

ORTHOPHRAGMINIDS (FORAMINIFERA) ACROSS THE PALEOCENE–EOCENE TRANSITION FROM NORTH AFRICA: TAXONOMY, BIOSTRATIGRAPHY, AND PALEOBIOGEOGRAPHIC IMPLICATIONS

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ABSTRACT

The platform margin and slope deposits in Galala, Egypt, record a larger benthic foraminiferal turnover (LFT), previously proposed to coincide with the Paleocene-Eocene (P/E) boundary based on the negative carbon isotope excursion (CIE) consistent with the Paleocene-Eocene Thermal Maximum (PETM). The LFT in these deposits was established on the basis of supposed synchronous first appearances of such taxa as *Alveolina*, *Nummulites*, and *Orbitolites* at or around the P/E boundary, although the response of orthophragminids, assigned only to the genus *Discocyclina*, was not studied. The orthophragminids in the late Paleocene–early Eocene interval in some of these deposits (sections B3, D5, D6, and D8) are represented by species of *Discocyclina* Gümbel, *Orbitoclypeus* Silvestri, and *Nemkovella* Less, reported for the first time from the southern margin of the Tethys. The Thanetian orthophragminids consist of *Orbitoclypeus multiplicatus*, *O. schopeni*, *Discocyclina seunesi*, and *D. tenuis*, while assemblages in the early Eocene are characterized by *Discocyclina archiaci*, *D. dispansa*, *Orbitoclypeus schopeni*, and *Nemkovella stockari*, suggesting a significant change in composition through the sections. The assemblages below and above the P/E boundary, only recorded in sections B3 and D8, mark the orthophragminid zones OZ 1B and 3, respectively. The OZ 2, correlated to shallow benthic zones SBZ 5 and 6 in the basal part of the Eocene and recognized by the first appearance of asterocyclinids, nemkovellids, and some ribbed orbitoclypeid species in northern Tethyan platforms, was not found. This may suggest either a hiatus, recorded previously in section D8 based on calcareous plankton, across the P/E transition in section B3 or an artifact of sampling. Consequently, our data raise some doubts about the aforementioned compositional changes related to the LFT and P/E boundary. We discovered an advanced developmental stage of *N. stockari* (*N. stockari bejaensis* n. subsp.) from a new section in Tunisia. This subspecies seems to be a key taxon for the early Eocene of the southern Tethyan platforms and extends the geographic and stratigraphic range of the species. We conclude that orthophragminids at Galala bear a close resemblance to those in the northern Tethyan platforms, especially assemblages from Turkey.

INTRODUCTION

The Paleocene-Eocene (P/E) boundary is a well-studied portion of geological time that now is correlated globally on the basis of a significant negative carbon isotope excursion (CIE), recognized in both marine and terrestrial systems (Aubry et al., 2007, and references therein). The carbon excursion was linked to a global-warming event, namely the Paleocene-Eocene Thermal Maximum (PETM; Zachos et al., 2001), and is associated with significant paleontologic changes. In marine systems, the response of deep-sea benthic and planktonic foraminifera and dinoflagellates to the warming event is recognized by major modifications in composition, diversity, and abundance, and the synchronicity of these events provide a sound basis for regional and global correlations across the P/E boundary. One of the most notable CIE biotic events, involving the extinction of many deep-sea benthic foraminifera, is known as the benthic extinction event or BEE (Thomas, 2003, 2007, and references therein). It involved a main extinction phase during the CIE, domination of opportunistic taxa, and a prominent turnover in the composition of foraminifera inhabiting the bathyal and abyssal sea bottom. The extinction of benthic foraminifera in outer-shelf environments, however, was a minor event (Speijer et al., 1995, 2012; Aubry et al., 2007).

The larger benthic foraminifera (LBF) are major contributors to shallow-marine sediments in the tropic and subtropics during the early Paleogene, and occasionally they formed prolific accumulations along the northern and southern margins of the Tethys (Hottinger, 1960; Drobne, 1977; Schaub, 1981; Racey, 2001; Özcan, 2002). In addition to some stratigraphically important groups such as miscellanids and rotaliids (Hottinger, 2009), the nummulitids, alveolinids, and orthophragminids constitute a reasonable portion of the LBF in the platform deposits during the P/E transition (Serra-Kiel et al., 1998). Because of the uncertainties in the delineation of the P/E boundary and its correlation to the Ypresian and Ilerdian stages, the exact distribution of these groups with respect to the P/E boundary has remained ambiguous (Molina et al., 1992). The concept of a boundary interval zone, spanning <1 Myr, was adopted in the shallow benthic zonation (SBZ) scheme of Serra-Kiel et al. (1998), in which a major turnover in LBF takes place in the interval corresponding to SBZ 5/6 (Fig. 1). In fact, a similar but less pronounced trend occurring around the loosely defined P/E boundary was recognized much earlier in alveolinids and nummulitids (Hottinger, 1960; Hottinger & Schaub, 1960; Schaub, 1981), based on the first appearances of *Alveolina* spp., true involute *Nummulites* spp., and *Orbitolites* sp. in SBZ 5, which was placed at the base of the Ilerdian and in the upper part of the late Thanetian by Serra-Kiel et al. (1998).

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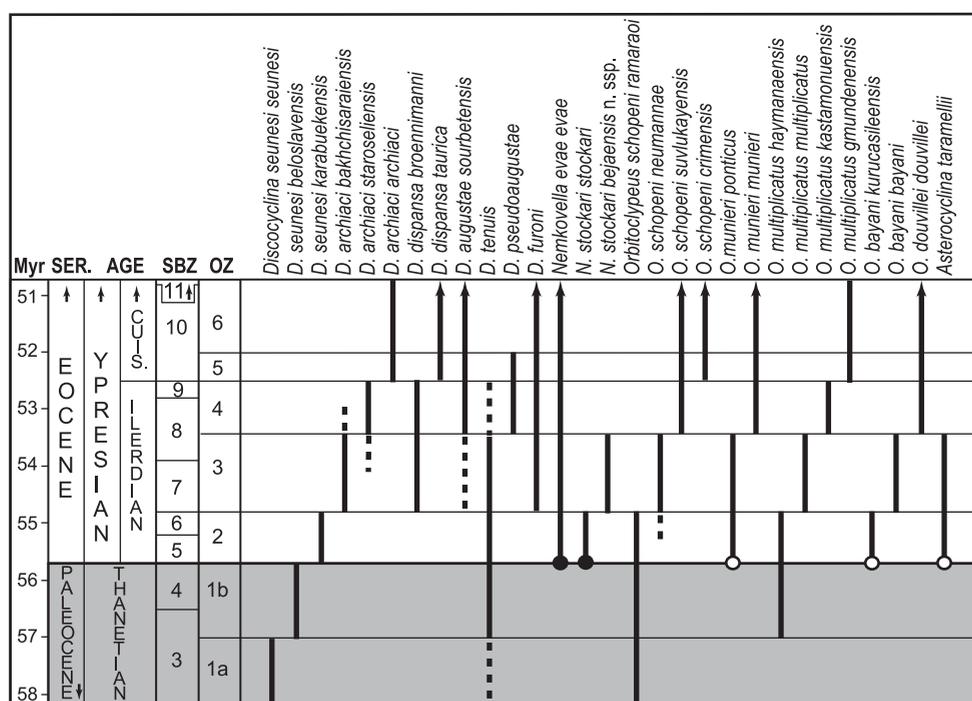


FIGURE 3. Distribution of orthophragminids across the Paleocene/Eocene (P/E) boundary and correlation of orthophragminid zones (OZ) to shallow benthic zones (SBZ) in the Tethys (after Less, 1998; Özcan et al., 2001; Less et al., 2007). The ribbed orbitoclypeid and asterocyclinid species first appearing across the P/E boundary in northern Tethyan platforms are marked by open circles and nemkovellids by black circles. The stratigraphic range of *Nemkovella stockari* is updated to cover OZ 2 and 3 in light of the present data from Galala and Tunisia. The correlation of OZ zones to SBZ zones and the time scale are after Özcan et al. (2010). CUIS. = Cuisian.

LBF assemblages, the number of megalospheric orthophragminid specimens is much greater than the number of microspheric ones in any other LBF groups (Hottinger, 2001). The equatorial chambers, with the exception of some taxa in the American Province, are divided into chamberlets of different shapes as observed in equatorial sections (compare Figs. 4D, E). The western Tethyan orthophragminids include four genera: *Discocyclus* Gümbel, 1870, *Nemkovella* Less, 1987, *Orbitoclypeus* Silvestri, 1907, and *Asterocyclina* Gümbel, 1870, classified under the families Discocyclusidae Galloway, 1928, and Orbitoclypeidae Brönnimann, 1946, after Brönnimann (1945). The Discocyclusidae and Orbitoclypeidae are distinguished by their different microspheric juvenaria only observable in equatorial section (Figs. 4F, G; Less, 1987; Ferrández-Cañadell & Serra-Kiel, 1992; Ferrández-Cañadell, 1998a, b). The embryonic apparatus (hereafter abbreviated to “embryon”) of the megalospheric specimens consists of a spherical to subspherical protoconch (P) enclosed more or less by the second chamber, the deuterococonch (D; Figs. 4C–E and Fig. 5). Both chambers communicate to each other through a large single protoconchal stolon (ps; Fig. 4C). Based on the relationship between both chambers in equatorial sections, about ten configurations are used in the description of the embryon (Less, 1987; Fig. 5). The first annulus includes those chamberlets (ch) developed simultaneously around the deuterococonch; adauxiliary chamberlets (adc) and principal auxiliary chamberlets (pac) arise from the junction of P and D (Figs. 4C–G). The communication between the chamberlets of the same annulus is through the annular stolons (as) in *Discocyclusina*, although such stolons

do not exist in other genera. The radial stolons (rs) are positioned along the septum(s) of the distal chamberlet walls for communication between the successive annular chambers.

TETHYAN ORTHOPHRAGMINIDS ACROSS THE P/E BOUNDARY: A SYNTHESIS OF THE RELATIONSHIP BETWEEN THE ORTHOPHRAGMINID ZONATION (OZ) AND THE SHALLOW BENTHIC ZONATION (SBZ)

DISTRIBUTION OF ORTHOPHRAGMINIDS ACROSS THE P/E BOUNDARY

Tethyan orthophragminids, represented by *Orbitoclypeus schopeni* and *Discocyclusina seunesi*, are first recorded in Thanetian deposits. These species are dimorphic with microspheric (B-forms) and megalospheric (A-forms) generations; the latter have large embryos around which the annular (cyclical) growth starts immediately through the numerous deuterococonchal stolons (Özcan et al., 2001; Less et al., 2007). This is also true for Central American orthophragminids in which megalospheric specimens of Thanetian species have large embryos followed immediately by annular chambers (Vaughan, 1929, 1936; Cole, 1969; Robinson & Wright, 1993).

The western Tethyan orthophragminid genera (*Discocyclusina*, *Nemkovella*, *Orbitoclypeus*, and *Asterocyclina*) include more than 50 species in the Thanetian–Priabonian. Of these, 15 occur in the Thanetian–early Eocene from OZ 1A–OZ 4 (Fig. 3). In northern Tethyan platforms, Thanetian

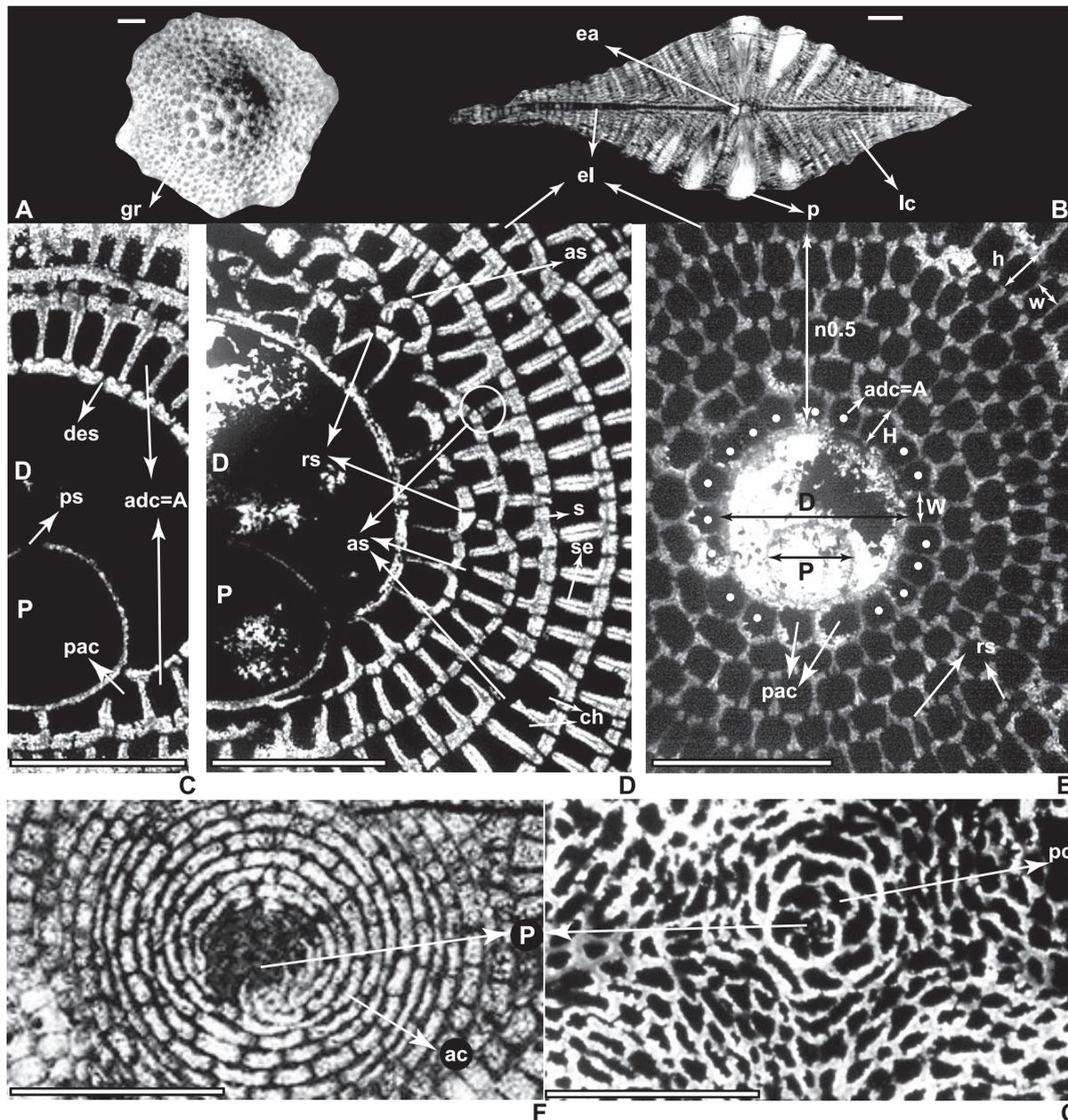


FIGURE 4. The morphologic and morphostructural features of orthophragminids and illustrations of the parameters used in the description of taxa; scale bars = 200 μ m. **A** External view of the test showing the distribution of granules (gr) in *Orbitoclypeus haynesi* (early Bartonian, Gökçeada, Turkey). **B** A vertical section of *O. haynesi* illustrating the bilocular embryonic apparatus (ea), equatorial layer (el), lateral chambers (lc), and pillars (piles; p). **C, D** Equatorial sections showing the embryonic chambers and peri-embryonic chambers/chamberlets in *Discoeyclina archiaci* (Ypresian, Karakaya, Turkey). P: protoconch, D: deutoconch, ps: protoconchal stolon, des: deutoconchal embryonic stolons, pac: principal auxiliary chamberlets, adc: adauxiliary chamberlets, ch: chamberlets, s: septum, se: septulum, rs: radial stolon, as: annular stolon; the circle indicates the annular stolons at proximal and almost central part of the septulum. **E** Biometric parameters P, D, A (marked by white circles), H, W, n0.5, h, and w used in the description of megalospheric orthophragminids as exemplified by *Orbitoclypeus douvillei* (late Ypresian/early Lutetian transition in Arabin, Turkey); P and D: outer diameter of protoconch and deutoconch perpendicular to their common axis, A: number of adauxiliary chamberlets, H and W: height and width of the adauxiliary chamberlets, h and w: height and width of equatorial chamberlets around the peripheral part of the equatorial layer, n0.5: number of annuli within 0.5-mm distance measured from the deutoconch along the axis of the embryo. **F, G** Comparison of neponic stages of two different microspheric orthophragminid juvenaria; **F**: early spiral part followed by subdivided falciform chambers and first annular chamber (ac), characteristic of the Discocyclinidae; **G**: early spiral chambers followed by orbitoidal isolated chamberlets, which become annular in the later stage of development after the introduction of a progressive chamber (pc) and are characteristic of the Orbitoclypeidae.

