



Integrated biostratigraphy across the Eocene/Oligocene boundary at Noroña, Cuba, and the question of the extinction of orthophragminids

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With 4 figures and 1 plate

Abstract. Integrated biostratigraphy by means of planktic foraminifera, calcareous nannofossils and larger benthic foraminifera from a continuous marine section at Noroña (Cuba) suggests that the extinction of orthophragminids lies in the Rupelian (early Oligocene). Three levels containing larger benthic foraminifera are found in the lower and middle part of the planktic foraminiferal Zone O1(P18) and in the middle part of the calcareous nannofossil Zone NP21(CP16) (Rupelian). Furthermore, a traditional larger foraminifera Eocene marker, *Fallotella cookei*, is abundant in the Oligocene at the Noroña section, consistent with data reported from lower Oligocene sediments from Cuba, Florida and Jamaica. In order to solve the question of the orthophragminid extinction, which has been shown in some places to coincide with the Eocene/Oligocene boundary, data from the Noroña section are discussed in the view of the presence of these larger benthic foraminifera in lower Oligocene strata in other sections world wide. Our data from Noroña, as well as those from other previously studied sections, suggest that the extinction of the orthophragminids could be diachronous, with disappearances near the Eocene/Oligocene boundary in the low latitudes of the Indo-Pacific region (e. g., Tanzania) as opposed to the Rupelian in the low latitudes of the Caribbean-American bioprovince (e. g. Cuba and Jamaica) and in the middle latitudes of the Tethys (e. g., Italy and Spain).

Key words. Planktic foraminifera, calcareous nannofossils, larger foraminifera, Eocene/Oligocene, Cuba

1. Introduction

Planktic foraminifera and calcareous nannofossils are two of the most widely used fossil groups for biostratigraphy at least since the Cretaceous. Several planktic foraminiferal biozonations for the Paleogene have

been proposed (Blow 1979, Bolli et al. 1985, Berggren et al. 1995, Pearson et al. 2006, Wade et al. 2011, among others). Most of them were established for the low and middle latitudes, where species diversity is higher, and are considered as standard biozonations. Similarly, calcareous nannofossil biozonations for the

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Paleogene have been proposed (Martini 1971, Bukry 1973, Perch-Nielsen 1985, Bown 1998, among others) and are routinely used. To achieve more precise dating, planktic foraminifera and calcareous nannofossils have been studied in the same sections and samples, yielding an integrated stratigraphy for pelagic marine sediments. Larger benthic foraminifera are useful for biostratigraphy in neritic marine sediments, where planktic microfossils are rare. Integrated biozonations between planktic and large benthic foraminifera have been proposed for the Paleocene and Eocene (Serra-Kiel et al. 1998) and for the Oligocene (Cahuzac and Poignant 1997).

Within the framework of the Global Stratotype Section and Point (GSSP) initiative, the International Subcommission on Paleogene Stratigraphy has created working groups to define the different Paleogene GSSPs. Stage and biozone boundaries are constantly updated by studies that also use magnetostratigraphy (Rodríguez-Pinto et al. 2012, among others), and in recent years the approach of integrating stratigraphic data from both planktic and benthic organisms has been followed in a number of studies (e.g., Cotton and Pearson 2011, Gebhardt et al. 2013, Egger et al. 2013).

The boundary between the two stages studied in this paper, the Priabonian and Rupelian, corresponds to the Eocene/Oligocene (E/O) boundary, which has been defined at the extinction level of hantkeninid foraminifera at the Massignano section near Ancona, Italy. This level coincides with the planktic foraminiferal boundary of zones E16/O1 and falls within the calcareous nannofossil zones NP21 and CP16a (Premoli Silva et al. 1988, Premoli Silva and Jenkins 1993). The deep-marine Massignano section yields no larger benthic foraminifera to be correlated with the planktic biozonations, and experts on neritic environments generally have used the extinction of orthophragminids to mark the E/O boundary (Versey, in Zans et al. 1963, Adams et al. 1986, among others). However, Brinkhuis and Visscher (1995) studied the dinoflagellate cysts of the stratotype of the Priabonian Stage and were able to correlate it with the E/O boundary defined in Massignano. The GSSP places the E/O boundary below the top of the Bryozoan Limestone or the Micritic Bed as suggested by Barbin and Bignot (1986), more precisely below the *Asterodiscus* (= *Asterocyclus*) Beds placed within the middle Priabonian stage. At Priabona, *Discocyclus* and *Asterocyclus* disappear in Subunit IIIC and recur in Unit IV, which corresponds to the Gse dinocyst zone; both groups then become extinct in Unit V, slightly above the correlative level of

the transposed E/O boundary at Priabona (Houben et al. 2012). Consequently, the upper Priabonian stage stratotype and the orthophragminids occurrence fall into the early Oligocene, and their extinction level can no longer be used to mark the E/O boundary.

Some authors considered that orthophragminids found in Oligocene strata were reworked (Ferrandez-Cañadell et al. 1999), while others have found apparently not reworked orthophragminids associated with a pristinely preserved Oligocene planktic foraminiferal fauna (Applin and Applin 1944, Martínez-Gallego and Molina 1975, Molina 1980, 1986, Comas et al. 1985, Monechi 1986, Molina et al. 1986, 1988, Bowen-Powell 2010), which implies that orthophragminids became only extinct in the Rupelian.

The E/O extinction event in planktic foraminifera has been associated with the emergence of the circum-Antarctic current (Molina 2015) that would have triggered the prolonged cooling across the Late Eocene, giving rise to the formation of an ice cap in the Antarctic, culminating in the Oi-1 glaciation near the E/O boundary (Kennett and Shackleton 1976). Furthermore, a deepening of the calcite compensation depth occurred synchronously with the stepwise growth of the Antarctic ice-sheet (Coxall et al. 2005).

