi.org/10.1016/S0031-0182(03)00333-X).