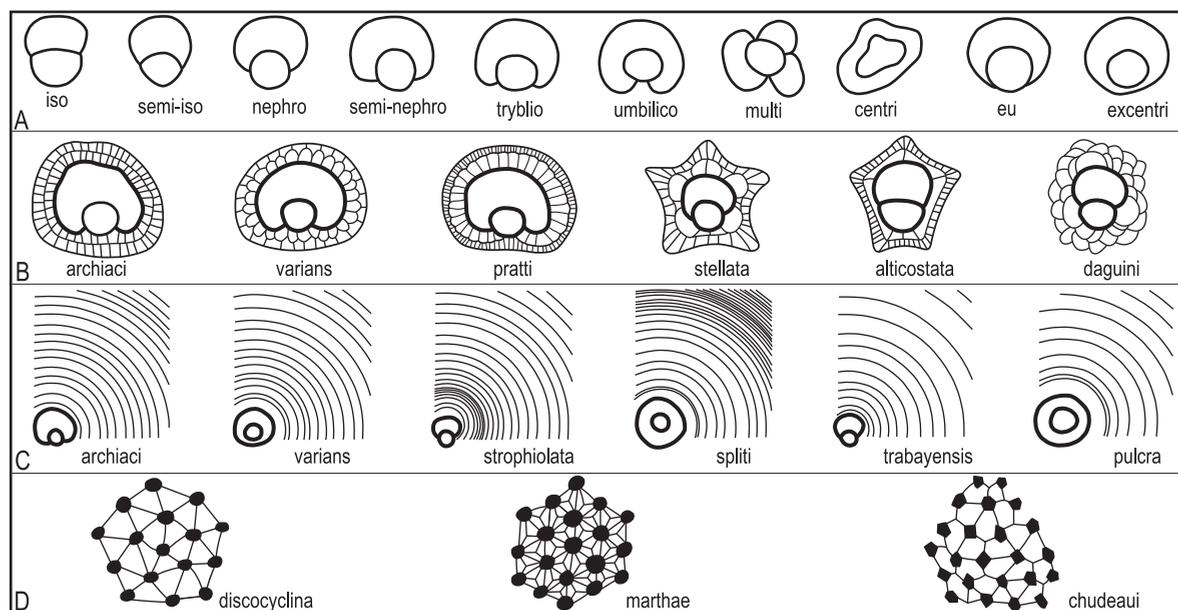


FIGURE 5. The qualitative features of the Tethyan orthophragminids. **A** Types of embryo configurations (suffix “-lepidine” is to be added). **B** Types of adauxiliary chamberlets. **C** Different growth patterns of the equatorial annuli. **D** Network of granules and lateral chamberlets on the test surface (redrawn from Less, 1987).

orthophragminids are represented by four species: *Discocyclina seunesi* Douvillé, *D. tenuis* Douvillé, *Orbitoclypeus schopeni* (Cecchia-Rispoli) and *O. multiplicatus* (Gümbel) (Fig. 3). *Discocyclina seunesi* is one of the earliest and most widely recognized upper Paleocene taxa, described from Bénése in the Aquitaine Basin (France) by Douvillé (1922). Its stratigraphic position in previous literature has been controversial, described as Danian (Douvillé, 1922), Paleocene (Neumann, 1958) or Thanetian (Less, 1987). The systematics of *D. seunesi* were also debated, since it has been assigned either to *Discocyclina* (Douvillé, 1922; Neumann, 1958; Samuel et al., 1972; Less, 1998; Özcan et al., 2001; Less et al., 2007) or *Orbitoclypeus* (Less, 1987). The stratigraphic range of this species has recently been redefined by extending its upper range into the early Eocene based on its advanced members (*D. seunesi karabuekensis*) found in association with early, small *Nummulites* and orthophragminids characteristic of OZ 2 in the Safranbolu-Karabük Basin, Turkey (Less et al., 2007). Thus, the stratigraphic range of *D. seunesi* covers the interval between Thanetian to earliest Eocene. *Discocyclina seunesi* was considered to be the only orthophragminid in the Paleocene until Less (1998) showed that two more species, *Orbitoclypeus schopeni* and *Discocyclina tenuis*, occur in Thanetian deposits in France (Fig. 3). The coexistence of the above three taxa has been observed in several Thanetian shallow-marine sections in Haymana Basin, central Turkey, associated with *Orbitoclypeus haymanaensis* (Özcan et al., 2001). Since *O. haymanaensis* bears characteristic features of the early Eocene species *O. multiplicatus*, it has been regarded as the most primitive developmental stage (*O. multiplicatus haymanaensis*) of this species (Less et al., 2007). Thus, the accepted range of *O. multiplicatus* (observed only in OZ 3/SBZ 7–8 from Spilecco, northern Italy by Less, 1998) has been extended into the Thanetian.

This species occurs in the late early Ypresian (represented by *D. multiplicatus kastamonuensis*) and in the late Ypresian (represented by *D. multiplicatus gmundenensis*), based on material from Turkey (Less et al., 2007) and Austria (Dulai et al., 2010), respectively. In Haymana Basin, *O. multiplicatus* and *D. seunesi* are the most common orthophragminid species through the succession of shallow-marine carbonates and fine clastics. The evidence of a Thanetian age is also provided by other foraminifera such as *Assilina yvettae* Schaub, 1981, *Glomalveolina primaeva* (Reichel, 1937), *Glomalveolina* cf. *G. pilula* Hottinger, 1960, *Operculina heberti* Munier-Chalmas, 1884, *Vania anatolica* Sirel & Gündüz, 1985, and *Miscellanea yvettae* Leppig, 1988, as well as planktonic foraminifera and calcareous nannoplankton in the deep-marine marls overlying the carbonates and clastics (Özcan et al., 2001).

In northern Tethyan platforms, a remarkable diversification in orthophragminids at or around the P/E boundary is recognized by the first appearance of nemkovellids, asterocyclinids, and ribbed orbitoclypeids. The characteristic species (Fig. 3) are *Nemkovella stockari*, *N. evae* Less, *Orbitoclypeus munieri* (Schlumberger), *O. bayani* (Munier-Chalmas), and *Asterocyclina taramellii* (Munier-Chalmas). The last three species are characterized by the presence of external ribs, a morphologic feature not observed in Thanetian orthophragminids. Among the newly appearing taxa, *N. stockari* has a short stratigraphic range in the early Eocene. This species, described from Kurucaşile in northern Turkey (Less et al., 2007), was recorded in two regions in Turkey in association with *Nummulites* spp. and orthophragminids characteristic of OZ 2 (Özcan et al., 2010). The Galala and Tunisian specimens, assigned herein to *N. stockari bejaensis* n. subsp., are represented by the more advanced developmental stage of species in OZ 3, and hence, the stratigraphic range of *N. stockari* is extended to

cover OZ 2 and 3 (Fig. 3). Species such as *Discocyclina archiaci*, *D. dispansa*, and *D. furoni* first appear almost simultaneously in OZ 3. Of these, *D. archiaci* is the fastest evolving and most abundant species in northern Tethyan platforms, and it is a key taxon in assigning orthophragminid assemblages to the OZ zones in the early Eocene.

ORTHOPHRAGMINID ZONATION (OZ) ACROSS THE P/E BOUNDARY AND ITS CORRELATION TO SBZ ZONES

The OZ zones are, in fact, Opeelian zones characterized by assemblages of different developmental stages of orthophragminid species. The developmental stages are recognized by the artificial division of species into subspecies by measurable and quickly evolving parameters. The size of the deuteroconch (D) is the most quickly evolving parameter (Less & Kovács, 1996). A detailed description of OZ zones in the late Paleocene and early Eocene is given in Less et al. (2007). The first orthophragminid biostratigraphy proposed by Less (1987) includes 16 orthophragminid zones ranging from Thanetian to Priabonian. Less (1998) modified this biostratigraphic scheme by subdividing OZ 1 and OZ 8 into two zones each (OZ 1A, B and OZ 8A, B), and proposed correlation of these zones to the SBZ zones. The late Thanetian-early Eocene part of the OZ zonation has been updated recently in light of new data from numerous shallow-marine sections in Turkey and Bulgaria (Özcan et al., 2001; Less et al., 2007). The modifications in calibration of OZ zones to SBZ zones around the P/E boundary are shown in Figures 1 and 2. According to the revised calibration (Özcan et al., 2010), OZ 1A is correlated to a part of SBZ 3, while OZ 1B to a part of 3 and to 4. The orthophragminids diagnostic for OZ 1A are *Discocyclina seunesi seunesi*, which is the zonal marker, and *Orbitoclypeus schopeni ramaraoi*. The key sections for OZ 1A are located in France (Nouts-Oraas and Boussan Mare) and Bulgaria (Beloslav). The orthophragminids in OZ 1B are represented by the zonal marker *Discocyclina seunesi beloslavensis*, *D. tenuis*, *O. schopeni ramaraoi*, and *O. multiplicatus haymanaensis*. The key sections for OZ 1B are located in the Haymana Basin in Turkey (Özcan et al., 2001) and in Beloslav in Bulgaria (Less et al., 2007).

The OZ 2 is correlated to SBZ 5 and 6, and OZ 3 to SBZ 7 and a part of 8. Among these orthophragminid zones the most crucial one is OZ 2 across the P/E boundary, since its position with respect to SBZ zones and the P/E boundary has been debated in the past (Figs. 1, 2). This zone was previously characterized only by the orthophragminid assemblages at Ruisseau de Bec, the key locality for OZ 2 in southern France (Less, 1998), which was later assigned to OZ 1 (Less et al., 2007). After this modification, two localities in Turkey, Kurucaşile and Karaevli, are now considered key localities for OZ 2 (Less et al., 2007). In both sections, *Nummulites* sp. are accompanied by a rich and diverse orthophragminid taxa shown in Figure 3. The diagnostic taxa for OZ 2 are ribbed orthophragminids, such as *Orbitoclypeus bayani*, *O. munieri*, and *A. taramellii*, the zonal marker *D. seunesi karabuekensis*, and *Nemkovella stockari stockari*. The orthophragminid assemblages representing OZ 3 are more numerous compared to OZ 2. The

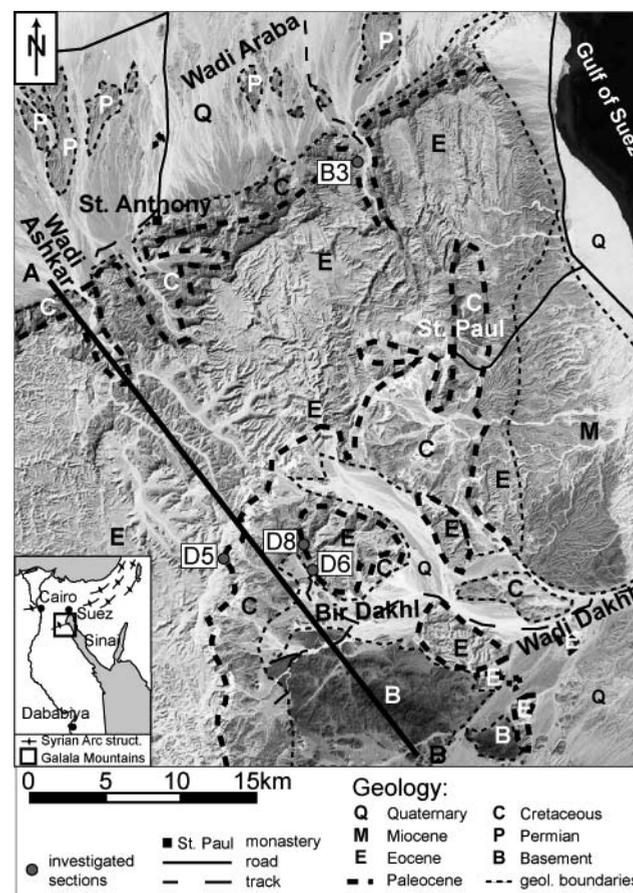


FIGURE 6. Locations of sections B3, D5, D8, and D6 in South Galala Mountains. The profile A/B marks the position of the cross section in Figure 7 (after Scheibner & Speijer, 2009). As the Paleocene outcrop is very narrow, it is represented by a thick dashed line.

diagnostic taxa for OZ 3 are *Discocyclina archiaci bakhchisaraiensis*, *Orbitoclypeus schopeni neumannae*, *O. multiplicatus multiplicatus* and *O. bayani bayani*, which are zonal markers, and *N. stockari bejaensis* n. subsp. The key sections for OZ 3 are located in France (Gamarde), Italy (Spilecco), Crimea (Bakhchisarai), and Turkey (Sakarya, Şile, Ağaçkese, and Kastamonu C; Less et al., 2007, and references therein).

MATERIALS AND METHODS

Orthophragminids have been sampled in four sections in South Galala, Egypt, where over the past 10 years the second author and his colleagues have investigated the platform morphology, biostratigraphy and distribution of calcareous nannofossils and ostracods, and the LBF (Scheibner et al., 2003, 2005; Scheibner & Speijer, 2008, 2009; Boukhary & Scheibner, 2009; Morsi & Scheibner, 2009). Orthophragminids are also described for the first time in this study from a complementary early Eocene section, El Munchar, near Beja in Tunisia. In Galala orthophragminids occur at numerous levels, and we managed to obtain free specimens from the matrix in marly and limy samples and in debris flows at sixteen levels (Figs. 6–8). We assume that orthophragminids are reworked in some cases, considering the facies and

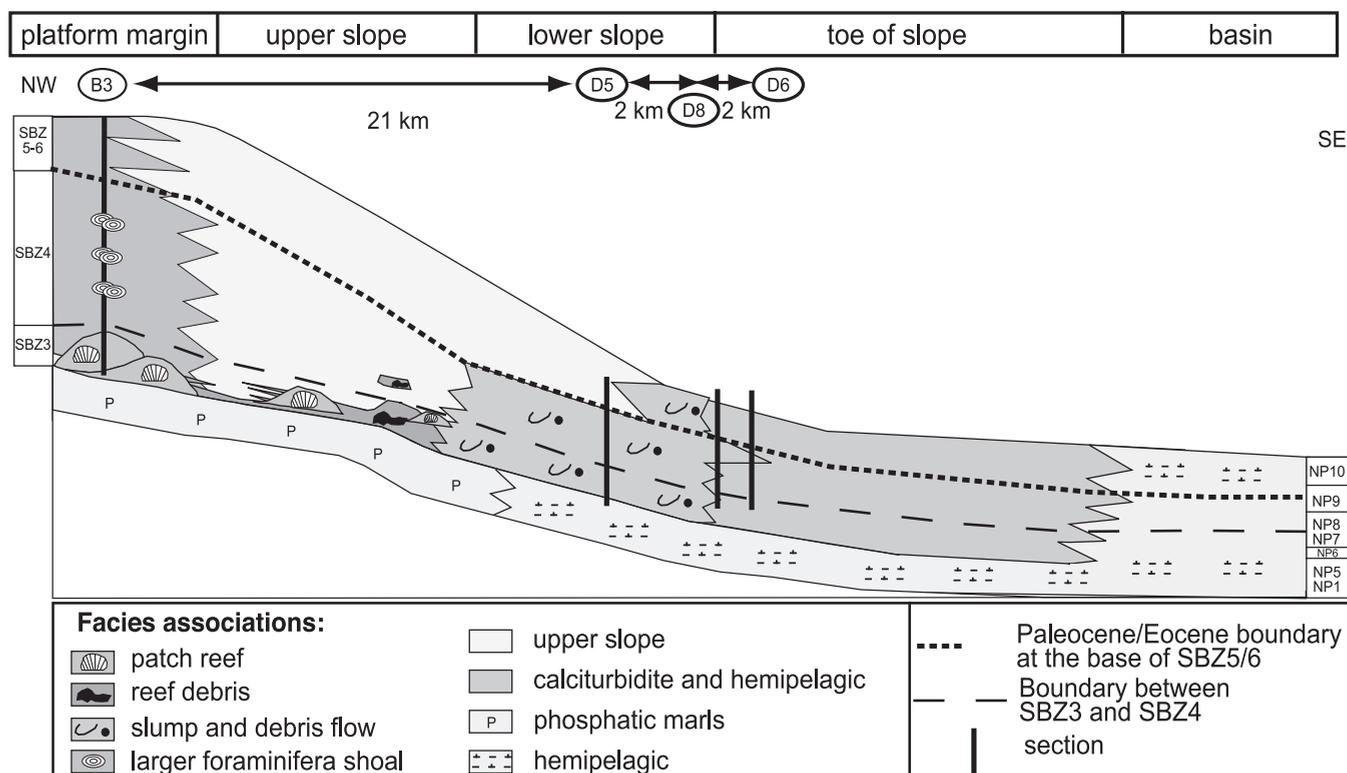


FIGURE 7. Position of sections B3, D5, D8, and D6 along platform-to-basin transect in the South Galala Mountains. The tentative position of the P/E boundary, SBZ zones, and NP zones previously proposed by Scheibner & Speijer (2009) are shown alongside the correlation scheme (after Scheibner & Speijer, 2009). The platform assignments refer to the Paleocene.

depositional setting of the deposits. In the El Munchar section, orthophragminids have been isolated from loosely cemented, friable limestones at nine levels (Fig. 9). The specific and subspecific identifications of orthophragminids are not possible in random thin sections. Thus, oriented thin sections of megalospheric specimens (A-forms) have been prepared for the biometric and taxonomic studies, since the most important evolutionary parameters are associated with megalospheric generations, their embryos, and features of the equatorial chambers (Less, 1987). This requires the grinding of the lateral parts of the free test on both sides of the equatorial layer by a fine grinding paper to a certain level in the equatorial layer to obtain a section exposing the embryo and surrounding annular chambers. The biometric measurements and counts were executed on these sections. Using the terminology proposed by Less (1987, 1993), eight measurements (in μm) and counts and some qualitative data from 234 specimens were used to characterize the taxa, as illustrated in Figure 4E. These measurements and counts are: P and D, outer diameter of the protoconch and deuteroconch perpendicular to their common axis; A, number of adauxiliary chamberlets; H and W, height and width of the adauxiliary chamberlets; n0.5, number of annuli within a 0.5 mm distance measured from the deuteroconch along the axis of the embryo; and h and w, height and width of the equatorial chamberlets around the peripheral part of the equatorial layer.

In addition, some vertical sections have been prepared to complement the identifications. The biometry of

orthophragminids from El Munchar is also integrated into Table 1 for comparison and to complement the biometric data.