In order to solve the question of the orthophragminid extinction at the E/O or in the early Oligocene, we have studied the Noroña section in Cuba, which is a continuous marine sequence rich in planktic foraminifera and calcareous nannofossils. A detailed integrated biostratigraphy of three microfossil groups enables us to precisely date three Oligocene levels that contain well-preserved and relatively diverse larger benthic foraminiferal assemblages including many orthophragminids. Therefore, orthophragminids managed to survive the E/O boundary, at least for a while, in Cuba. Together with the observation that earlier extinctions occur at some other locations this suggests that the extinction of orthophragminids was diachronous.

2. Geological setting

The Noroña section is located along an abandoned railway line south-east of the village of Noroña, Guanajay township, in the northern part of Havana province, western Cuba (latitude: 22° 57' 22.907" N; longitude: 82° 41' 43.023" W). The studied section comprises late Eocene to Recent sediments (Iturralde-Vinent 1994). The section is slightly deformed, with

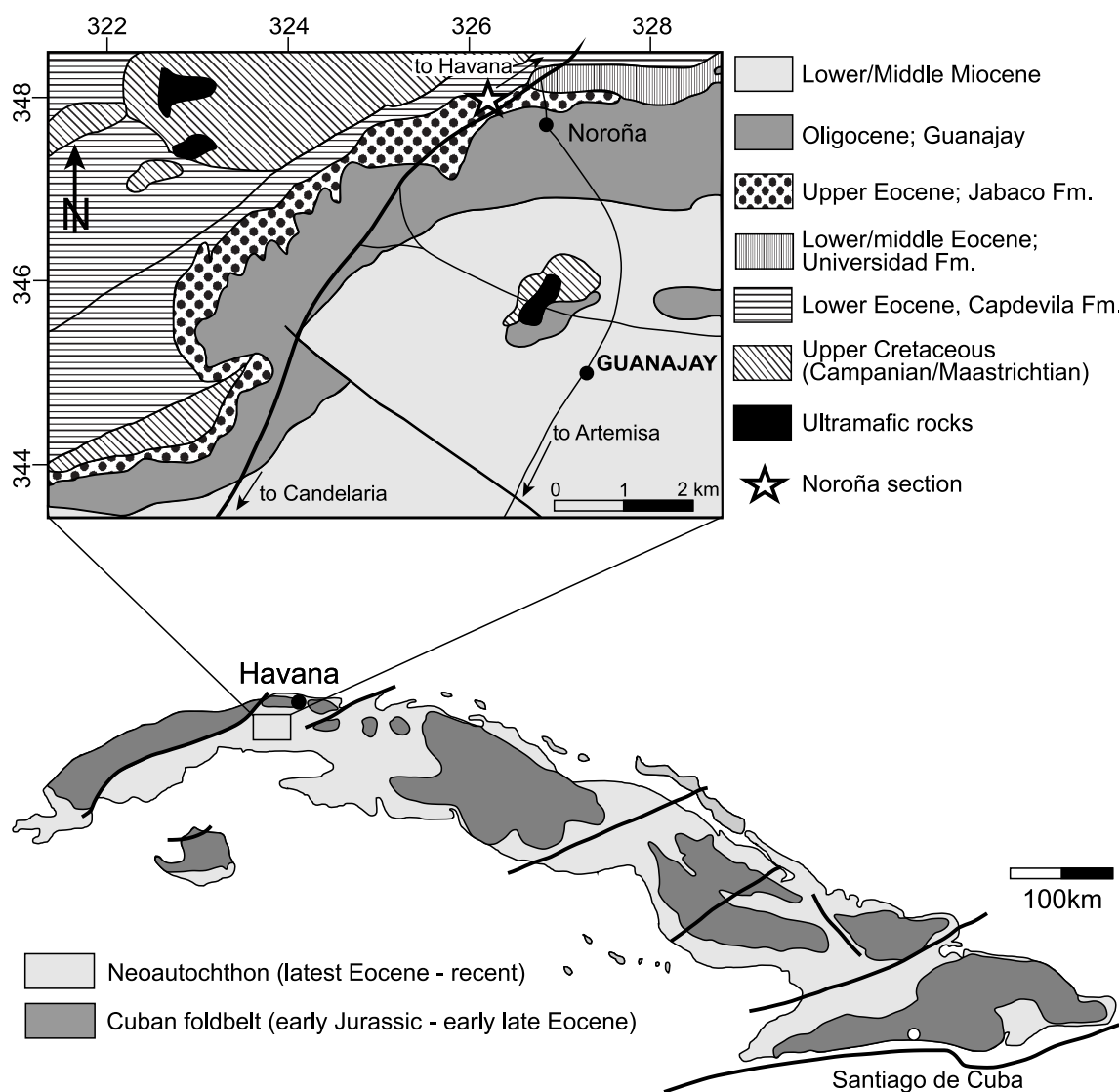


Fig. 1. Geographical and geological setting of the Noroña section in Cuba.

carbonate and clastic sediments that have not been significantly displaced since deposition and unconformably overlie the folded Cuban Belt (Iturralde-Vinent 1994). Previous biostratigraphic and assemblage studies of late Eocene and Oligocene deposits were carried out by Bermúdez (1937, 1950) and Brönnimann and Rigassi (1963), primarily using planktic and small benthic foraminifera. More recent studies, such as Blanco-Bustamante et al. (1987), García-Delgado and Torres-Silva (1997) and Torres-Silva et al. (2001) have focused on the stratigraphic distribution of the larger benthic foraminifera within the postorogenic formations. The nearly 50-m-thick Noroña section, which includes the E/O boundary, is composed of marls with intercalated argillaceous limestones and

occasional sandstone beds assigned here to the Jabaco Formation (Priabonian) and the lower part of the overlying Guanajay Formation (Rupelian) (Fig. 1). The hemipelagic marls and limestones have a distinctive grey-green colour and are rich in both planktic foraminifera and calcareous nannofossils. Larger benthic foraminifera (LBF) are found abundantly in three of the marl beds (Fig. 4).

Small benthic foraminifera have previously been studied by Fenero (2010) and Fenero and Molina (2011). Quantitative analysis of small benthic foraminifera assemblages permitted the reconstruction of the paleoenvironmental and paleoclimatic evolution throughout the section, from the late Eocene to the early Oligocene. This analysis indicates a middle-lower

bathyal depth of deposition, about 1,000 m deep for most of the studied section. Hemipelagic marls interbedded with turbiditic sandstone layers, and the presence of mixed assemblages (sub-litoral and bathyal taxa) could be related to the formation of deep-water channels. A possible glaciation event (Oi-1), which occurred at high latitudes during the early Oligocene (Kennett and Shackleton 1976), was identified at Noroña based on the changes in benthic foraminiferal assemblages (Fenero and Molina 2011).

3. Material and methods

A total of 35 samples were collected at the Noroña section (Priabonian and Rupelian) for an integrated study of the planktic foraminifera, calcareous nannofossils and larger benthic foraminifera. The sample material consists predominantly of marls and, to a lesser degree, of limestones and calcarenites.

Samples for planktic foraminiferal studies were disaggregated in water with diluted H_2O_2 , washed through a 63- μm sieve, and dried at 50°C. The analysis and taxonomic study were based on representative splits of approximately 300 specimens from the > 100 μm fraction, obtained with a modified Otto micro-splitter. The remaining residue was analysed for rare species. All representative specimens were mounted on microslides for identification, and a permanent record is available at the Department of Earth Sciences, University of Zaragoza, Spain.

All samples were prepared for the investigation of calcareous nannofossils using the standard method described by Perch-Nielsen (1985). Smear slides were studied semi-quantitatively using a Leica DMLP transmitted light microscope at 1000x magnification. Results were used to provide a biostratigraphic framework of the section. The zonal schemes of Martini (1971), Okada and Bukry (1980) and Agnini et al. (2014) were applied.

Larger benthic foraminifera were found abundantly in three of the samples from the marls, and these samples were further studied. Samples were prepared using the standard method of washing through a sieve, particularly well-preserved specimens were selected and their external morphology was described in detail using morphologic parameters such as diameter, thickness, shape, and ornamentation. A total of 112 oriented thin sections were prepared in equatorial and axial sections in order to study internal features. The identification of the LBF at the species level was carried out

based on detailed biometric analyses of the internal morphology of the oriented thin sections. For most of the lepidocyclinids, orthophragminids and nummulitids, measurements of the proloculus, deuteroloculus, number of whorls, and shape of equatorial and lateral chambers were essential for identification. Exceptionally well-preserved specimens of most species identified were studied using high-resolution micro-computer tomography (micro CT). This method allows a three-dimensional biometric quantification without any destructive preparation of the test (Briguglio et al. 2014). Equatorial and axial sections were obtained to be viewed virtually from the same specimen (Benedetti and Briguglio 2012, Ferrández-Cañadell et al. 2014). This technique allows the measurement of specific morphological parameters that are crucial for the differentiation of larger foraminifera at the species level (Briguglio et al. 2011, 2013, Briguglio and Hohenegger 2014). The scanner used was a Skyscan 1163 high-energy micro CT at the Department of Paleontology at the University of Vienna, Austria. Taxonomic concepts and biostratigraphic ranges of the larger foraminifera species identified at Noroña were reported according to Butterlin (1981) and Robinson and Wright (1993).

4. Results

The planktic foraminiferal biostratigraphy of the Eocene and Oligocene deposits in the areas of Pinar del Rio, and La Habana was originally established by Bermúdez (1937, 1950) and Brönnimann and Rigassi (1963). More recently, Cruz (2008) recognized four planktic foraminifera biozones (O1 to O4) in the Oligocene of the Noroña section, but the correlation with calcareous nannofossil datums and our planktic foraminiferal data suggests that his biostratigraphic classification is erroneous. We have therefore re-examined the planktic foraminifera biostratigraphy at Noroña in this paper. A total of 29 samples containing rich assemblages of well-preserved planktic foraminifera were studied (Fig. 2). Following Pearson et al. (2006), zones E14, E15 and E16 (Priabonian, late Eocene) and O1 (Rupelian, early Oligocene) were identified. These biozones are correlative with zones P15 to P18 (Berggren et al. 1995). The five lowermost samples contain the most diverse assemblages, which are characterised by *Globigerinatheka semiinvoluta*, *G. index*, *Cribohantkenina inflata*, *Turborotalia cocoensis*, *T. cunialensis*, *Hantkenina primitiva*, *H. alabamensis*, *Cribohantkenina lazzarii*, and *Pseudo-*