GEOLOGIC SETTING, SECTION DESCRIPTIONS, AND BENTHIC FORAMINIFERAL ASSOCIATIONS

THE GALALA MOUNTAINS, EGYPT

The Galala Mountains are located on the western side of the Gulf of Suez ~ 200 km southeast of Cairo. They form a plateau separated into North and South Galala by the 30-km wide Wadi Araba. The sections analyzed for this study, D5, D6, D8, and B3, are all found near South Galala (Fig. 6). Section B3 is located in a wadi, running north into Wadi Araba. The other three sections (D5, D6, D8) are all grouped in the Bir Dakhl area, south of South Galala. The sections can be arranged on a carbonate platform margin-to-basin transect, where section B3 is located at the platform margin in the north and the sections in the Bir Dakhl area are located at the transition from the lower slope to toe-of-slope in the south (Fig. 7). More detailed information for section descriptions and facies development is given in Scheibner & Speijer (2009).

Section B3

This is a 100-m thick sequence of marls and limestones with occasional debris flows and slumps in the lowermost part of the section, deposited in a platform margin setting (Fig. 7). Orthophragminids are rare throughout the section

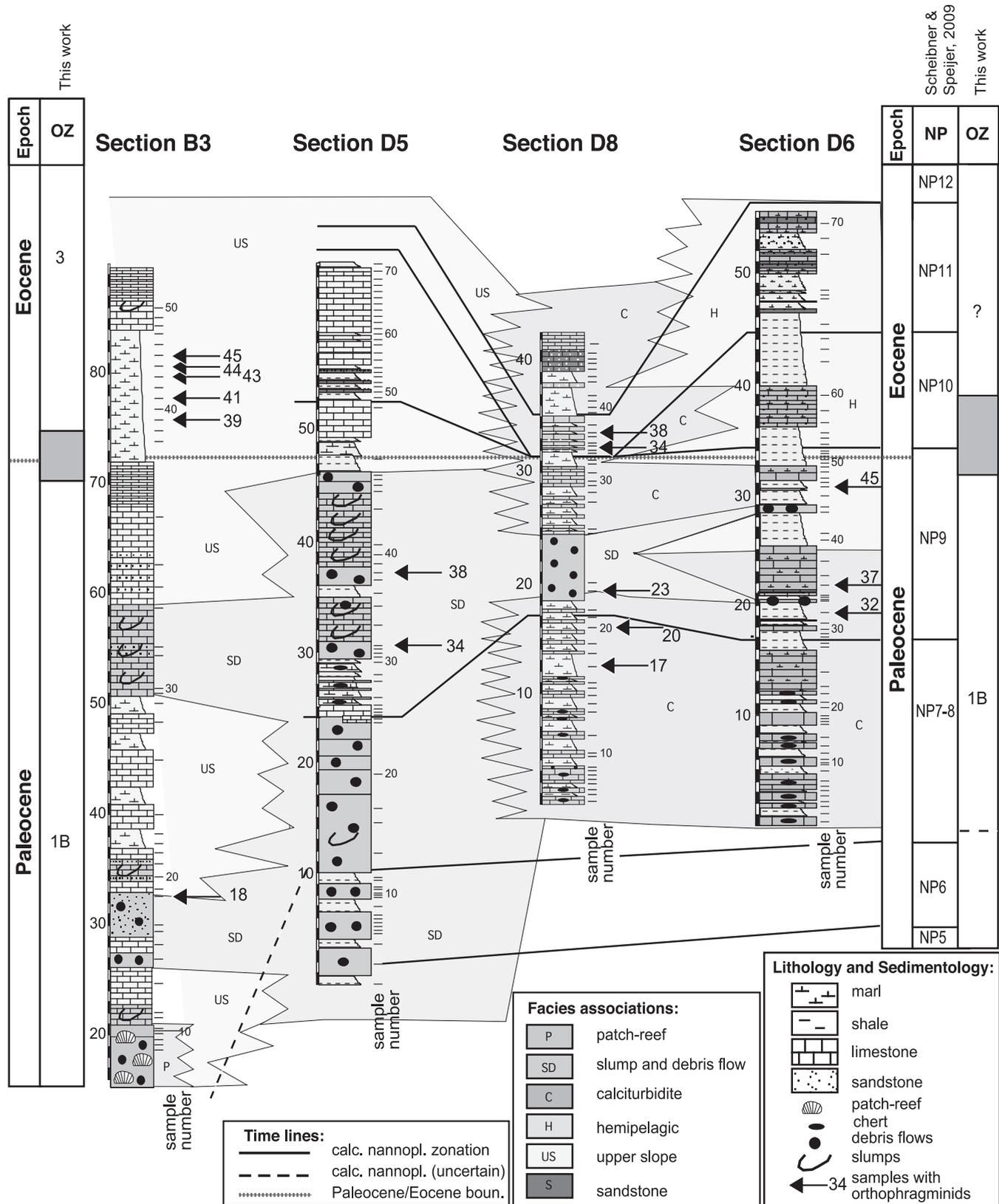


FIGURE 8. Lithostratigraphic correlation and distribution of facies associations in the studied sections (after Scheibner & Speijer, 2009). The numbers to the right and left of the stratigraphic columns indicate samples numbers and section thicknesses in meters, respectively. Arrows indicate levels studied for orthofragminids. The gray area across the P/E boundary in the OZ zonation marks the CIE interval.

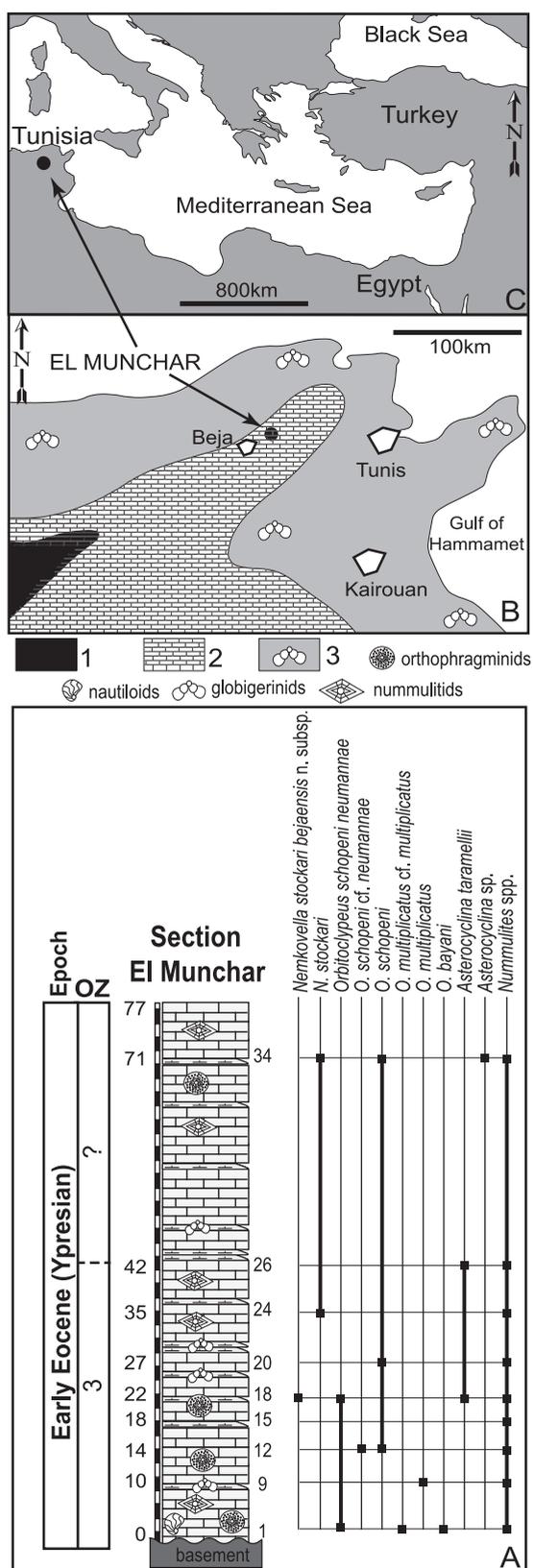


FIGURE 9. A Simplified stratigraphic column and distribution of orthophragminids and associated LBF in the El Munchar section near Beja, Tunisia. The numbers to the right and left of the stratigraphic column indicate samples numbers and section thickness in meters, respectively. B Position of the section on a late Ypresian (early Eocene)

compared to other LBF and are found occasionally in the lower part (spl. 18) and more abundantly in an interval just above the poorly developed CIE in samples 39, 41, 43, 44, and 45 (Fig. 10). Only sample 18 yielded a single specimen of *Discocyclina seunesi*, suggesting OZ 1 (= SBZ 3 and 4) for this level. The interval between samples 39–45 contains *D. archiaci bakhchisaraiensis*, *D. archiaci* cf. *bakhchisaraiensis*, *D. dispansa* cf. *broennimannitaurica*, and *Orbitoclypeus schopeni ramaraoi*. The assemblages of these taxa suggest OZ 3 (SBZ 7 and 8).

Section D5

This is about a 60-m thick sequence of debris flows and slumps intercalated with hemipelagic sediments that represent a lower-slope depositional setting along the platform-to-basin transect (Fig. 7). In spite of the continuous occurrence of orthophragminids throughout the section, we have only been able to collect specimens in two debris flow samples (34 and 38, Fig. 10). The interval including both samples is correlated with NP 9 and SBZ 4 based on calcareous nannofossils and larger foraminifera (Scheibner & Speijer, 2009). The Thanetian part of the sequence contains an LBF assemblage represented by *Hottingerina lukasi* Drobne, 1975, *Miscellanea* sp., *Glomalveolina* sp., and *Ranikothalia* sp. A single specimen of *O. schopeni* was identified in sample 34, and sample 38 contained an association of *O. schopeni ramaraoi* and *O. multiplicatus haymanaensis*. Sample 34 lacks key taxa; however, sample 38 can be confidently assigned to OZ 1B by the association of *O. schopeni ramaraoi*, *O. multiplicatus haymanaensis*, and *H. lukasi*.

Section D8

This is a 42-m thick sequence of calciturbidites and hemipelagic sediments representing a lower-slope depositional setting (Fig. 7). It covers the Thanetian–early Eocene interval, although the absence of NP 10 indicates a hiatus corresponding almost to the P/E boundary (Scheibner & Speijer, 2009). The first appearance of *Nummulites* is recorded just above the hiatus, while *Orbitolites* occurs towards the upper part of the section. The orthophragminids below the hiatus (spls. 17, 20, 23) are represented by *Discocyclina seunesi* cf. *beloslavensis*, *O. multiplicatus haymanaensis*, *O. schopeni ramaraoi*, and *O. aff. O. multiplicatus* (Fig. 11). Samples 20 and 23, previously assigned to SBZ 4 (Scheibner & Speijer, 2009), are now referred to OZ 1B. The upper part of the section above the hiatus was not assigned to any SBZ zone in Scheibner & Speijer (2009) and was correlated with NP 11 based on calcareous nannoplankton (Fig. 8). This part of the section belongs to OZ 3 based on the occurrence of *N. stockari* cf. *bejaensis* n. subsp. and *O. schopeni* cf. *neumannae* accompanied by a badly

paleogeographic map (simplified from Bishop, 1988), showing the distribution of shallow-marine limestones (El Garia Formation and its equivalents) in north and central Tunisia; 1: emergent area, 2: El Garia Formation, 3: pelagic limestones with globigerinids. C The present geographic position of the El Munchar section.

TABLE 1. Statistical data for orthoforminids from South Galala, Egypt, and El Munchar (EL MUN), Tunisia. See Figure 4E for explanation of parameters. N = number of specimens studied in the sample. All ranges and means for the cross-diameter of the embryo and height and width of chamberlets are in microns.

Sample	Outer cross-diameter of the embryo						Aauxiliary chamberlets			Equatorial chamberlets			Species/subspecies
	Deuteroconch			Protoconch			Number	Height	Width	Annuli/0.5 mm	Height	Width	
	Range	Mean±s.e	Range	Range	Mean	Range							
							N	Range	Range	Range	Range	Range	
B3.18	1	295.0	175.0	19	50-55	45-75	15	40-45	25-35				<i>Discocyclina seunesi</i>
D8.20	2	280-285	282.5	150-160	155.0	21	45-50	35-40	20-25				<i>D. seunesi cf. belostavensis</i>
D6.37	2	270-325	297.5	160-175	167.5	15-23	50-75	25-60	25-40				
D6.45	1		425.0		180.0	26	60-90	30-45	25-50				<i>D. tenuis</i>
B3.44	1		155.0		90.0	13	25-30	20-45	20-35				<i>D. dispansa</i>
B3.45	1		130.0		85.0	8	25-30	30-50	30-40				
B3.41	3	140-175	160.0	80-105	94.5	10-12	40-45	30-40	25-35				<i>D. dispansa cf. hvocemimammi-taurica</i>
B3.39	2	250-250	250.0	150-160	155.0	17	50-60	30-55	30-45				<i>D. archiaci cf. bakhchisaraiensis</i>
B3.44	2	175-235	205.0	115-135	125.0	14	50-60	30-50	25-30				
B3.45	3	185-290	228.3	110-140	121.6	14-19	30-45	30-40	30-40				
B3.41	15	195-400	266.3±15.01	110-200	146.0	15-21	35-70	25-45	25-45				<i>D. archiaci bakhchisaraiensis</i>
B3.43	10	200-330	265.5±15.64	110-200	145.0	15-21	50-75	30-70	30-45				<i>Nemkovella stockari</i>
EL MUN.24	1		110.0		120.0								
EL MUN.34	1		125.0		130.0								
D8.38	2	135-140	137.5	130-140	135.0				25-40				<i>N. stockari cf. bejaensis n. subsp.</i>
EL MUN.18	14	115-150	130.4±2.6	110-150	124.3				35-45				<i>N. stockari bejaensis n. subsp.</i>
EL MUN.20	1		240.0		135.0								<i>Orbitoclypeus schopeni</i>
EL MUN.22	1		210.0										
EL MUN.24	1		240.0		130.0								
D8.34	1		200.0		90.0								
D5.34	1		190.0		115.0								
D6.45	1		180.0		100.0								
B3.39	1		185.0		85.0								
B3.43	1		205.0		105.0								
D6.32	3	160-210	180.0	85-105	96.6	11-15	30-35	35-50	25-35				<i>O. schopeni cf. ramaraoi</i>
D8.23	3	185-200	191.6	90-95	93.3	16-17	35-45	25-30	25-40				<i>O. schopeni ramaraoi</i>
D6.37	4	175-190	181.2±2.72	100-100	100.0	15-20	40-45	25-40	30-40				
D8.20	5	130-195	173.0±10.35	90-95	91.7	15-18	25-40	25-50	20-35				
D5.38	5	170-205	185.0±5.48	80-125	98.0	12-18	40-45	25-45	25-40				
B3.41	7	160-245	185.7±9.87	80-125	95.8	15-17	40-45	30-55	30-40				
EL MUN.12	2	220-250	235.0	120-130	125.0								<i>O. schopeni cf. neumanna</i>
D8.38	2	190-285	237.5	105-170	137.5	18	35-45	25-50	25-45				<i>O. schopeni neumanna</i>
EL MUN.1	13	185-250	219.6±6.8	90-175	125.4	17-24	30-40	25-45	25-35				
EL MUN.18	23	170-270	219.1±4.83	100-170	119.1	15-26	30-50	25-40	25-35				
D8.17	3	195-235	210.0	95-150	115.0	16-21	35-45	25-45	20-40				<i>O. multiplicatus cf. haymanaensis</i>
D8.20	14	195-290	233.6±7.50	100-150	120.7	19-25	35-50	30-50	25-40				<i>O. multiplicatus haymanaensis</i>
D8.23	12	205-280	227.8±4.54	95-150	118.7	24-26	45-55	30-50	30-45				
D5.38	21	185-250	215.8±5.17	85-120	105.4	21-26	30-50	25-45	25-35				
D6.37	8	180-235	211.8±4.59	100-125	111.2	15-25	45-55	30-50	30-35				
D6.45	10	220-320	258.0±9.33	105-160	127.2	24-29	40-55	25-60	25-40				<i>O. multiplicatus cf. multiplicatus</i>
EL MUN.1	2	340-455	397.5	165-250	207.5								<i>O. multiplicatus</i>
EL MUN.9	1		330.0		150.0								<i>O. aff. O. multiplicatus</i>
D6.45	5	350-475	396.0±19.67	175-255	209.0	32-34	50-70	25-45	30-40				
D8.20	4	345-400	360.0±11.59	205-215	210.0	31-33	45-70	30-40	25-40				
EL MUN.1	1		375.0		185.0								<i>O. bayani</i>
EL MUN.18	10	100-150	127.0±4.37	70-95	82.5	8-11	25-30	25-50	20-30				<i>Asterocyclina taramellii</i>
EL MUN.26	2	115-150	132.5	70-80	75.0	10							<i>Asterocyclina sp.</i>
EL MUN.34	1		170.0										