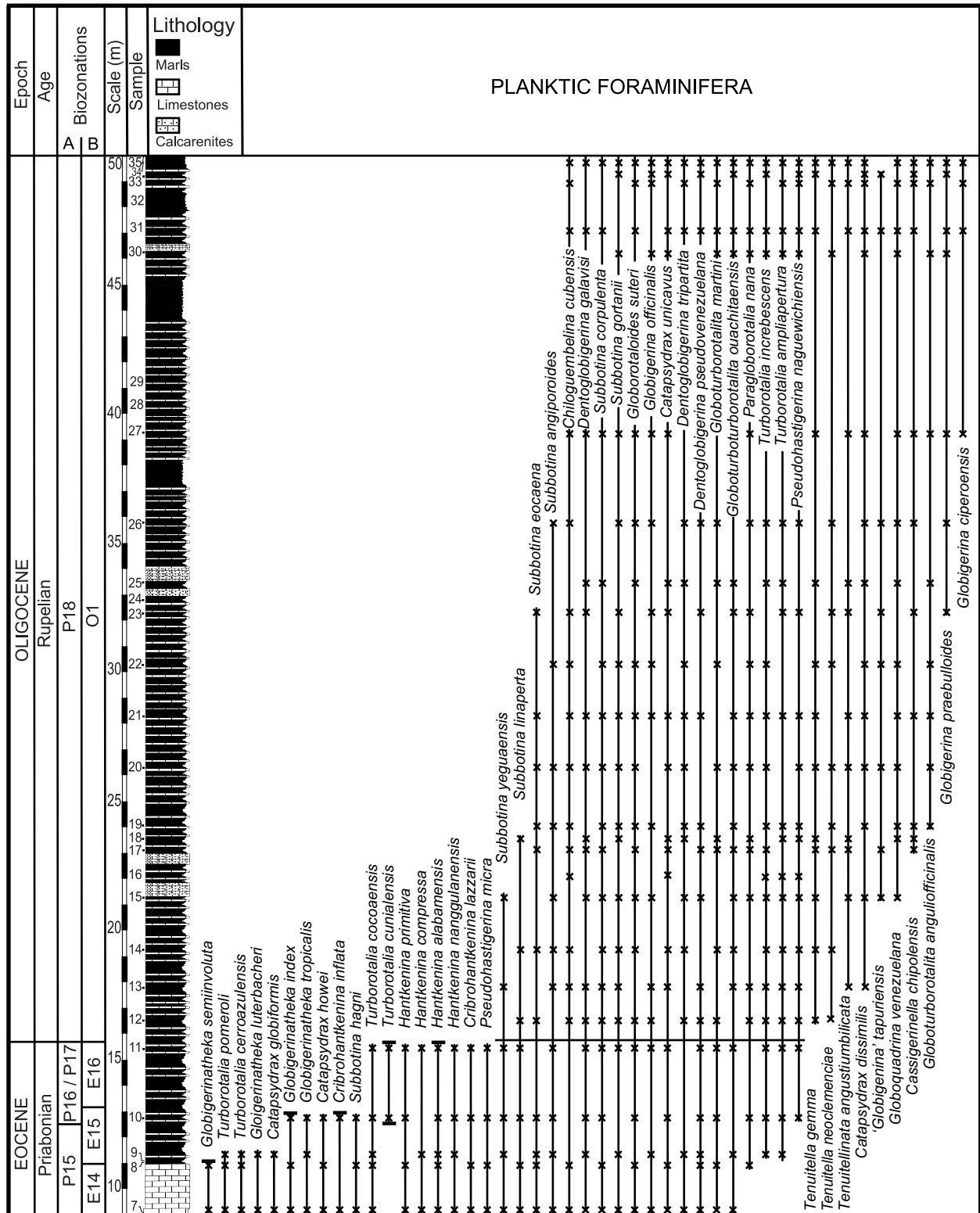


Fig. 2. Planktic foraminiferal biostratigraphy and species ranges at the Noroña section. A: biozonation according to Berggren et al. (1995); B: biozonation according to Pearson et al. (2006).

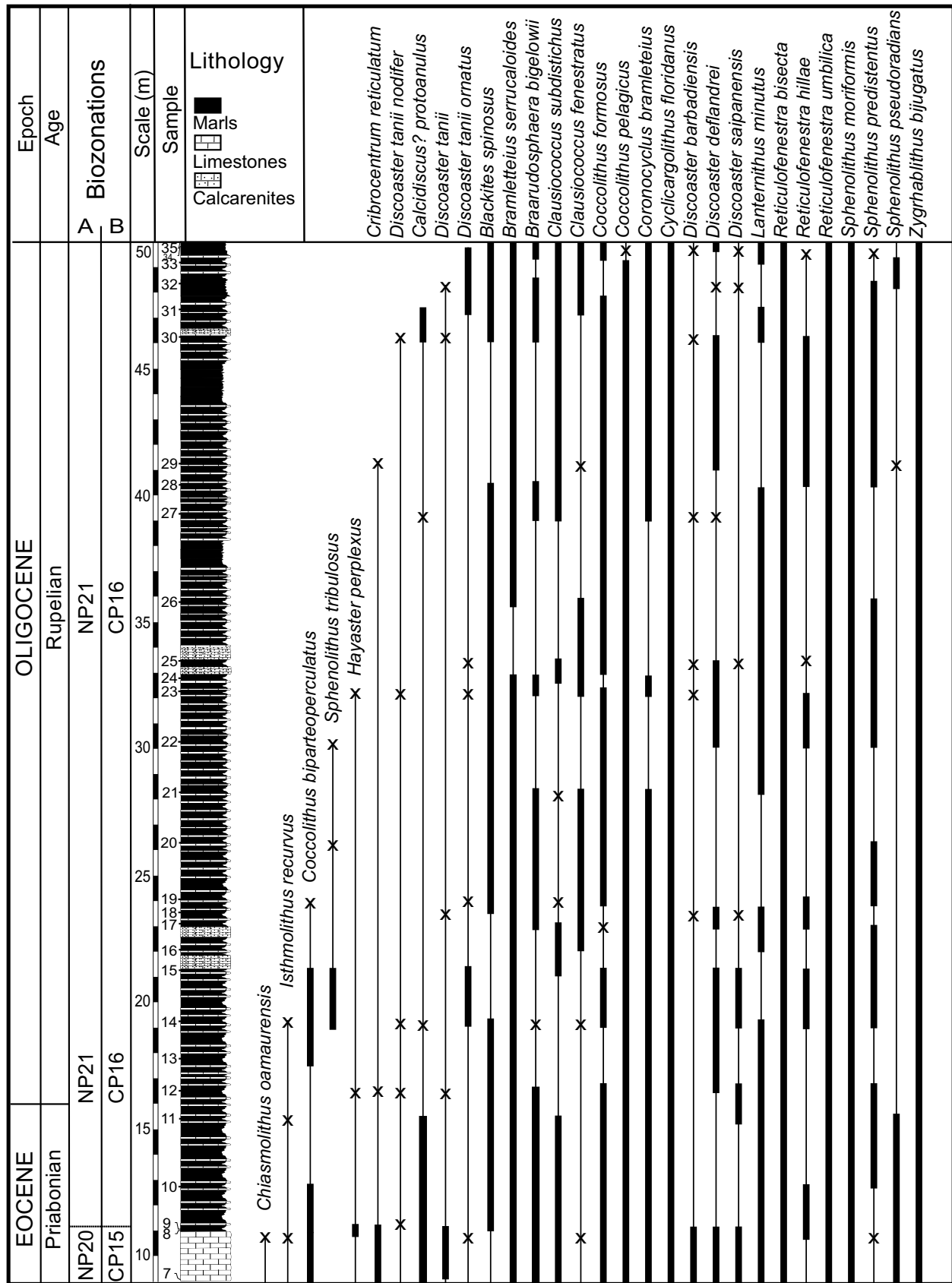


Fig. 3. Calcareous nannofossil biostratigraphy and species ranges at the Noroña section. A: biozonation according to Martini (1971); B: biozonation according to Bukry (1973).

hastigerina micra, which became extinct below or at the E/O boundary. Following previous authors (Martínez-Gallego and Molina 1975, Molina et al. 1986, 1988, Molina 1986, 2015) the small *Pseudohastigerina micra* that apparently survived in the early Oligocene are here included in *P.nagewichiensis*. These species were better adapted to warm/temperate waters and are k-strategists (Molina 2015, among others). Less diverse assemblages characterize the lower Rupelian Zone O1, where taxa dominating the assemblages are mainly cosmopolitan, r-strategists. The most characteristic species are: *Pseudohastigerina nagewichiensis*, *Tenuitella gemma*, *Turborotalia ampliapertura*, *Catapsydrax dissimilis*, “*Globigerina*” *tapuriensis*, and *Cassigerinella chipolensis*. These taxa are adapted to cooler waters and could be interpreted to reflect a temperature decrease connected to the Oi-1 glacial event.

Calcareous nannofossils from the area of Noroña were first investigated by Brönnimann and Stradner (1960), Stradner and Papp (1961), and Brönnimann and Rigassi (1963). These authors described calcareous nannofossil zones from the Eocene of Cuba based on the distribution of discoasterids; through this effort they achieved a correlation with other Eocene sections from the Caribbean-American bioprovince.

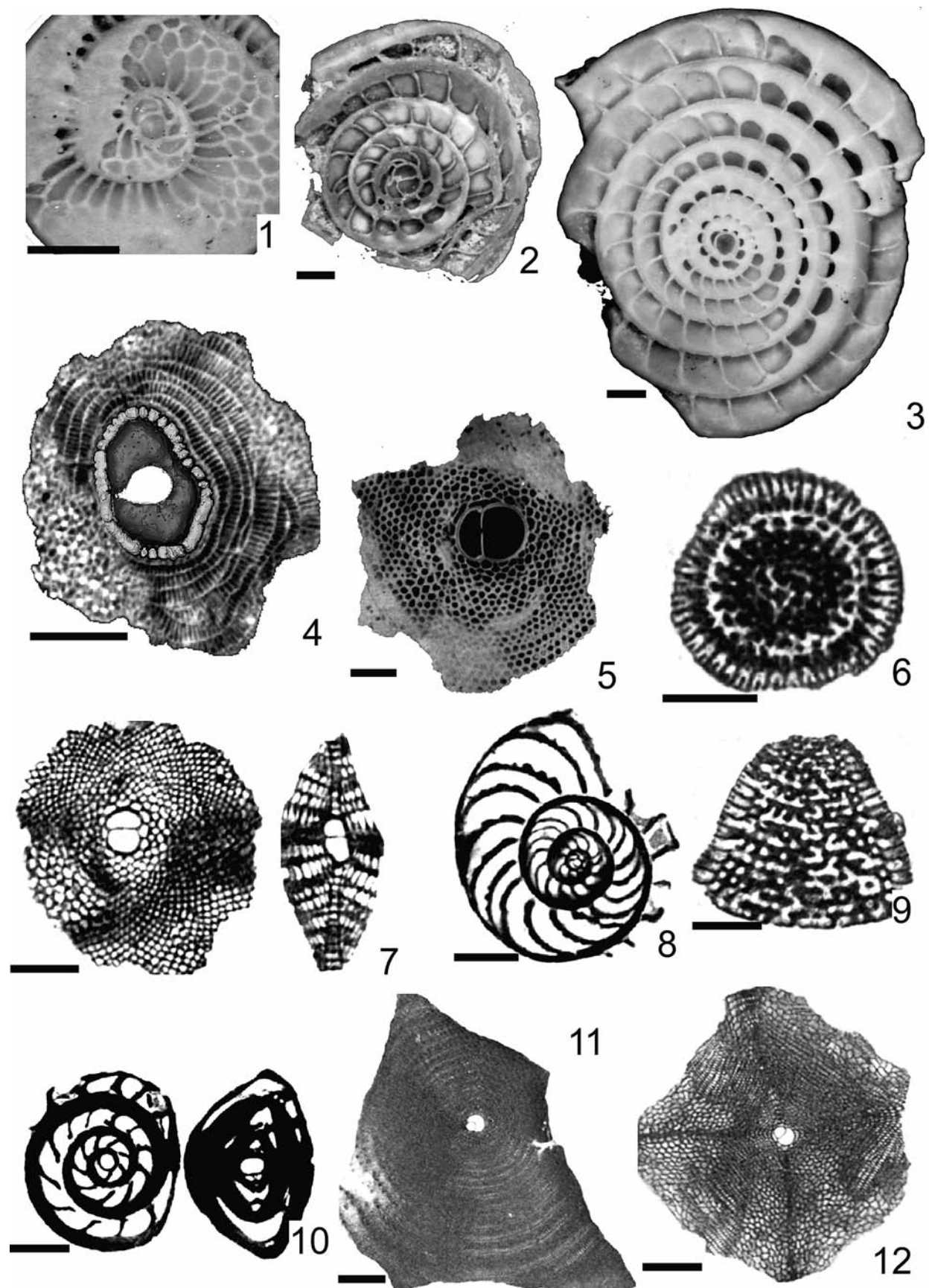
The calcareous nannofossil assemblages from the Noroña section (Fig.3) are highly diverse (up to 67 taxa in the lowermost part of the section) and very well preserved. All samples are dominated by common *Cyclicargolithus floridanus* and *Bramletteius serraculoides*. Furthermore, *Blackites spinosus*, *Coccolithus formosus*, *C.pelagicus*, *Clausiococcus subdistichus*, *Lanternithus minutus*, and *Zygrhablithus bijugatus* occur regularly. Discoasters are rare and only appear continuously in the lowermost part of the section (samples 7–11). They are represented by *Discoaster barbadiensis*, *D.deflandrei*, *D.gemmeus*, *D.gemmifer*, *D.saipanensis*, *D.tanii*, and *D.tanii ornatus*. Among reticulofenestrids the most common and regularly occurring species are *Reticulofenestra bisecta*, *R.hillae*, *R.stavensis*, and *R.umbilicus*, while the sporadically occurring species are *R.dictyoda*, *R.lockeri*, *R.minuta*, and *R.scrippsae*. Helicoliths are represented by *Helicosphaera bramlettei*, *H.compacta*, *H.euphratis*, *H.reticulata* and *H.seminulum*. *Sphenolithus moriformis* and *S.predistentus* could be identified in all samples, whereas *S.tribulosus* is restricted to samples 14–22. *Braarudosphaera bigelowii*, *Micrantholithus astrum*, *M.atenuatus*, *M.crenulatus*, *M.excelus*, and *Pemma basquensis* occur irregularly. Very