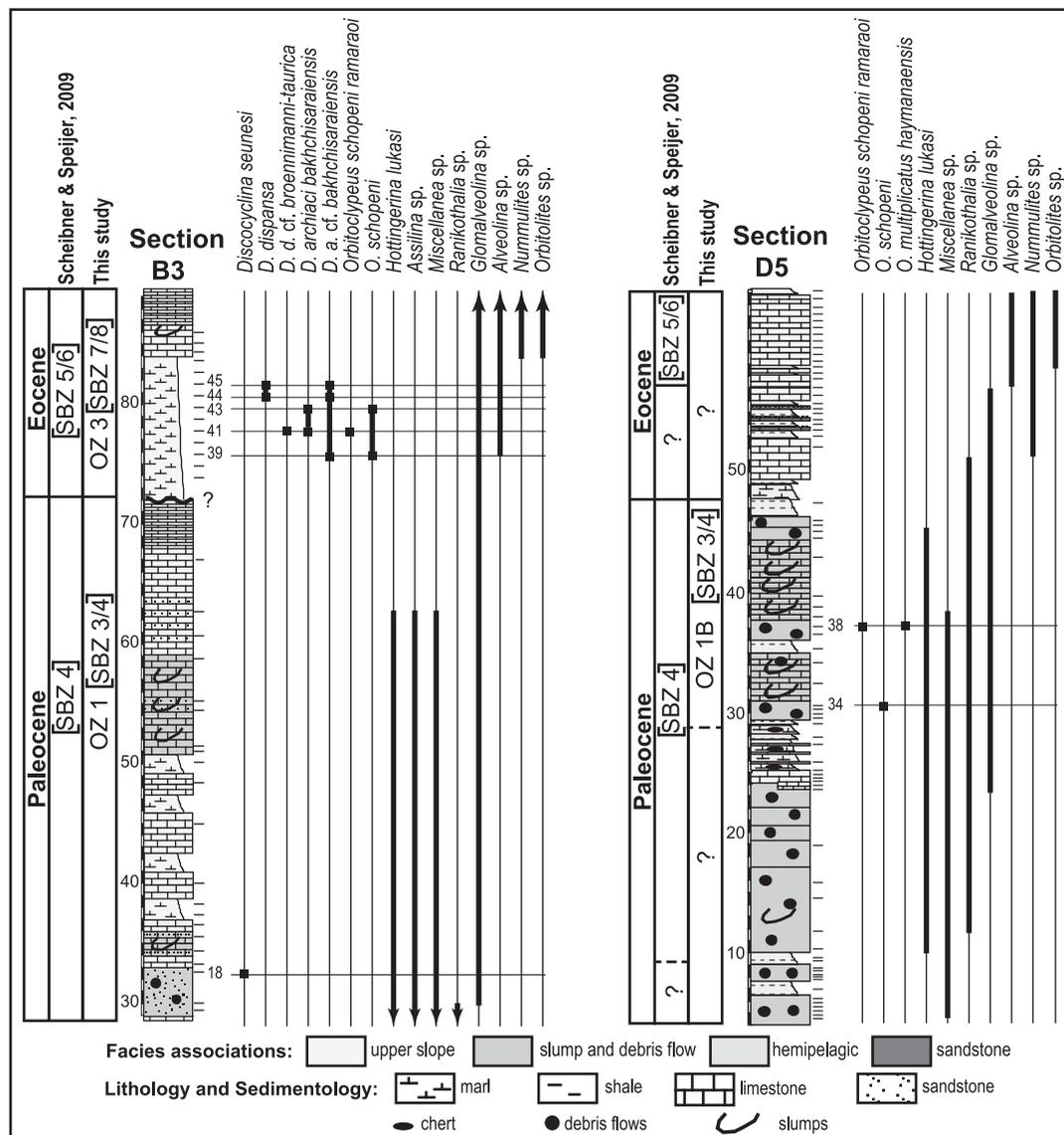


FIGURE 10. Distribution of orthophragminids and other stratigraphically important benthic foraminifera in sections B3 and D5, and inferred orthophragminid (OZ) and shallow benthic (SBZ) zones. The P/E boundary and distribution of benthic foraminifera are from Scheibner & Speijer (2009). The proposed hiatus at the P/E boundary in section B3 below the massive marls is from the present study, and the question mark indicates uncertainty about the exact position of the unconformity. The numbers to the right and left of the stratigraphic column indicate samples numbers and section thicknesses in meters, respectively.

preserved discocyclinid specimen, which can be assigned either to *D. archiaci* or to *D. tenuis* in sample 38. Orthophragminids are rare in sample 34, and only one specimen of *O. schopeni* has been identified.

Section D6

This is a 55-m thick sequence of calciturbidites and hemipelagic sediments with thin layers of debris flows in the middle part of the section, and represents a depositional setting at the toe-of-slope (Fig. 7). The orthophragminids, as other LBF, are reworked and occur in samples 32, 37, and 45 (Fig. 8). They belong to SBZ 4 (Scheibner & Speijer, 2009) and are represented by *D. seunesi* cf. *beloslavensis*, *D. tenuis*, *O. schopeni ramaraoi*, *O. multiplicatus haymanaensis* and *O. aff. O. multiplicatus* (Fig. 11). Samples 37 and 45 are

confidently assigned to OZ 1B, whereas sample 32 lacks key taxa.

EARLY EOCENE ORTHOPHRAGMINIDS FROM EL MUNCHAR, BEJA, TUNISIA

Section El Munchar

During the Mesozoic and Cenozoic, Tunisia was a part of the southern margin of the Tethys Ocean. The present mountain ranges (Atlas Mountains), trending almost E–W from Morocco to Tunisia, represent the deformed African continental margin and foreland deposits (Piqué et al., 1998). The shallow-marine carbonates of Eocene age are widely exposed in central and north Tunisia, and were grouped only in the upper Ypresian El Garia Formation

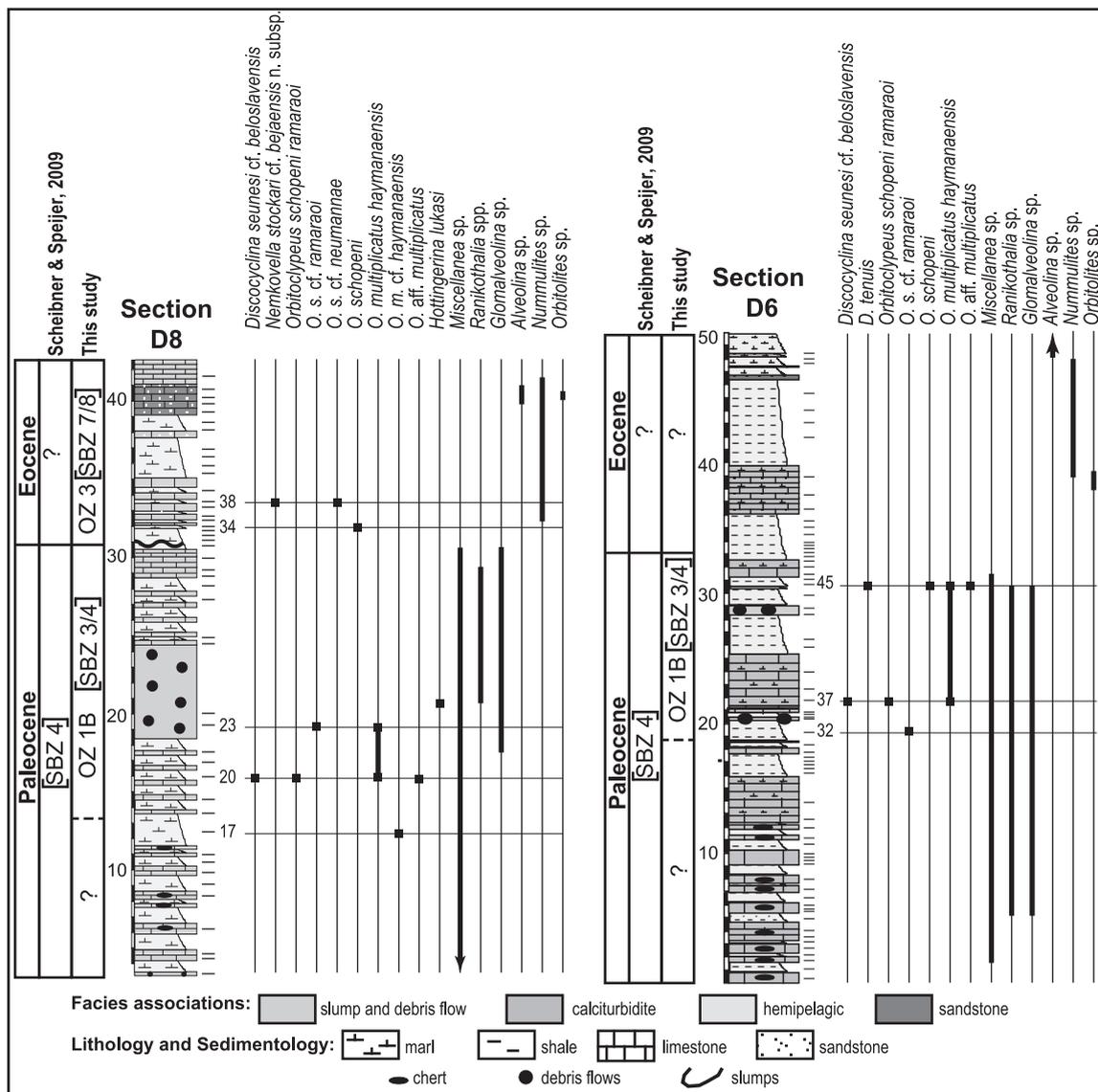


FIGURE 11. Distribution of orthophragminids and other stratigraphically important benthic foraminifera in sections D8 and D6, and inferred orthophragminid (OZ) and shallow benthic (SBZ) zones. The P/E boundary, distribution of benthic foraminifera, and the position of the hiatus in section D8 are from Scheibner & Speijer (2009). The numbers to the right and left of the stratigraphic column indicate samples numbers and section thicknesses in meters, respectively.

(Fournié, 1978; Bishop, 1988), although now it appears that some of these carbonate outcrops in N Tunisia are not strictly time-equivalent to this unit and their stratigraphic development is quite different. The El Garia Formation, extensively studied in central Tunisia for its sedimentological features (Jorry, 2004; Beavington-Penney et al., 2005), comprises nummulitic wackestone, packstone, and grainstone, deposited on a ramp with localized palaeohighs (Beavington-Penney et al., 2005). Based on nummulitids, the age of this unit in central Tunisia was reported to be upper Ypresian, although the uppermost part corresponds to the Ypresian/Lutetian transition (corresponding to SBZ 11-12/13; Jorry, 2004). A shallow-marine carbonate sequence with nummulitids and abundant orthophragminids is exposed in a quarry close to El Munchar village near Beja, 65 km west of Tunis (Fig. 9; Kujawski, 1969; Rouvier,

1985). These outcrops have been ascribed to the El Garia Formation in previous maps and regional interpretations (Fournié, 1978; Bishop, 1988; Mejri et al., 2006). At the El Munchar section Kujawski (1969) reported the occurrence of *Nummulites atacicus* Leymerie in the lower and upper part and *N. subatacicus* Douvillé and *N. globulus* Leymerie in the middle, implying an early Ypresian age (SBZ 8) for the whole unit after the shallow-benthic zonation scheme of Serra-Kiel et al. (1998).

The El Munchar section includes ~77 m of shallow-marine limestone and thin marl intercalations. The interval between samples 1–26 yielded *N. stockari bejaensis* n. subsp., *N. stockari*, *O. schopeni neumannaee*, *O. multiplicatus* cf. *multiplicatus*, *O. bayani*, and *Asterocyclina taramellii*, and the uppermost sample (34) yielded *N. stockari* and *O. schopeni*, recorded for the first time in Tunisia. The

orthophragminids between samples 1–26 are safely assigned to OZ 3 (SBZ 7/8), suggesting that shallow-marine sequences northeast of Beja are not strictly time equivalent to the El Garia Formation in central Tunisia. We here only illustrate *N. stockari bejaensis* n. subsp. (Figs. 16.13–16.16; Fig. 18), *O. schopeni neumannae* (Figs. 16.20, 16.21) and *A. taramellii* (Fig. 16.22) to compare them with early Eocene orthophragminids from Galala. We find that *N. stockari* and *O. schopeni* have almost the same developmental stages at both localities and both taxa are very abundant throughout the section. A detailed description of the El Munchar section and its benthic foraminifera are beyond the scope of this paper.

SYSTEMATIC PALEONTOLOGY

In the synonymies, we only refer to the original description of the taxa; a comprehensive synonym list for each species/subspecies has been given in Less (1987), Özcan et al. (2001), and Less et al. (2007). A detailed description (with biometry) of late Paleocene–early Eocene orthophragminids from northern Tethyan platforms is given in Less et al. (2007). The biometric data based on the eight measurements and counts illustrated in Figure 4E are given in Table 1. All specimens from the South Galala and El Munchar sections are repositied in the Özcan collection in the Department of Geological Engineering, İstanbul Technical University (İstanbul).

Order FORAMINIFERIDA Eichwald, 1830
Family DISCOCYCLINIDAE Galloway, 1928
Genus *Discocyclina* Gümbel, 1870
Type species: *Orbitolites prattii* Michelin, 1846

Discocyclina seunesi Douvillé, 1922
Figs. 12.1–12.5, 13.19, 14.3, 14.4, 17.1

Discocyclina seunesi Douvillé, 1922, p. 64, 65, pl. 4, figs. 1–4, text-figs. 1, 6, 15.

Diagnosis. *Discocyclina seunesi* is a discoidal, small to medium-sized, and moderately flattened or slightly inflated form with a smooth test surface (see Douvillé, 1922, Özcan et al., 2001, and Less et al., 2007, for illustrations depicting the surface of the test and development of equatorial layer and lateral chamberlets in vertical sections). The rosette is mostly of the “*Discocyclina*” type (see Fig. 5). The megalospheric embryo is eulepidine and may also be excentriplepidine only in the most advanced members at the latest stage of its phylogeny (*D. seunesi karabuekensis* in OZ 2). The embryonic chambers, protoconch (P), and deuteroconch (D) are moderately small. The adauxiliary chamberlets are arcuate in shape and of the “*varians*” type, few to average in number, and moderately narrow and low. The equatorial chamberlets are moderately wide and rather low, their annuli are circular, and the growth pattern is of the “*varians*” type. This species includes the subspecies: *D. s. seunesi* Douvillé, 1922; $D_{\text{mean}} < 250 \mu\text{m}$; *D. s. beloslavensis* Less & Özcan, 2007; $D_{\text{mean}} = 250\text{--}310 \mu\text{m}$; and *D. s. karabuekensis* Less & Özcan, 2007; $D_{\text{mean}} > 310 \mu\text{m}$ (Less et al., 2007).

Remarks. This species was sparse in the studied material and represented by *D. seunesi* cf. *beloslavensis* in samples D8.20 and D6.37. It is found with *Orbitoclypeus schopeni ramaraoui* and *O. multiplicatus haymanaensis* in sample

D6.37 and with *O. schopeni ramaraoui*, *O. multiplicatus haymanaensis* and *O. aff. O. multiplicatus* in D8.20. These samples were assigned to OZ 1B (correlated with the upper part of SBZ 3 and SBZ 4 in Figs. 11, 13, and 14). A single specimen in sample B3.18 cannot be assigned to any subspecies (Figs. 10, 17.1), although the diameter of the deuteroconch of this specimen is within the limits of *D. seunesi beloslavensis*. *Discocyclina seunesi* differs from *O. schopeni* by having a larger eulepidine-type embryo and almost rectangular annular chamberlets and from *O. multiplicatus* by its embryo configuration and shape of the annular chamberlets, which are excentriplepidine and hexagonal, respectively, in the latter species.

Discocyclina tenuis Douvillé, 1922
Figs. 12.6, 12.7, 14.19

Discocyclina tenuis Douvillé, 1922, p. 87, pl. 4, fig. 9.

Diagnosis. *Discocyclina tenuis* is a small to medium-sized, flattened, unribbed form with “*Discocyclina*”-type rosette. The medium-sized embryo is semi-nephrolepidine to trybliolepidine (see Fig. 5). The relatively numerous “*archiaci* and *varians*”-type adauxiliary chamberlets are moderately wide and high like the equatorial chamberlets that are arranged in circular annuli of the “*archiaci* and *varians*”-type growth pattern. The available data are not yet sufficient to subdivide the species into subspecies (Less et al., 2007).

Remarks. *Discocyclina tenuis*, a very rare taxon in the Thanetian and early Eocene, is associated with *D. seunesi* and the early developmental stages of *D. archiaci* in northern Tethyan platforms (Less et al., 2007). In South Galala, only one specimen in sample D6.45 was found with *O. schopeni*, *O. multiplicatus haymanaensis*, *O. aff. O. multiplicatus*, *Ranikothalia* sp., and *Glomalveolina* sp., an assemblage assigned to OZ 1B. This species differs from *O. schopeni* and *O. multiplicatus* by having a large trybliolepidine-type embryo and by rectangular annular chamberlets, which are wide and long (Fig. 14.19).

Discocyclina archiaci (Schlumberger, 1903)
Figs. 15.18–15.24, 16.1–16.8, 17.8–17.18

Orthophragmina archiaci Schlumberger, 1903, p. 277, pl. 8, figs. 5, 11.

Diagnosis. *Discocyclina archiaci* is an unribbed form having semi-nephrolepidine to trybliolepidine embryos in the older members (*D. archiaci bakhchisaraiensis* and *D. archiaci staroseliensis*) and trybliolepidine and umbilicolepidine embryos in the advanced members (see Fig. 5). The adauxiliary chamberlets are moderately wide, of average height, and of the “*archiaci*” type. Equatorial chamberlets are moderately wide and high, with “*archiaci*”-type growth pattern. This species includes four subspecies: *D. a. bakhchisaraiensis* Less, 1987; $D_{\text{mean}} < 305 \mu\text{m}$; *D. a. staroseliensis* Less, 1987; $D_{\text{mean}} = 305\text{--}390 \mu\text{m}$; *D. a. archiaci* (Schlumberger, 1903); $D_{\text{mean}} = 390\text{--}600 \mu\text{m}$; and *D. a. bartholomei* (Schlumberger, 1903); $D_{\text{mean}} > 600 \mu\text{m}$ (Less, 1998).