rare reworked nannofossils from the late Cretaceous (*Arkhangelskiella maastrichtiana*, *Eiffellithus gorkae*, *Placozygus fibuliformis*, *Praediscosphaera cretacea*, among others) and late Paleocene–early Eocene (*Discoaster lodoensis* and *D.multiradiatus*) were observed.

The lower part of the section can be assigned to NP19–20/CP15 based on the co-occurrence of *Sphenolithus pseudoradians*, *Isthmolithus recurvus*, *Discoaster barbadiensis* and *D.saipanensis*. The E/O boundary is usually positioned slightly above the top of NP20/CP15, defined by last occurrences (LOs) of *D.barbadiensis* and *D.saipanensis* (Perch-Nielsen, 1985). The E/O boundary at the Massignano section lies within the calcareous nannofossil Zone NP21/CP16 (Premoli Silva and Jenkins 1993). According to the zonation of Agnini et al. (2014), *D.saipanensis* has its last occurrence shortly before the E/O boundary and defines the top of Zone CNE21. The common occurrence of *Clausiococcus subdistichus* occurs very close to this boundary and is used to identify the E/O boundary. In the Noroña section this taxon is absent or occurs only very sporadically; thus, it cannot be used for biostratigraphic purposes here.

Discoaster barbadiensis occurs continuously in the lowermost part of the section up to sample 10, and *D.saipanensis* up to sample 12. The rare and irregular occurrences of these disc-shaped discoasters in the middle and upper part of the section are probably the result of resedimentation. *Coccolithus formosus*, whose last occurrence defines the top of NP21/CP16a, is present throughout the entire section. The occurrence of the typical early Oligocene taxon *Sphenolithus tribulosus* from samples 14 to 22 indicates an early Oligocene age.

The larger benthic foraminiferal tests are generally small and characterized by empty chamber lumina and an embryonic apparatus. The taxa *Lepidocyclina chaperi*, *L.pustulosa*, *Heterostegina ocalana*, *Palaeonummulites floridensis*, *P.willcoxi*, *Amphistegina cubensis*, *Fallotella cookie*, and *Asterocyclina* spp. are present in all three samples. At the highest level (sample 24) *Discocyclina* sp. and *Pseudophragmina* sp. occur rarely. The assemblages are dominated by the megalospheric forms of *Lepidocyclina pustulosa*, *Palaeonummulites floridensis* and several species of asterocyclinids. The species *Heterostegina ocalana*, *Amphistegina cubensis*, *Lepidocyclina chaperi* and *Fallotella cookie* are less abundant. The LBF assemblages found have a stratigraphic distribution from the middle through the late Eocene (e.g. Butterlin 1981,



Robinson and Wright 1993, Blanco-Bustamante et al. 1987). The taxon *Lepidocyclina chaperi* and the earliest American hereosteginid *Heterostegina ocalana* appear to be common and restricted to the Upper Eocene of the Caribbean realm (Butterlin 1987, Frost and Langenheim 1974, Robinson and Wright 1993).

5. Discussion

Larger benthic foraminifera at the Noroña section are found in marly beds as uncemented grains. They have been displaced from the shelf into deep waters where they are preserved together with planktic foraminifera and calcareous nannofossils. The sedimentary environment of the region is described as a fairly active scenario (Butterlin and Moullade 1983, Fourcade and Butterlin 1988) where biogenic carbonate grains such as LBF, originating from the proximal shelf, are intermittently resedimented downslope because of changes in sea-level or due to tectonic events. This environment explains the reduced size of the LBF in Noroña as having resulted from sorting during downslope transportation. It also explains the calcarenitic beds where the foraminifera are preserved as the remnant of a more energetic condition. Similar conditions are described by Cotton and Pearson (2011) for Tanzania. Since the estimated water depth for the Noroña deposits is about 1,000 m (Fenero 2010, Fenero and Molina 2011), LBF were transported for several kilometres, which normally leads to abrasion, erosion or even destruction of their tests. Hence, the preservation of the tests would be expected to be extremely poor (Beavington-Penney and Racey 2004, Briguglio and Hohenegger 2011). In contrast, the LBF tests from Noroña are exceptionally well preserved with most of the chambers being still empty and not recrystallized. This is only possible if the downslope transport was

via suspension in medium-high density flows, and lead to syndepositional deposition of the LBF that can therefore be dated by using the associated plankton.

The larger foraminiferal assemblage from Noroña was previously attributed to the late Eocene due to the occurrence of *L. chaperi* and *H. ocalana*. However, the E/O boundary is marked by the extinction of hantkeninids. At Noroña, this event is placed 18 m below the uppermost sample containing larger benthic foraminifera (Fig. 4). This, in turn, implies that the larger foraminifera assemblage is Oligocene (Rupelian) in age, being positioned within planktic foraminiferal Zone O1(P18) and calcareous nannofossil Zone NP21(CP16).

The occurrences of orthophragminids, a group whose extinction conventionally marks the end of the Eocene in the Caribbean as elsewhere (Versey in Zans et al. 1963, Serra-Kiel et al. 1998, BouDagher-Fadel 2008) in the Oligocene samples is, however, not surprising. Similar late Eocene LBF assemblages have been reported from Florida and are interpreted as early Oligocene in age based on the associated calcareous nannofossil content (Applin and Applin 1944, Bowen-Powell 2010). *Fallotella cookei* is usually considered to have an Eocene distribution. However, the high abundance of this taxon at Noroña suggests that the stratigraphic range may extend into the early Oligocene. This interpretation is consistent with data from Cuba (Beckmann 1958), Florida (Applin and Jordan 1945) and Jamaica (Robinson and Wright 1993). Moreover, Strontium isotope data measured on LBF of the Jamaica at the E/O transition suggest that the genus *Fallotella* likely passes the E/O boundary (Robinson 2003).

In the Tethyan region, within the type area of the Priabonian stage, the uppermost occurrences of orthophragminids *Asterodiscus* (= *Asterocyclina*) Beds were considered late Eocene in age (Barbin and Bignot

Plate 1. Larger benthic foraminifera at the Noroña section illustrated by high-resolution micro-computer tomography. Bars are 0.5 mm.

1 – *Heterostegina ocalana* Cushman, 1921 (equatorial section, megalospheric-form). Sample Nor 15; 2 – *Palaeonummulites willcoxi* (Heilprin), 1882 (equatorial section, megalospheric-form). Sample Nor 15; 3 – *Nummulites striatoreticulatus* Ruten, 1928 (equatorial section, megalospheric-form). Sample Nor 24; 4 – *Discocyclina* sp. (equatorial section, A-form). Sample Nor 24; 5 – *Lepidocyclina chaperi* Lemoine and Douvillé, 1904 (equatorial section, megalospheric-form). Sample Nor 15; 6, 9 – *Fallotella cookei* (Moberg), 1928 (transverse and axial sections). Sample Nor 16; 7 – *Lepidocyclina pustulosa* (Douvillé), 1917 (equatorial and axial sections, megalospheric-form). Sample Nor 15; 8 – *Palaeonummulites floridensis* (Heilprin), 1885 (equatorial section, megalospheric-form). Sample Nor 16; 10 – *Amphistegina cubensis* Palmer, 1934 (equatorial and axial sections, megalospheric-form). Sample Nor 24; 11 – *Pseudophragmina* sp. (equatorial section, megalospheric-form). Sample Nor 24; 12 – *Asterocyclina minima* (Cushman, 1918) (equatorial section, megalospheric-form). Sample Nor 24.