Remarks. This species, recorded only in section B3, was represented by *D. archiaci bakhchisaraiensis* (spl. B3.41 and 43) or *D. archiaci* cf. *bakhchisaraiensis* Less, 1987 (spl. B3.39, 44, and 45) and, in terms of average size of the deuteroconch (D), which is <270 microns in all studied material, had the most primitive features compared to *D.*

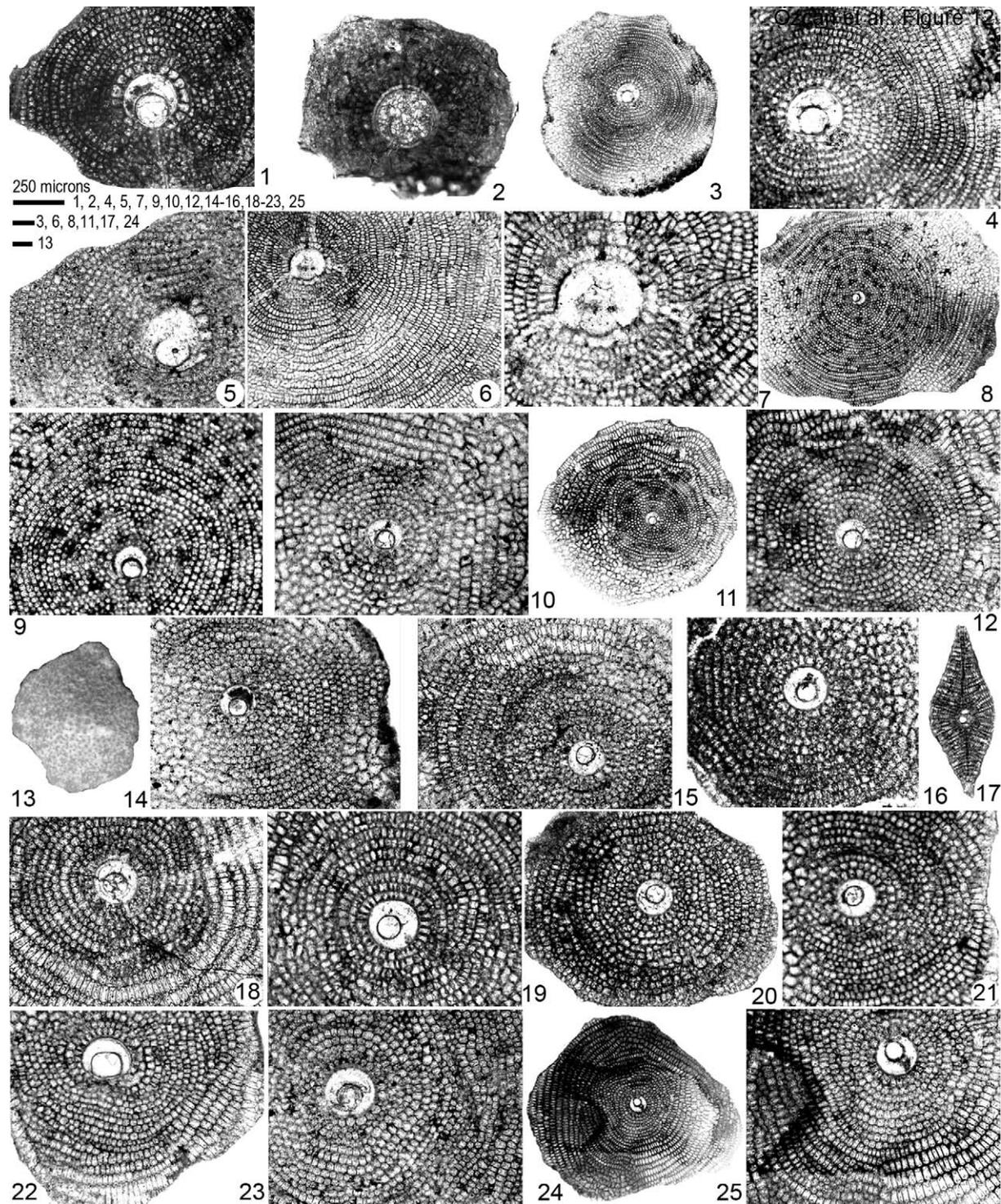


FIGURE 12. Late Paleocene orthoforminids from South Galala. 1–4 *Discocyclina seunesi* cf. *beloslavensis* Less and Özcan, OZ 1B: 1, D6.37-15; 2, D6.37-7; 3, 4, D8.20-19. 5 *D. seunesi* Douvillé, OZ 1B, B3.18-1. 6, 7 *Discocyclina tenuis* Douvillé, OZ 1B, D6.45-1. 8, 9 *Orbitoclypeus schopeni* (Cecchia-Rispoli), OZ 1B, D6.45-11. 10–12 *O. schopeni* cf. *ramaraoui* (Samanta), OZ 1B: 10, D8.23-28; 11, 12, D8.23-16. 13, 14 *O. schopeni* *ramaraoui* (Samanta), OZ 1B, D8.20-25. 15–19, 21–25 *O. multiplicatus haymanaensis* Özcan et al., OZ 1B: 15, D5.38-12; 16, D5.38-16; 17, D5.38-19; 18, D6.37-5; 19, D6.45-8; 21, D8.20-4; 22, D8.20-8; 23, D8.20-12; 24, 25, D8.23-12. 20 *O. multiplicatus* cf. *haymanaensis* Özcan et al., OZ 1B?, D8.17-4. The specimen numbers denote section, sample number, and specimen number (e.g., D6.37-15). 13: external view, 17: vertical section. Others are equatorial sections of A-forms.

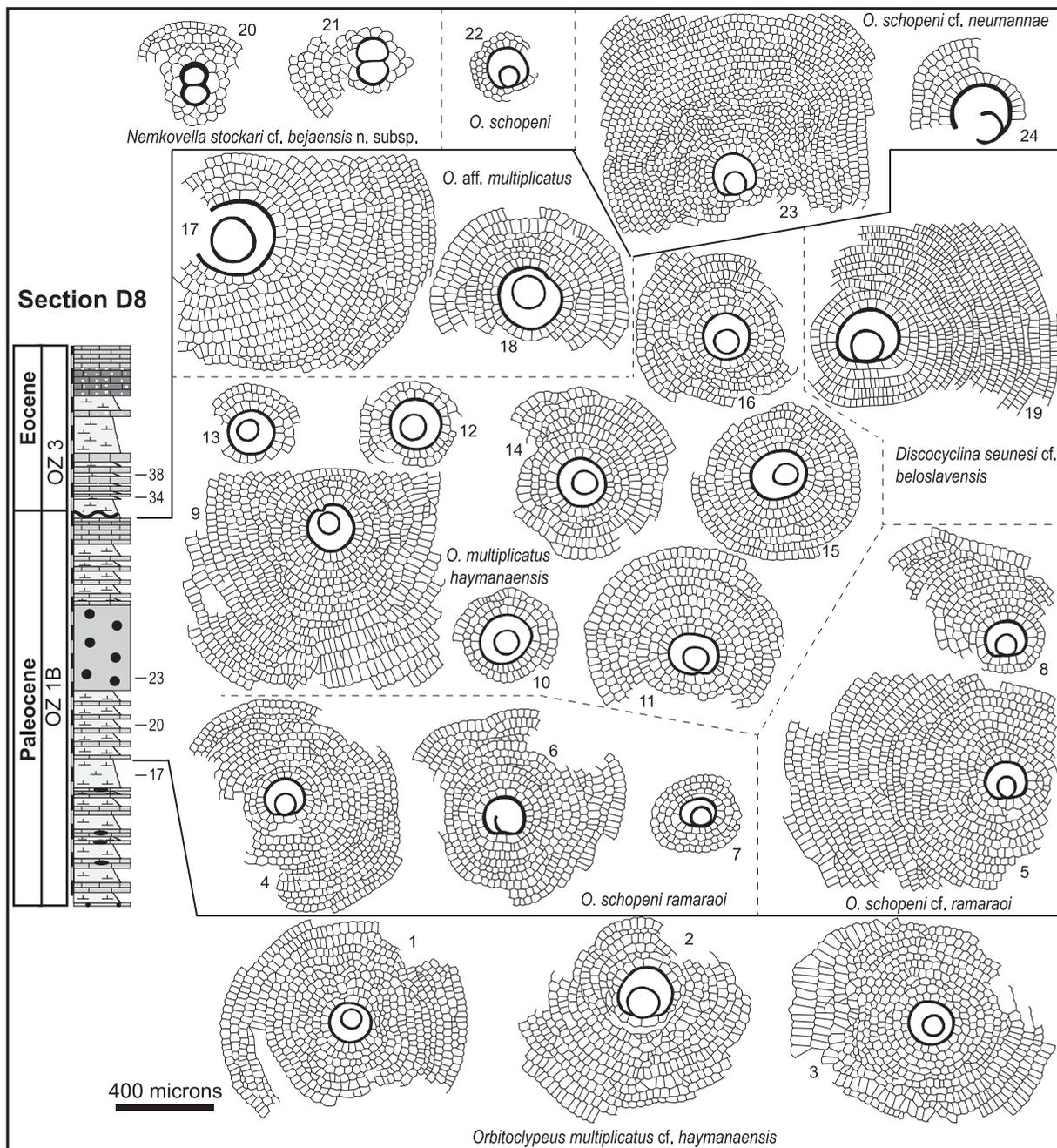


FIGURE 13. Embryon features and the development of annular chambers in late Paleocene (1–19) and early Eocene (20–24) orthophragminids from section D8. 1–3 *Orbitoclypeus multiplicatus* cf. *haymanaensis* Özcan et al., OZ 1B: 1, D8.17-4; 2, D8.17-2; 3, D8.17-5. 4, 6, 7 *O. schopeni ramaraoi* (Samanta), OZ 1B: 4, D8.20-25; 6, D8.20-14; 7, D8.20-15. 5, 8 *O. schopeni* cf. *ramaraoi* (Samanta), OZ 1B: 5, D8.23-13; 8, D8.23-28. 9–16 *O. multiplicatus haymanaensis* Özcan et al., OZ 1B: 9, D8.23-12; 10, D8.20-11; 11, D8.20-2; 12, D8.23-21; 13, D8.20-4; 14, D8.23-2; 15, D8.23-9; 16, D8.23-23. 17, 18 *O. aff. O. multiplicatus* (Gümbel), OZ 1B: 17, D8.20-23; 18, D8.20-22. 19 *Discocyclina seunesi* cf. *beloslavensis* Less & Özcan, OZ 1B, D8.20-19. 20, 21 *Nemkovella stockari* cf. *bejaensis* n. subsp., OZ 3: 20, D8.38-1; 21, D8.38-2. 22 *O. schopeni* (Checchia-Rispoli), OZ 3, D8.34-1. 23, 24 *O. schopeni* cf. *neumannae* (Toumarkine), OZ 3: 23, D8.38-6; 24, D8.38-5. The numbers to the right of the stratigraphic column indicate samples numbers. The specimen numbers denote section, sample number, and specimen number (e.g., D8.17-4). See Figure 11 for lithologic key.

archiaci assemblages described in the Tethys (Less, 1998; Özcan et al., 2007b). The first appearance of this species in northern Tethyan platforms is within OZ 3, where it is associated with some newly appearing taxa such as *D. dispansa* that has also been identified in South Galala (Fig. 3). In Galala, this species is, however, associated with *O. schopeni ramaraoi* only in one sample (spl. B3.41), which

is confined to OZ 2 at its upper stratigraphic range. Based on the association of *D. archiaci* and *D. dispansa*, the upper part of the succession in section B3 above the hiatus is assigned to OZ 3. A single, badly preserved discocyclinid specimen from sample D8.38, found in association with *N. stockari* cf. *bejaensis* n. subsp., may belong to this species. *D. archiaci* is differentiated from *O. schopeni* by having a

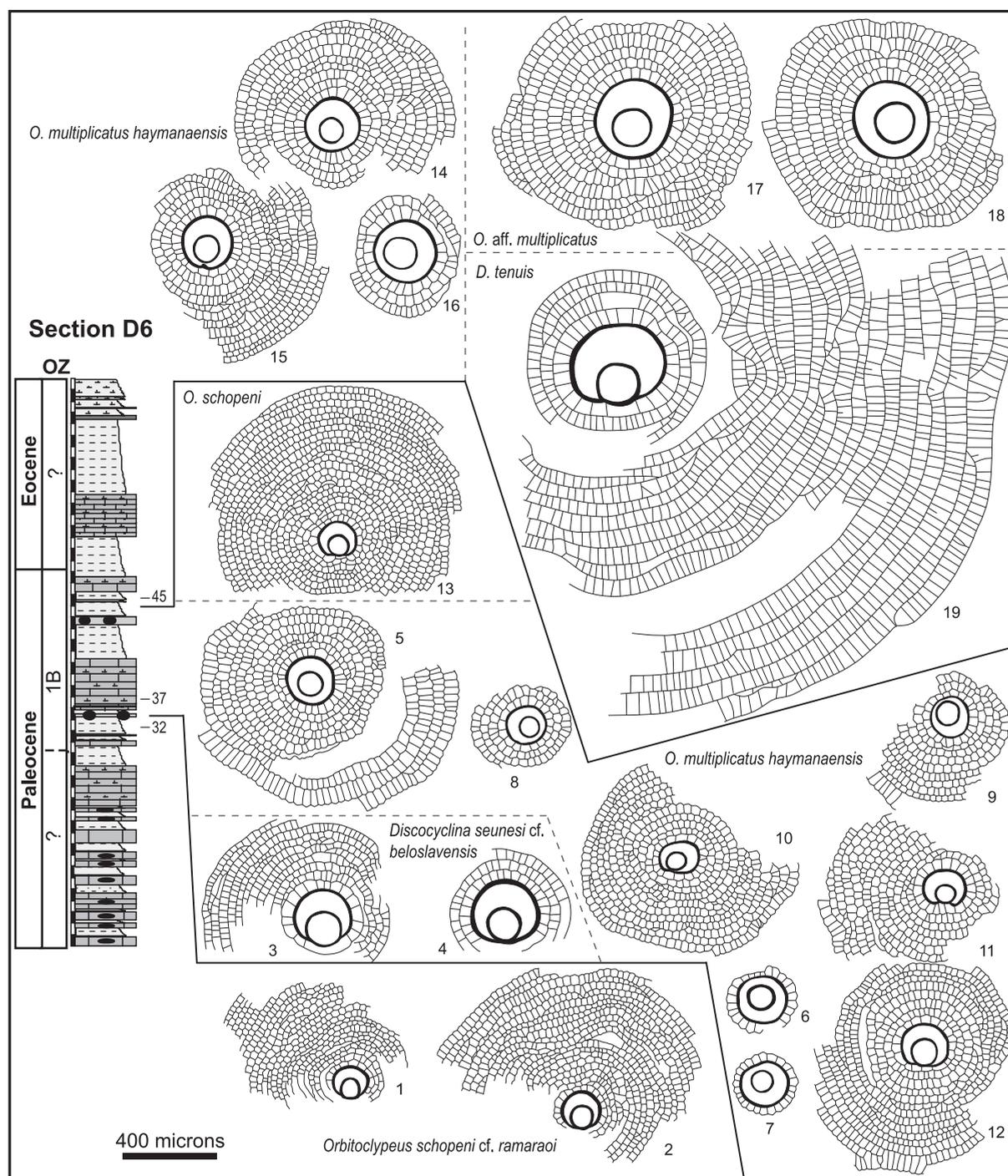


FIGURE 14. Embryon features and the development of annular chambers in late Paleocene orthophragminids from section D6. All belong to OZ 1B. **1, 2** *Orbitoclypeus schopeni* cf. *ramaraoi* (Samanta): 1, D6.32-1; 2, D6.32-3. **3, 4** *Discocyclina seunesi* cf. *beloslavensis* Less & Özcan: 3, D6.37-15; 4, D6.37-7. **5-12, 14-16** *O. multiplicatus haymanaensis* Özcan et al.: 5, D6.37-5; 6, D6.37-12; 7, D6.37-3; 8, D6.37-2; 9, D6.37-1; 10, D6.37-13; 11, D6.37-4; 12, D6.37-8; 14, D6.45-8; 15, D6.45-5; 16, D6.45-9. **13** *O. schopeni* (Cecchia-Rispoli), D6.45-11. **17, 18** *O. aff. O. multiplicatus* (Gümbel): 17, D6.45-10; 18, D6.45-14. **19** *D. tenuis* Douvillé, D6.45-1. The numbers to the right of the stratigraphic column indicate samples numbers. The specimen numbers denote section, sample number, and specimen number (e.g., D6.32-1). See Figure 11 for lithologic key.

semi-nephrolepidine to trybliolepidine-type embryo and typical rectangular annular chamberlets.

Discocyclina dispansa (Sowerby, 1840)

Figs. 16.9-16.12, 17.19, 17.20

Lycophris dispansus Sowerby, 1840, p. 327, pl. 24, figs. 16a, b.