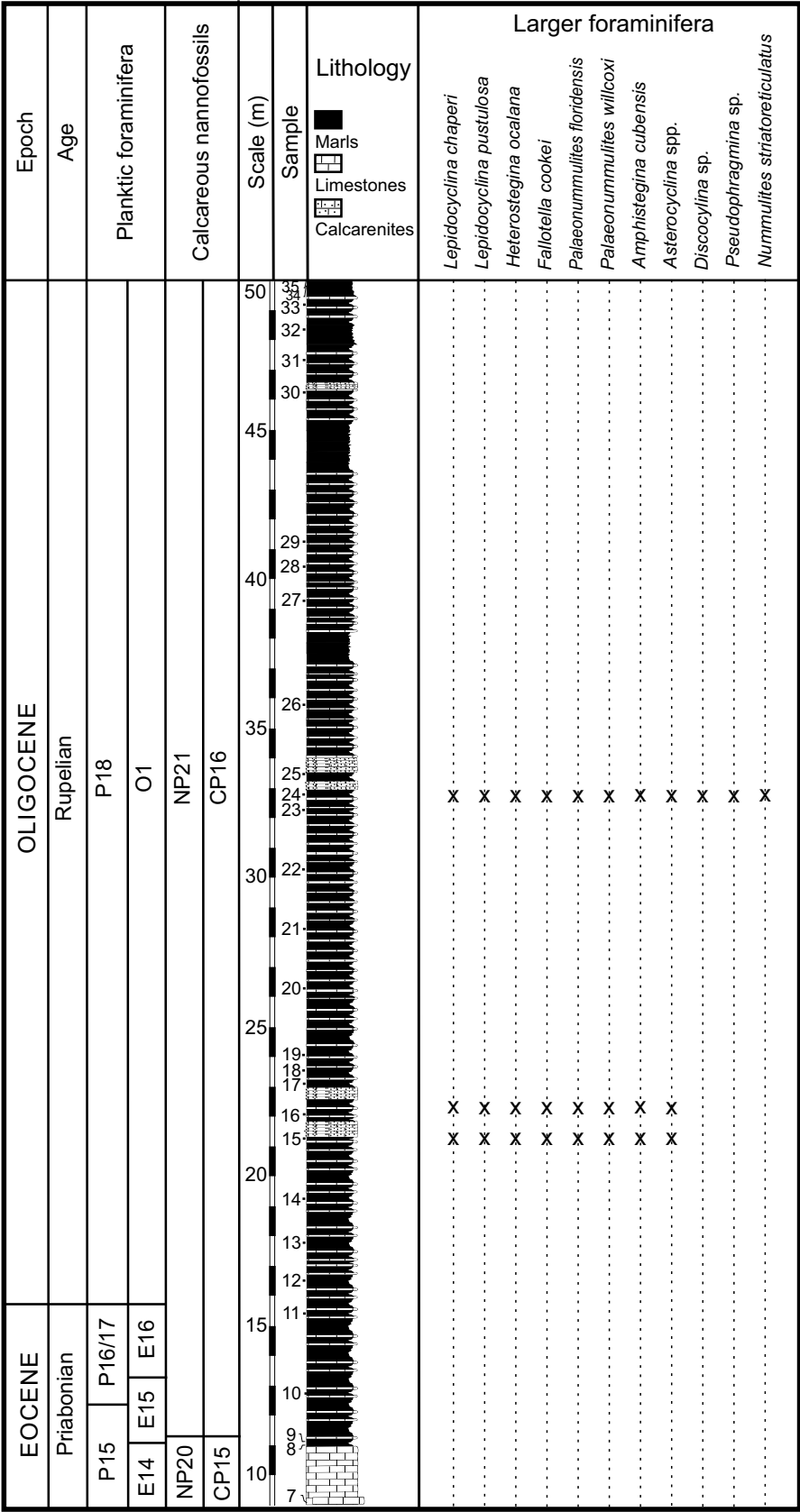


Fig. 4. Stratigraphic distribution of larger benthic foraminiferal at the Noroña section.

1986). Dinoflagellate cysts found in the section were assigned to the Gse dinoflagellate cyst zone, which corresponds to the basal Oligocene interval at Massignano in Italy, containing the E/O boundary stratotype (Brinkhuis 1994, Brinkhuis and Visscher 1995, Mietto 2000). This suggests that the extinction of orthophragminids at the Priabonian type locality occurred within the early Oligocene, consistent with the biostratigraphic and geochemical results from several sections in northern Italy (Jaramillo-Vogel et al. 2013), where the last occurrence datum of *Discocyclina* is found just above the E/O boundary. In the Betic Cordillera (Southern Spain), the occurrence of orthophragminids into the Oligocene has been reported from the Torre Cardela (Martínez-Gallego and Molina 1975, Molina 1980), Fuente Caldera (Molina 1980, 1986, Comas et al. 1985, Molina et al. 1986, 1988) and Molino de Cobo sections (Molina et al. 1988). In these sections, orthophragminids last occur in the middle part of the Rupelian and lepidocyclinids first occur in the late Rupelian (Molina et al. 1988). Nevertheless, Cotton (2012) considers that although the survival of orthophragminids across the E-O transition cannot be completely ruled out given the significant reworking at the Fuente Caldera section, it cannot be demonstrated conclusively either. Furthermore, in the San Vicente de la Barquera section (Pyrenees, Northern Spain), larger foraminifera were found (Heck and Drooger 1984) and orthophragminids have been considered reworked by Ferrández-Cañadell et al. (1999). However, this is a different scenario where orthophragminids may be reworked in this specific depositional setting; moreover, the section is very poor in planktic foraminifera and the correlation to pelagic sections is therefore very uncertain.

The extinctions of some major and widespread LBF groups are associated with the Eocene–Oligocene transition in Caribbean shallow-water sections, including the orthophragminids, some Nummulitidae and Lepidocyclinidae species and the genus *Fabiania* (Butterlin 1981, Robinson and Wright 1993, Robinson 2003). These extinctions seem to have been triggered by a global sea-level fall (Adams et al. 1986). However, in Tanzania, Cotton and Pearson (2011) found that the disappearance of major groups of LBF (including orthophragminids) precedes the sea-level fall by 200,000 years, a result that has been confirmed recently by Cotton et al. (2014) for the Melinau Limestone, Sarawak. These data indicate that the extinction of orthophragminids is possibly diachronous. The presence of orthophragminids in early Oligocene strata

is not unusual, and the question is how long they survived after the E/O boundary. Since the E/O boundary was formally defined by the extinction of hantkeninids (Premoli Silva and Jenkins 1993), the extinction of the orthophragminids at the Priabonian stage stratotype lies in the Oligocene (see Brinkhuis and Visscher 1995, Houben et al. 2012). Consequently, the late Priabonian stage stratotype and the extinction of orthophragminids are in fact of Oligocene (Rupelian) age, and the orthophragminid extinction should no longer be used to mark the E/O boundary.

6. Conclusions

The Noroña section is one of the few sections that contains orthophragminids, planktic foraminifera and calcareous nannofossils, enabling a precise integrated biostratigraphy and correlation across the E/O boundary. Orthophragminids are present in three levels at 6, 8 and 18 meters above the E/O boundary. These levels are dated as the early and middle part of Zone O1(P18) and the middle part of Zone NP21(CP16) (early Rupelian, Oligocene). Orthophragminids occur in the lower Oligocene at the Priabona stage stratotype and in the San Valentino section (Italy). Additionally, in the Molino de Cobo and Fuente Caldera sections in Spain, orthophragminids have a last occurrence in the middle Rupelian and lepidocyclinids first occur within the upper Rupelian. Nevertheless, in Tanzania orthophragminids disappear very close to the E/O boundary. The discrepancy in the last occurrence datum of orthophragminids suggests that their extinction could be diachronous, with a disappearance near the E/O boundary in low latitudes such as the Indo-Pacific region (e.g. Tanzania) and becoming extinct in the Rupelian at low latitudes of the Caribbean-American bioprovince (e.g. Cuba and Jamaica) and at middle latitudes of the Tethys (e.g., Italy and Spain). Due to the possibility of reworking, further studies of sections with isolated occurrences of larger foraminifera and plankton are required to determine the precise timing of their extinction. The integration of these studies with oxygen, carbon and strontium isotope records is necessary to provide an independent age constraint.

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