Diagnosis. *Discocyclina dispansa* is a small to large-sized, flat to saddle-shaped, unribbed form. The small to medium-sized megalospheric embryo is semi-nephrolepidine in the older members (e.g., *D. d. broennimanni* and *D. d. taurica*) and is trybliolepidine in the phylogenetically advanced members. The adauxiliary chamberlets are moderately wide

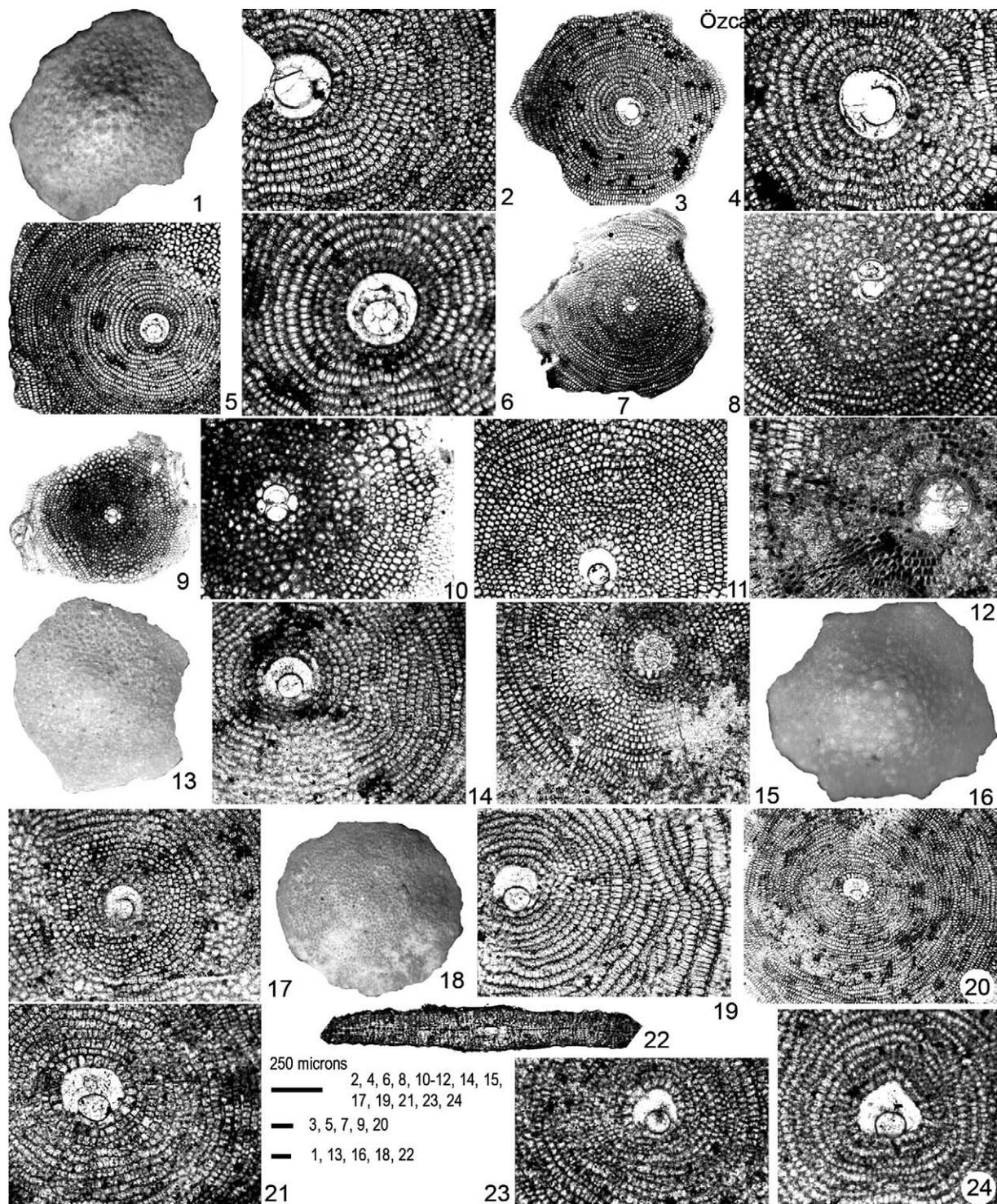


FIGURE 15. Late Paleocene and early Eocene orthophragminids from South Galala. **1–6** *Orbitoclypeus* aff. *O. multiplicatus* (Gümbel), OZ 1B: 1, 2, D8.20-23; 3, 4, D6.45-14; 5, 6, D6.45-10. **7–10** *Nemkovella stockari* cf. *bejaensis* n subsp., OZ 3: 7, 8, D8.38-2; 9, 10, D8.38-1. **11, 12, 17** *O. schopeni* (Cecchia-Rispoli), OZ 3: 11, 12, D8.38-6; 17, B3.43-4. **13–16** *O. schopeni ramaraoi* (Samanta), OZ 3: 13, 14, B3.41-23; 15, B3.41-25; 16, B3.41-27. **18–24** *Discocyclina archiaci bakhchisaraiensis* Less, OZ 3: 18, 19, B3.43-14; 20, 21, B3.43-2; 22, B3.43-12; 23, B3.41-10; 24, B3.41-12. The specimen numbers denote section, sample number, and specimen number (e.g., D8.20-23). 1, 13, 16, 18: external view, 22: vertical section. Others are equatorial sections of A-forms.

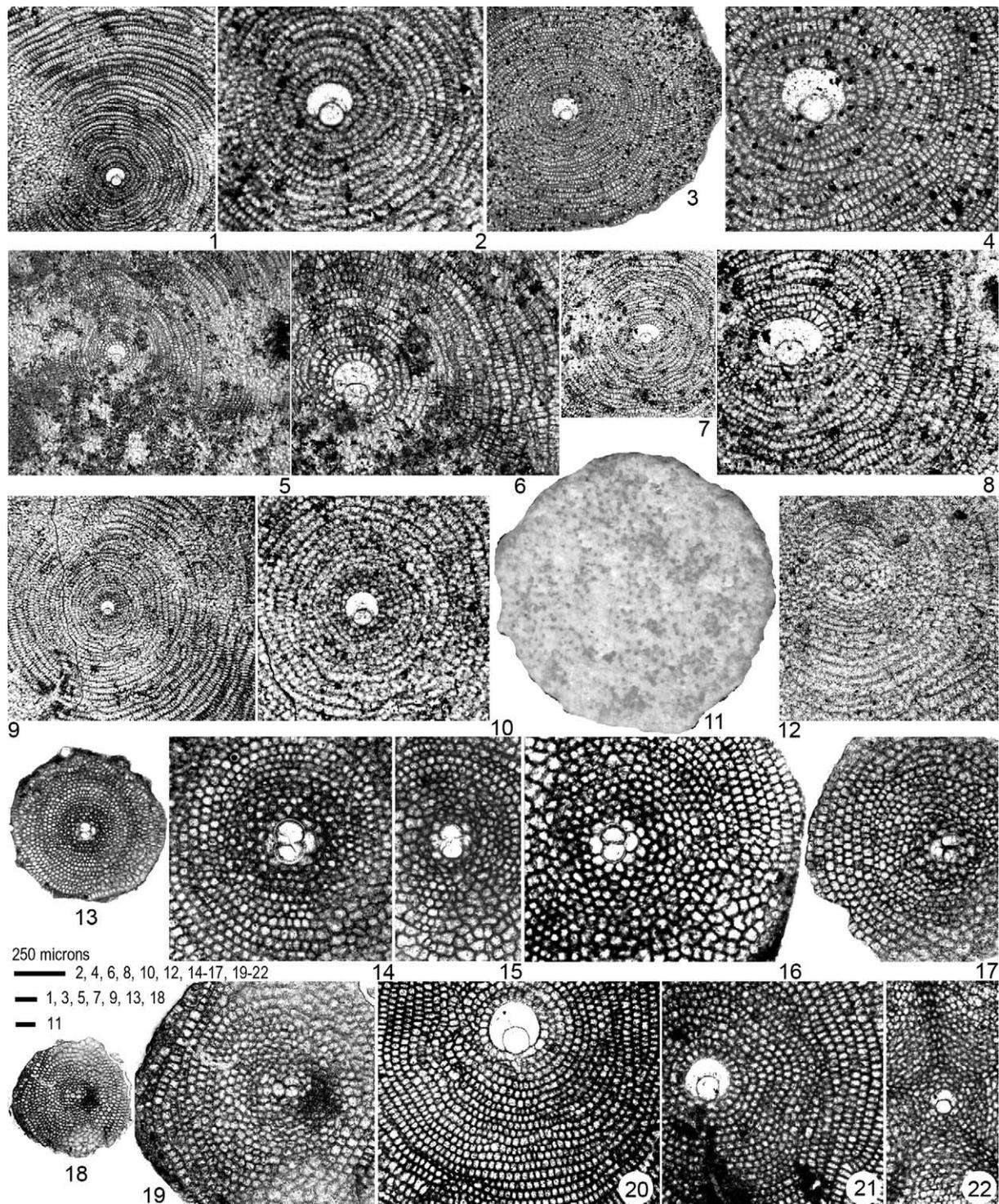


FIGURE 16. Early Eocene orthoforminids from South Galala (1–12) and comparative specimens of *Nemkovella stockari*, *Orbitoclypeus schopeni*, and *Asterocyclina taramellii* from Tunisia (13–16, 20–22) and Turkey (17–19): 1–4 *Discocyclina archiaci bakhchisaraiensis* Less, OZ 3: 1, 2, B3.41-11; 3, 4, B3.41-13. 5–8 *D. archiaci* cf. *bakhchisaraiensis* Less, OZ 3: 5, 6, B3.45-1; 7, 8, B3.45-5. 9–12 *D. dispansa* (Sowerby), OZ 3: 9, 10, B3.44-3; 11, 12, B3.45-4. 13–16 *Nemkovella stockari bejaensis* n. subsp., OZ 3: 13, 14, EL MUN.18-1; 15, EL MUN.18-46; 16, EL MUN.18-53. 17–19 *N. stockari stockari* Less & Özcan, OZ 2: 17, KURUC-64; 18, 19, KURUC-69. 20, 21 *Orbitoclypeus schopeni neumanna* (Toumarkine), OZ 3: 20, EL MUN.18-7; 21, EL MUN.18-9. 22 *Asterocyclina taramellii* (Munier-Chalmas), OZ 3, EL MUN.18-24. The specimen numbers denote section, sample number, and specimen number (e.g., B3.41-11). 11: external view; others are equatorial sections of A-forms.

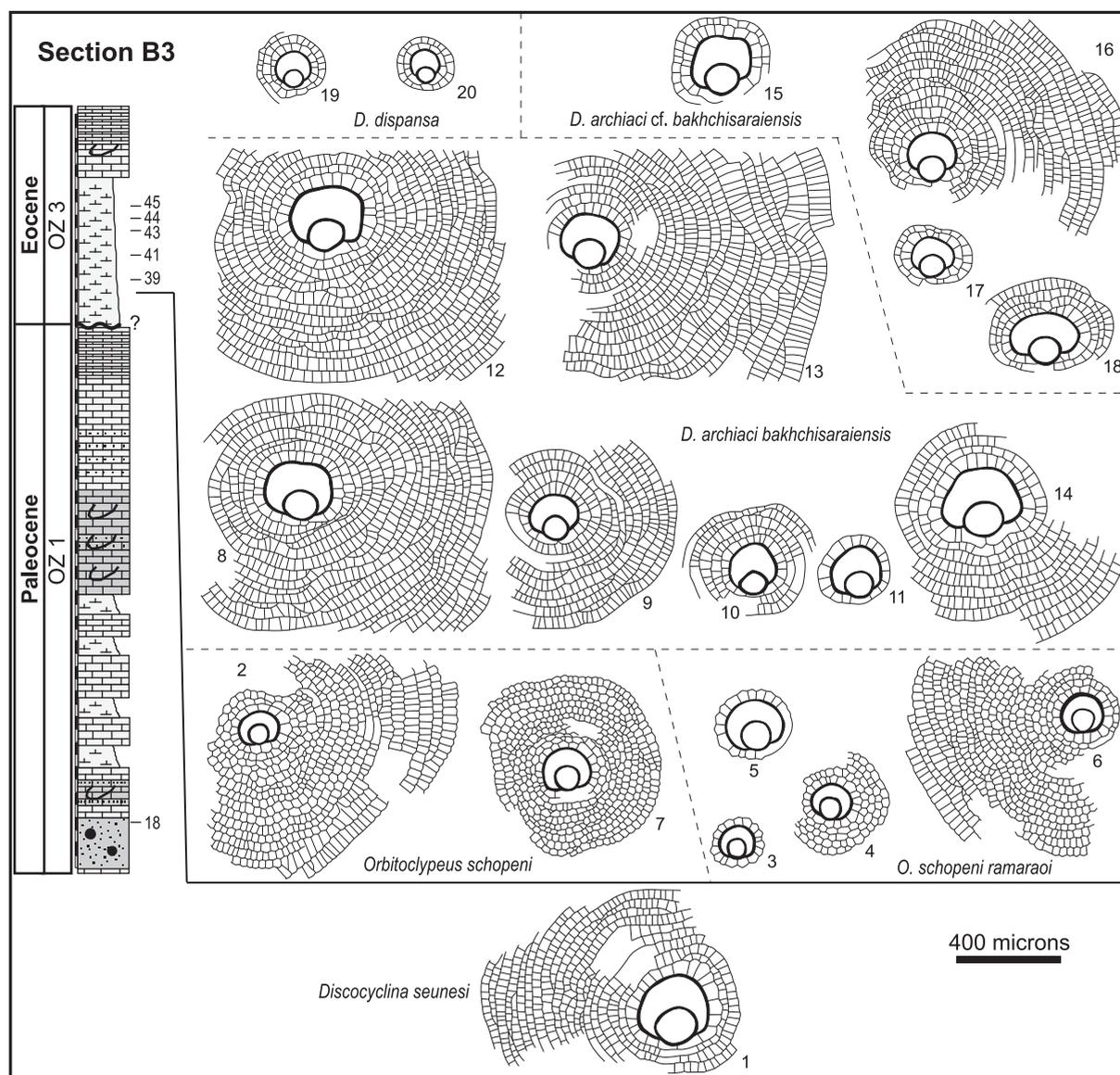


FIGURE 17. Embryon features and the development of annular chambers in late Paleocene (1) and early Eocene (2–20) orthophragminids from Section B3 in OZ 1 and OZ 3, respectively. 1 *Discocyclina seunesi* Douvillé, B3.18-1. 2, 7 *Orbitoclypeus schopeni* (Cecchia-Rispoli): 2, B3.39-4; 7, B3.43-4. 3–6 *O. schopeni ramaraoi* (Samanta): 3, B3.41-1; 4, B3.41-4; 5, B3.41-23; 6, B3.41-25. 8–14 *D. archiaci bakhchisaraiensis* Less: 8, B3.41-13; 9, B3.41-11; 10, B3.41-5; 11, B3.41-10; 12, B3.43-2; 13, B3.43-14; 14, B3.43-11. 15–18 *D. archiaci cf. bakhchisaraiensis* Less: 15, B3.39-1; 16, B3.45-1; 17, B3.45-6; 18, B3.45-5. 19, 20 *D. dispansa* (Sowerby): 19, B3.44-3; 20, B3.45-4. The numbers to the right of the stratigraphic column indicate samples numbers. The specimen numbers denote section, sample number and specimen number (e.g., B3.18-1). See Figure 10 for lithologic key.

and high, and of the “archiaci” type. The equatorial chamberlets are also moderately wide and high. This species includes six subspecies: *D. d. broennimanni* Less, 1987; $D_{\text{mean}} < 160 \mu\text{m}$; *D. d. taurica* Less, 1987; $D_{\text{mean}} = 160\text{--}230 \mu\text{m}$; *D. d. hungarica* Kecskeméti, 1959; $D_{\text{mean}} = 230\text{--}290 \mu\text{m}$; *D. d. sella* (d’Archiac, 1850); $D_{\text{mean}} = 290\text{--}400 \mu\text{m}$; *D. d. dispansa* (Sowerby, 1840); $D_{\text{mean}} = 400\text{--}520 \mu\text{m}$; and *D. d. umbilicata* (Deprat, 1905), $D_{\text{mean}} > 520 \mu\text{m}$ (Less, 1998).

Remarks. *Discocyclina dispansa*, recorded only in section B3, was represented by *D. dispansa cf. broennimanni/taurica* associated with *O. schopeni ramaraoi* and *D. archiaci bakhchisaraiensis* in sample B3.41, assigned to OZ 3. Single

specimens also occurred in samples B3.44 and 45, associated with *D. archiaci cf. bakhchisaraiensis*. This species is differentiated from *D. archiaci* by having a small, semi-nephrolepidine-type embryo in the same assemblage in which they occur together.

Genus *Nemkovella* Less, 1987

Type species: *Orbitoides strophiolata* Gümbel, 1870

Nemkovella stockari Less & Özcan, 2007, emend. herein

Nemkovella stockari Less & Özcan, 2007, p. 436–438, pl. 2, figs. 1–6, fig. 13.

Emended diagnosis. *Nemkovella stockari* is a small (<2-mm diameter), moderately inflated, and unribbed form with a

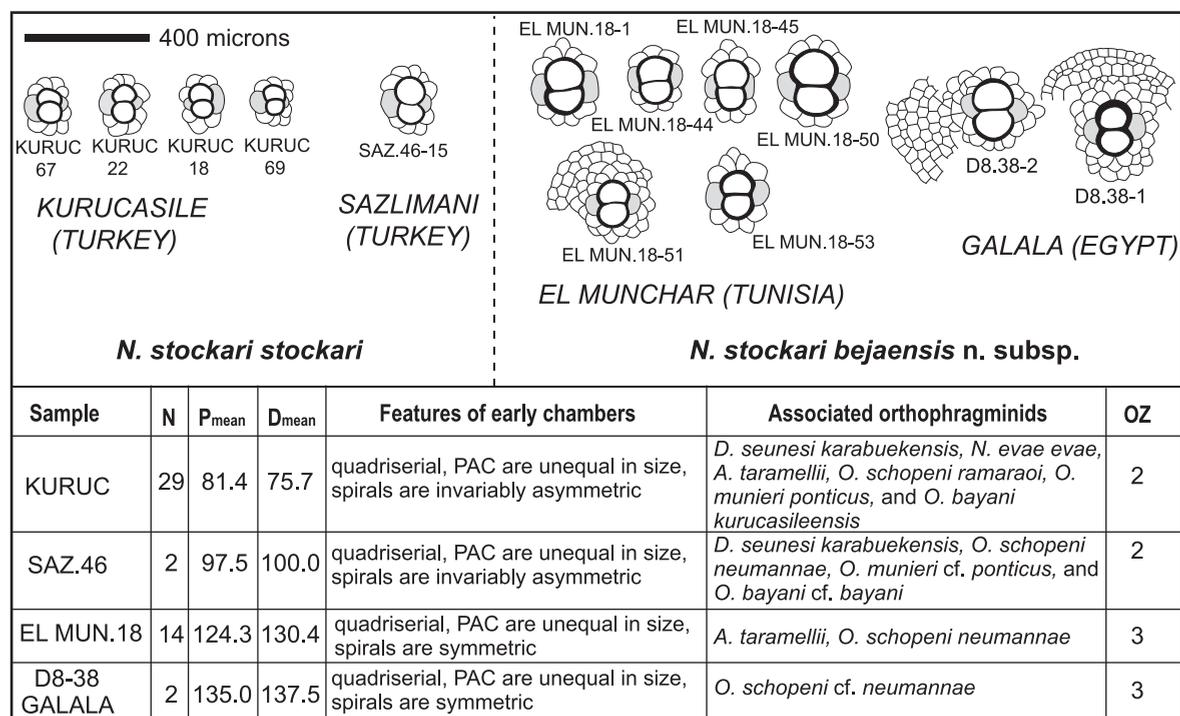


FIGURE 18. Comparison of *N. stockari stockari* (specimens from samples KURUC and SAZ in Turkey, OZ 2) and *N. stockari bejaensis* n. subsp. (EL MUN.18 and D8 specimens from Tunisia and South Galala, respectively, OZ 3) in the early Eocene. The principal auxiliary chamberlets (PAC) are shaded. N = number of the specimens in sample. See Figure 4 for explanation of the biometric parameters.

smooth test surface. The megalospheric embryo is small, with a protoconch almost the same size as the deutoconch (of isolepidine-type configuration) or a little bit larger. The wall common to the protoconch and deutoconch is almost straight. The spirals around the embryo are quadriserial, asymmetric in the early-stage (“primitive” forms) and quadriserial and symmetric in the later stage (phylogenetically more “advanced” forms assigned to *N. stockari bejaensis* n. subsp. described in this study). The adauxiliary chamberlets were not observed. The principal auxiliary chamberlets (pac) are unequal in size in the early members and conspicuously equal in the stratigraphically advanced ones. The equatorial annuli are circular with relatively wide and moderately high chamberlets, which are spatulate in the inner cycles, and distinctly hexagonal in the external ones. Their growth pattern is of the “varians” type (Fig. 5). The available data permit us to subdivide the species into two subspecies: *N. s. stockari* Less & Özcan, 2007; $D_{\text{mean}} < 100 \mu\text{m}$, and *N. s. bejaensis* n. subsp.; $D_{\text{mean}} > 100 \mu\text{m}$.

Nemkovella stockari bejaensis n. subsp.

Özcan, Boukhalfa, and Scheibner

Figs. 13.20, 13.21, 15.7–15.10, 16.13–16.16, 18

Etymology. After the town of Beja (Tunisia), the type locality of the subspecies.

Holotype. Specimen EL MUN.18-1 (Figs. 16.13, 16.14, 18).

Repository. İstanbul Technical University, Department of Geological Engineering, İstanbul.

Paratypes. Specimens EL MUN.18-46, 53 (Figs. 16.15, 16.16).

Type locality. Beja, Tunisia, sample EL MUN.18.

Geographic distribution. South Galala, Egypt, and Beja, Tunisia

Type level. Early Eocene, OZ 3 orthofragminid zone.

Diagnosis. *Nemkovella stockari* population with $D_{\text{mean}} > 100 \mu\text{m}$.

Remarks. *N. stockari* is quite different than any other orthofragminid taxa by having an isolepidine-type embryo, around which spiral development is observed before the onset of annular chambers. Such taxa with spiral development around the embryo are very rare in Tethyan orthofragminids and the only known species with similar features is *Nemkovella daguini* (Neumann, 1958). In the type material from Turkey assigned to OZ 2, specimens of *N. stockari* possess a very small embryo and two principal auxiliary chamberlets, distinctly unequal in size (Figs. 16.17–16.19; Fig. 18). The specimens in South Galala and Tunisia have larger embryos, and the principal auxiliary chamberlets are characteristically equal in size. The spiral arising from these chamberlets is asymmetrical in the Turkish material and symmetrical in specimens in Galala and Tunisia. The advanced specimens in the El Munchar section, assigned to *N. stockari bejaensis* n. subsp., are associated with *O. schopeni neumannae*, a characteristic subspecies for OZ 3. The Galala specimens assigned to *N. stockari bejaensis* n. subsp. are also associated with rare *O. schopeni cf. neumannae*, in OZ 3. The microspheric generation of *N. stockari bejaensis* n. subsp. is unknown and its assignment to *Nemkovella* relies solely on the isolepidine-type embryo configuration and a spatulate and hexagonal shape of the equatorial chamberlets.

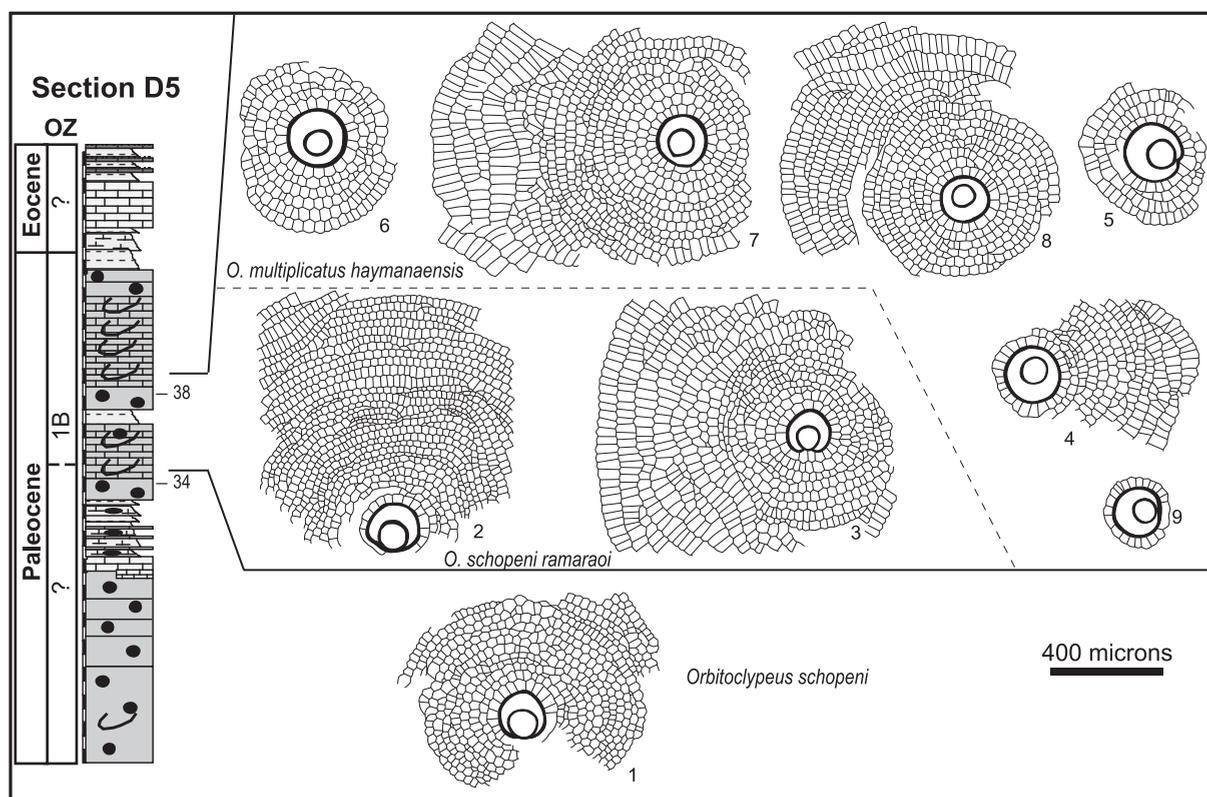


FIGURE 19. Embryon features and the development of annular chambers in late Paleocene orthophragminids from section D5; sample 34: OZ 1; sample 38: OZ 1B. 1 *Orbitoclypeus schopeni* (Checchia-Rispoli), D5.34-3. 2, 3 *O. schopeni ramaraoi* (Samanta): 2, D5.38-14; 3, D5.38-18. 4-9 *O. multiplicatus haymanaensis* Özcan et al.: 4, D5.38-6; 5, D5.38-1; 6, D5.38-16; 7, D5.38-13; 8, D5.38-12; 9, D5.38-4. The numbers to the right of the stratigraphic column indicate samples numbers. The specimen numbers in the samples denote section, sample number, and specimen number (e.g., D5.34-3). See Figure 10 for lithologic key.

Family ORBITOCLYPEIDAE Brönnimann, 1946

Genus *Orbitoclypeus* Silvestri, 1907

Type species: *Orbitoides varians* Kaufmann, 1867

Orbitoclypeus multiplicatus (Gümbel, 1870)

Figs. 12.15-12.25, 13.1-13.3, 13.9-13.16, 14.5-14.12, 14.14-14.16, 19.4-19.9

Orbitoides (Rhipidocyclina) multiplicata Gümbel, 1870, p. 704, 705, pl. 4, figs. 20, 21-24.

Diagnosis. *Orbitoclypeus multiplicatus* is a relatively small to moderately large, inflated to strongly inflated, unribbed species with a "marthae"-type rosette (Fig. 5). The test periphery can be occasionally undulated. In the equatorial section of the A-forms, the excentrilepidine (rarely eulepidine) embryo is medium sized to moderately large. The "variens"-type adauxiliary chamberlets are numerous, rather wide, and moderately high. The equatorial chamberlets are also fairly wide, medium high in the internal annuli and somewhat higher in the external ones. The annuli are close to circular to slightly undulate with 6-7 waves. Their growth pattern is of the "variens" type. This species includes four subspecies: *O. m. haymanaensis* Özcan, Sirel, Özkan-Altiner, and Çolakoğlu, 2001; $D_{\text{mean}} < 310 \mu\text{m}$; *O. m. multiplicatus* (Gümbel, 1870); $D_{\text{mean}} = 310-420 \mu\text{m}$; *O. m. kastamonuensis* Less & Özcan, 2007; $D_{\text{mean}} = 420-550 \mu\text{m}$; and *O. m. gmundenensis* Less, 2010; $D_{\text{mean}} > 550 \mu\text{m}$ (Less et al., 2007; Dulai et al., 2010).

Remarks. This species is the most abundant orthophragminid in the Thanetian sediments of Galala and was represented by *O. multiplicatus* cf. *haymanaensis* in sample D8.17, and by *O. multiplicatus haymanaensis* in samples D8.20, 23, D5.38, and D6.37, 45. The early Eocene representatives of this species (specimens of *O. multiplicatus multiplicatus*) were not recorded in Galala. The occurrence of *O. multiplicatus haymanaensis* in the late Thanetian of northern Tethyan platforms was only recorded in the Haymana Basin in Turkey (Özcan et al., 2001), while the more phylogenetically advanced *O. multiplicatus multiplicatus* occurs in central Europe (Less, 1998). Taxa such as *O. multiplicatus* and *O. schopeni* have similar external test features, and in this respect are undistinguishable from each other. In equatorial sections, this species is differentiated from *O. schopeni* by having a larger excentrilepidine-type embryo in the same assemblage. In addition, the equatorial chamberlets are slightly higher in *O. multiplicatus* (Table 1).

Orbitoclypeus aff. *O. multiplicatus* (Gümbel, 1870)

Figs. 13.17, 13.18, 14.17, 14.18, 15.1-15.6

Remarks. Some specimens very similar to *O. multiplicatus* but with very large embryos occur in the late Thanetian of sections D6 and D8. Their average deuteroconch size in samples D6.45 and D8.20 was $>350 \mu\text{m}$, and such values for *O. multiplicatus* are only characteristic for early Eocene

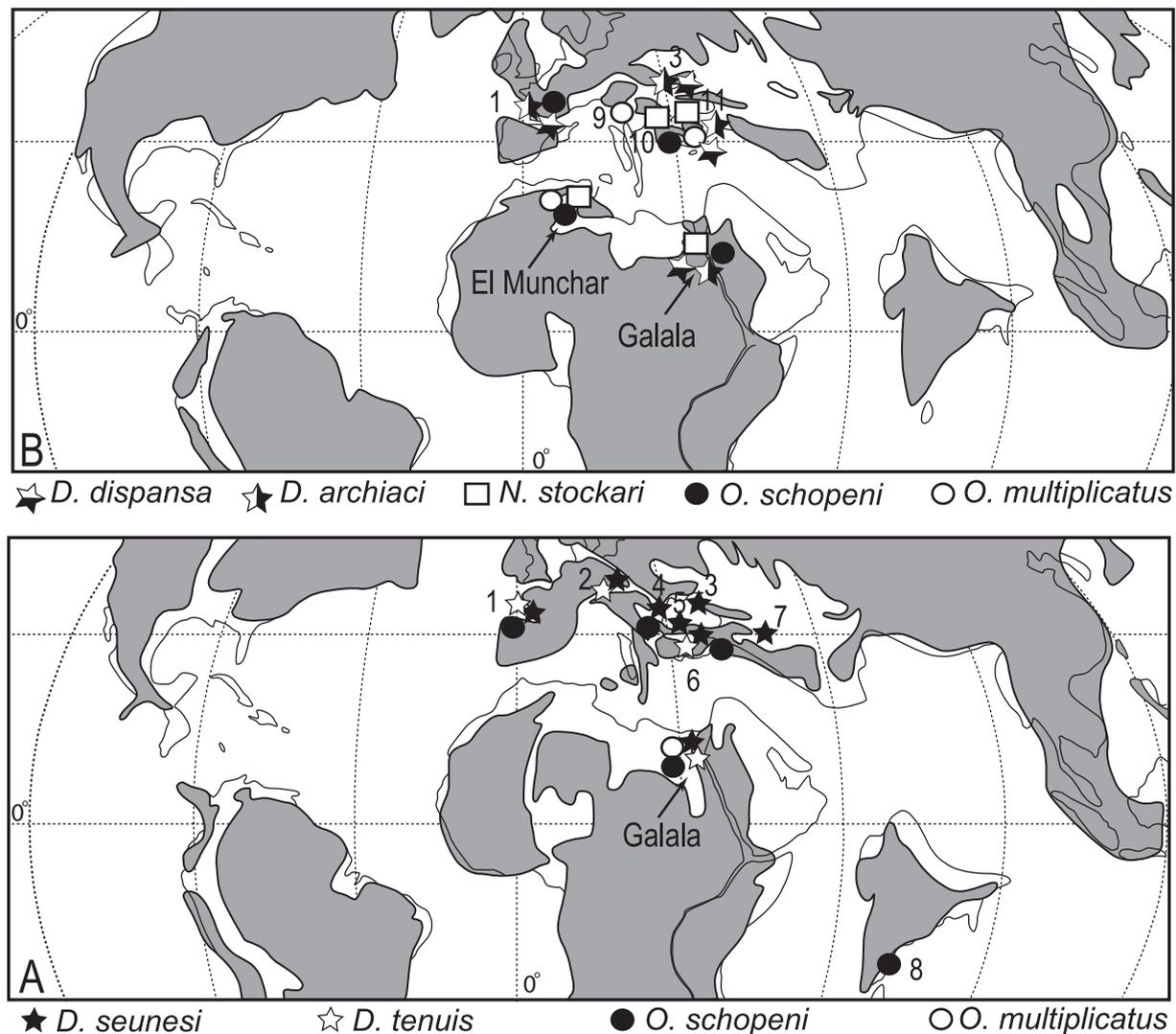


FIGURE 20. The paleogeographic distribution of Tethyan orthofragminids (*Discocyclina seunesi*, *D. tenuis*, *D. archiaci*, *D. dispansa*, *Orbitoclypeus multiplicatus*, *O. schopeni*, and *Nemkovella stockari*) in (A) Thanetian and (B) early Eocene time. Early Eocene species such as *Nemkovella evae*, *Orbitoclypeus munieri*, *O. bayani*, and *Asterocyclina taramellii*, unidentified in Galala, are not shown. The plots are based on previous records showing positive occurrences of taxa (with the exception of the Armenian locality). Paleocoastline maps at 60 Ma (Thanetian) and 53 Ma (early Eocene) are redrawn from Smith et al. (1994). 1, Aquitaine Basin (France): Schlumberger (1903), Douvillé (1922), Neumann (1958), and Less (1998). 2, west Carpathians (Slovakia): Samuel et al. (1972). 3, central and eastern Crimea (Ukrainia): Zernetskii (1977), Zakrevskaya (2007). 4, Bulgaria: Less et al. (2007). 5, Armutlu Peninsula (W Turkey): Özcan et al. (2012). 6, Haymana Basin (central Turkey): Özcan et al. (2001). 7, Armenia: Grigoryan (1986). 8, India: Samanta (1967). 9, Spilecco (Italy): Gümbel (1870), Less (1987), and Less et al. (2007). 10, Thrace Basin (Turkey): Özcan et al. (2010). 11, Kuruçaişile and Şile regions (W Turkey) and Safranbolu-Karabük Basin (central Turkey): Less et al. (2007) and Özcan et al. (2007b).

assemblages (Less et al., 2007). These forms may represent another evolutionary lineage unknown in northern Tethyan platforms, and we here provisionally assign them to *O. aff. O. multiplicatus* until we are able to describe more assemblages of *O. multiplicatus* and associated taxa from lower Eocene deposits of the southern Tethyan platforms.

Orbitoclypeus schopeni (Cecchia-Rispoli, 1908)

Figs. 12.8–12.14, 13.4–13.8, 13.22–13.24, 14.1, 14.2, 14.13, 15.11–15.17, 16.20, 16.21, 17.2–17.7, 19.1–19.3

Orbitoides (*Exagonocyclina*) *schopeni* Cecchia-Rispoli, 1908, p. 12.

Diagnosis. *Orbitoclypeus schopeni* is an unribbed species having a “*marthae*”-type rosette, a small to relatively large eulepidine, trybliolepidine, or excentriolepidine embryo,

narrow or medium-wide, low or medium-high “*varians*”-type adauxiliary chamberlets and also narrow or medium-wide equatorial chamberlets arranged into circular or slightly undulated annuli with usually “*varians*”-type growth pattern (Fig. 5). The distal margins of the annular chamberlets are typically arched or wedge-shaped. This species includes five subspecies: *O. s. ramaraoi* (Samanta, 1967); $D_{\text{mean}} < 195 \mu\text{m}$; *O. s. neumannae* (Toumarkine, 1967); $D_{\text{mean}} = 195\text{--}240 \mu\text{m}$; *O. s. suvlukayensis* Less, 1987; $D_{\text{mean}} = 240\text{--}300 \mu\text{m}$; *O. s. crimensis* Less, 1987; $D_{\text{mean}} = 300\text{--}500 \mu\text{m}$; and *O. s. schopeni* (Cecchia-Rispoli, 1908); $D_{\text{mean}} > 500 \mu\text{m}$ (Less, 1998).

Remarks. We show that at least two orbitoclypeid taxa, *O. schopeni* and *O. multiplicatus*, occurred in the Thanetian

beds at Galala, which is the second Tethyan locality after the Haymana Basin in Turkey (Özcan et al., 2001) where such an association is demonstrated. The specimens of *O. schopeni* in the Thanetian and early part of the lower Eocene invariably have eulepidine or trybliolepidine-type embryos that differentiate them from coeval *O. multiplicatus* individuals, which possess mainly excentrilepidine-type embryos (Less et al., 2007). The species is represented by *O. schopeni ramaraoi* (spl. D6.37, D5.38, D8.20) and by *O. schopeni* cf. *ramaraoi* (spl. D6.32, D8.23) in Thanetian beds in Galala. In early Eocene deposits, the latter subspecies was only identified in section B3 (spl. 41), where it was associated with a very primitive developmental stage of *D. archiaci*. In the lower Eocene part of section D8 (spl. 38), two specimens of *O. schopeni* cf. *neumannae*, occurred with *N. stockari*. The *O. schopeni* assemblage in the El Munchar section (spl. 18) in Tunisia, which is associated with *N. stockari bejaensis* n. subsp. as in sample D8.38, is represented by *O. schopeni neumannae*.

EVALUATION OF THE ORTHOPHRAGMINIDS FROM GALALA AND EL MUNCHAR, THEIR ASSIGNMENT TO OZ ZONES, AND A PALEOBIOGEOGRAPHIC SYNTHESIS

The previous records of orthophragminids in late Paleocene and Eocene Tethyan deposits are either from random thin-section studies or specific taxonomic studies, carried out by investigation of test features at preferred orientations. In most cases, identifications in random thin sections do not produce a reliable data set for taxonomy and paleobiogeography, and are open to speculation, although such approaches are very common in the literature and have a deleterious effect on taxonomic and paleobiogeographic synthesis. In our interpretations and comparisons, we mostly rely on previous works that properly described taxa, preferentially based on oriented thin sections.

The orthophragminids in some of our sections are found in debris flows and turbidites and, therefore, are allochthonous. Thus, in such cases, the mixing of “primitive” and “advanced” developmental stages of the same taxon is always possible. In Galala, the assemblages above the P/E boundary mostly contain the orthophragminid species first appearing above this boundary and are characteristics for the early Eocene. They are associated with rare, survivor late Paleocene orthophragminids. Thus, our data do not show a mixed-age faunal composition, with the exception of rare *O. schopeni ramaraoi* specimens in early Eocene sample 41 from section B3. Seven specimens assigned to this subspecies in that sample may indicate reworking from Paleocene levels.

The Thanetian and early Eocene orthophragminids described for the first time from the southern Tethyan margin at Galala suggest that they are closely linked to the orthophragminid species widely known in northern Tethyan platforms in Europe and the eastern Mediterranean region. We have identified seven species from these deposits, some of which straddle the P/E boundary. The orthophragminids, assigned to the genus *Discocyclina* at South Galala by Scheibner & Spejger (2009) are in fact

represented by *Orbitoclypeus*, *Discocyclina*, and *Nemkovella*. *Asterocyclina* has not been identified, although it occurs abundantly in the early Eocene (OZ 3) of the El Munchar section in Tunisia, thus confirming the occurrence of this genus in early Eocene deposits of northern Africa. The Thanetian orthophragminids are represented by *Discocyclina seunesi*, *D. tenuis*, *Orbitoclypeus schopeni*, *O. multiplicatus*, and *O. aff. O. multiplicatus*. Specimens of the latter may represent a new stock of Orbitoclypeidae in southern Tethyan platforms as they possess very large embryos. Nevertheless, the Thanetian representatives of *O. multiplicatus* have so far been recorded only in Turkey (Özcan et al., 2001) and information on biometric features of this species is limited. In Galala, *D. seunesi* and *D. tenuis* are only identified in Thanetian beds and their occurrence in the earliest Eocene cannot be justified, probably because of a stratigraphic gap in sections B3 and D8 during this time interval. Similar to its development in northern platforms, *O. schopeni* also crosses the P/E boundary in southern platforms, a fact also supported by the common occurrence of this species in the early Eocene of Tunisia.

The LBF record in Galala indicates that orthophragminids characteristic of the “early Eocene” in northern platforms are confined to levels above the CIE in the studied sections. These taxa are *Discocyclina archiaci*, *D. dispansa*, *Nemkovella stockari*, and *Orbitoclypeus schopeni*. Among these newly appearing taxa, *D. archiaci* and *D. dispansa* first appear in northern platforms in OZ 3, while *N. stockari* is in OZ 2. The latter species, found in the earliest Eocene deposits (spl. KURUC) from Kurucaşile in Turkey (Less et al., 2007), is characterized by an isolepidine-type embryonic configuration and asymmetric development of spirals around the embryo that make it quite distinct from the other associated orthophragminid taxa. Based on the material from Galala and Tunisia, we are now able to construct the evolutionary changes in this species, as the specimens from both localities represent a more “advanced” developmental stage of *N. stockari* in the early Eocene. The calcareous nannofossil data indicating NP 11 (Fig. 8) for sample D8.38 further support a younger stratigraphic position for Galala specimens compared to the type material. The type specimens of *N. stockari* (spl. KURUC), here assigned to *N. stockari stockari*, possess very small protoconchs and deuterococonchs, both <100 µm, with principal auxiliary chamberlets of unequal size (Fig. 18), and the spiral arising from these chambers are typically asymmetrical. In this sample, this species is associated with *D. seunesi karabuekensis*, *N. evae evae*, *A. taramellii*, *O. schopeni ramaraoi*, *O. bayani kurucasileensis*, and *O. muniere ponticus*, belonging to OZ 2 (Less et al., 2007). We have also identified *N. stockari stockari* in early Ypresian beds in Sazlimani (spl. SAZ) in the Thrace Basin in Turkey (Özcan et al., 2010) where it is associated with *D. seunesi karabuekensis*, *O. schopeni neumannae*, *O. muniere* cf. *muniere* and *O. bayani* cf. *bayani*. This sample was also assigned to OZ 2 on the occurrence of *D. seunesi karabuekensis*, although the presence of *O. schopeni neumannae* implies OZ 3. The size of the embryo in two SAZ specimens is intermediate between the KURUC and Galala/ El Munchar samples and the spirals are slightly asymmetric (Fig. 18). This sample may occupy an interme-

diate position from the upper part of OZ 2 through the lower part of OZ 3. In Galala, *N. stockari* is recognized only in sample D8.38 in association with *O. schopeni* cf. *neumannae* and *Nummulites* spp. just above the hiatus (Fig. 11). A badly preserved discocyclinid specimen, belonging to either *D. archiaci* or *D. tenuis*, has also been recorded. The specimens of *N. stockari* in D8.38 have larger embryos than those in sample KURUC and SAZ, and also possess symmetrical spirals developed from two equal-sized principal auxiliary chamberlets (pac). The specimens of *N. stockari*, assigned to *N. stockari bejaensis* n. subsp., in sample 18 from El Munchar, Tunisia, have embryonic and peri-embryonic features and embryo dimensions similar to those in Galala (Fig. 18). In sample 18, *N. stockari bejaensis* n. subsp. occurs with *O. schopeni neumannae* (Figs. 16, 20, 21) and *A. taramellii* (Fig. 16, 22), characteristic taxa for OZ 3. Thus, our present data allow us to discriminate two subspecies of *N. stockari* and to extend the stratigraphic range of this species into OZ 3. In the absence of microspheric forms, the generic assignment of *N. stockari bejaensis* to *Nemkovella* is not fully justified. The present assignment is based virtually on the isolepidine-type embryo configuration and shape of equatorial chamberlets, which are spatulate and hexagonal. In terms of embryo type and development of spiral chambers, this species closely resembles *Nemkovella daguini* (Neumann), appearing in the Lutetian (see Özcan et al., 2007a for a detailed description and illustrations of *N. daguini*).

The identified orthofragminid species and their assemblages in Galala characterize OZ 1, 1B, and 3 across the previously proposed P/E boundary. Most of section B3 was deposited at the platform margin in a comparatively shallower setting than sections D5, D6, and D8. The P/E boundary in section B3 was previously placed in the lower part of the marls at 72 m between samples 36 and 37, constrained by the poorly developed CIE and the first record of *Alveolina* in sample B.39, several meters above this level (Scheibner & Speijer, 2009). The succession was reported to be continuous. This section has yielded a poor orthofragminid assemblage below the level supposedly corresponding to the P/E boundary, and a single specimen of *D. seunesi*, suggesting OZ 1 for sample B3.18, occurs almost 40 m below this boundary. In this part of the sequence the only species that confidently indicates a late Thanetian age is *Hottingerina lukasi*, identified as high as 63 m in the section. The interval between 63–75 m encompassing the supposed P/E boundary is barren of larger foraminifera. The orthofragminids in the upper part of the section are abundant and diverse, characterized by *D. archiaci*, *D. dispansa*, and *O. schopeni*. Of these, the most important ones are *D. archiaci* cf. *bakhchisaraiensis* in sample B3.39, and *D. archiaci bakhchisaraiensis* and *D. dispansa* cf. *broennimanniltaurica* in sample B3.41, the first is a characteristic subspecies for OZ 3 and the latter for OZ 3–4 in northern Tethyan platforms. The rare *O. schopeni ramaraoi* in sample B3.41, however, suggests that this level may be assigned to OZ 2, while the deuteroconch size of a single *O. schopeni* specimen in sample B.43 stays within the biometric limits of *O. schopeni neumannae*, a diagnostic subspecies for OZ 3. Relying on the occurrence of *D. archiaci* and *D. dispansa* in the interval between samples 39–

45, we assign this interval to OZ 3, which is correlated to SBZ 7 and a part of SBZ 8. This interval has been attributed to SBZ 5/6 by Scheibner & Speijer (2009) considering its position with respect to the CIE and the association of *Alveolina* sp., *Nummulites* sp., and *Orbitolites* sp., although these taxa, identified only to the generic level, do not justify this assignment. Our data suggest either an hiatus across the P/E transition between samples 35–39, which requires denser sampling for its justification, or the P/E boundary is to be placed much lower in the LBF-barren part of the section.

In section D8, a stratigraphic gap at the P/E boundary was previously recognized by the absence of NP 10 calcareous nannofossils. In this section, the interval between the highest level with Thanetian orthofragminids (spl. 23) and lowest level with early Eocene ones (spl. 34) is separated by >10 m (Fig. 10). Thus, the record of orthofragminids across the P/E boundary is poor and does not permit a high-resolution biostratigraphy. Sample 20, containing *D. seunesi* cf. *beloslavensis*, *O. schopeni ramaraoi*, *O. multiplicatus haymanaensis*, and *O. aff. multiplicatus*, is safely assigned to OZ 1B. Sample 23 with *O. schopeni* cf. *ramaraoi* and *O. multiplicatus haymanaensis* is also assigned to OZ 1B because of *H. lukasi* also at this level. The samples above the hiatus (D8. 34 and 38) contain *N. stockari* cf. *bejaensis*, *O. schopeni* cf. *neumannae*, and *O. schopeni*. The first two taxa suggest OZ 3 for this part of the succession.

As evident from sections B3 and D8, the stratigraphic gaps pose some uncertainties in evaluating our findings relative to the LFT and P/E boundary. Moreover, the record of orthofragminids across the presumed P/E boundary is poor and does not permit a high-resolution biostratigraphy. Furthermore, the orthofragminids just above the boundary in both sections are assigned to OZ 3, which is correlated to SBZ 7–8, and OZ 2 is missing.

In section D5, Thanetian orthofragminids are characterized by the association of *O. schopeni ramaraoi* and *O. multiplicatus haymanaensis* in sample D5.38 and by *O. schopeni* in sample D5.34. The assemblage in D5.38 is assigned to OZ 1B based on the above occurrences as well as that of *H. lukasi*, a typical Thanetian species. Similarly, the orthofragminids in section D6, studied only below the P/E boundary, are represented by *D. seunesi* cf. *beloslavensis*, *O. schopeni neumannae*, and *O. multiplicatus haymanaensis* in sample D6.37, a typical assemblage for OZ 1B. Scheibner & Speijer (2009) located the P/E boundary in this section on the position of the CIE and the calcareous nannoplankton data.

The type localities for most Tethyan orthofragminids described around the P/E boundary are in Europe and Turkey, and no information is available on their distribution in North Africa, the Middle East and southern Asia. In Thanetian deposits, the most primitive developmental stage of *O. multiplicatus* (= *O. multiplicatus haymanaensis*) has only been recorded in central Turkey (Özcan et al., 2001), which was a part of northern Tethyan platforms at that time. This is the most abundant subspecies in Galala. Similarly, *N. stockari*, an early Ypresian species previously only known from Turkey, occurs in Egypt and Tunisia. Based on available data, these two species seem to be

confined to the eastern part of northern platforms and to southern platforms in northern Africa (Fig. 20). The other species described at Galala such as *D. seunesi*, *D. tenuis*, *D. archiaci*, *D. dispansa*, and *O. schopeni* are widespread in Europe and the eastern Mediterranean region (Less et al., 2007; Fig. 20). However, such ribbed taxa as *O. bayani*, *O. munieri*, and *A. taramellii* and unribbed species as *N. evae* occur in the early Ypresian of northern platforms (mainly from Turkey), but are not recorded in Galala. As explained above, this is most probably due to the hiatus that we recorded in two of the Galala sections. Based on our new data, we extend the geographic ranges of the aforementioned orthophragminid taxa to North Africa for the first time.

SUMMARY AND CONCLUSIONS

Although orthophragminids occur consistently at numerous levels in the late Paleocene–early Eocene marine succession in Galala, the free tests necessary to study morphological features were recovered from only a few levels across the previously proposed P/E boundary. At some levels, orthophragminids occur in reworked beds such as turbidites and debris flows, and their record in the studied sections is not as continuous as that of other previously studied fossil groups such as calcareous plankton and other LBF. Our data from Galala suggest that the orthophragminids widely known in northern Tethyan platforms are also a part of the shallow-marine foraminiferal communities across the P/E transition in Egypt, situated at the southern Tethyan margin during the Paleogene. This information allows us to extend the geographic ranges of late Paleocene–early Eocene orthophragminids from Europe and Turkey into North Africa for the first time. Based on the occurrences of *Orbitoclypeus multiplicatus haymanaensis* and *Nemkovella stockari* that are common only to Galala and some platforms in Turkey, we conclude that similarities in the composition of orthophragminids are closer in these two regions than they are to assemblages in Europe. Meanwhile, taxa such as *Discocyclina seunesi*, *D. dispansa*, *D. archiaci*, *D. tenuis*, and *Orbitoclypeus schopeni* appear to be common to platforms in Europe, Turkey, and Egypt.

The LFT, previously proposed to coincide to the CIE and P/E boundary in Galala based on the work of Scheibner & Speijer (2009), cannot be precisely tested for orthophragminids. We have identified late Thanetian orthophragminid assemblages assigned to OZ 1 or OZ 1B and characterized by the common occurrence of *Orbitoclypeus multiplicatus*, *O. schopeni*, and rare *D. seunesi* and *D. tenuis* always below the previously proposed P/E boundary. Although the orthophragminid assemblages above this boundary are completely different than those of the late Thanetian, they do not belong to the lowest orthophragminid zone (OZ 2) in the early Eocene. This is most probably due to a hiatus at or near the P/E boundary in the two sections (B3, D8) where we have studied the orthophragminid record both below and above the CIE. In section B3, previously interpreted to be continuous across the P/E boundary, the orthophragminid assemblages just above the boundary appear to belong to OZ 3. This is also true for section D8, where the orthophragminid assemblage above

the previously detected hiatus marks OZ 3. Thus, the taxa characterizing OZ 2 were not identified in this study. In northern Tethyan platforms the characteristic taxa for OZ 2 are represented by ribbed orthophragminids, such as *Orbitoclypeus bayani*, *O. munieri*, and *Asterocyclina taramellii*, and by an advanced developmental stage of *D. seunesi* (*D. seunesi karabuekensis*). Consequently, our data raise some doubts in using orthophragminids for determining the LFT in Galala, since the compositional changes in orthophragminids in sections B3 and D8 do not correspond to the P/E boundary. Because the early Eocene record of orthophragminids from these two sections was represented mainly by Discocyclinidae and unribbed orbitoclypeids, we refrain from making interpretations about the absence of other groups, such as some nemkovellids and ribbed orbitoclypeids.

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