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Late Campanian larger benthic foraminifera from the Zekeriyaköy Formation (İstanbul, NW Turkey): taxonomy, stratigraphy, and paleogeography

Mert Eren ERDEM[1], Ercan ÖZCAN[2,*], Ali Osman YÜCEL[2], Aral I. OKAY[2,3], Sadıkcan ERBAY[2], Sibel KAYĞILI[4], İsak YILMAZ[1]

[1]Department of Geological Engineering, Faculty of Engineering, İstanbul University-Cerrahpaşa, İstanbul, Turkey
[2]Department of Geological Engineering, Faculty of Mines, İstanbul Technical University İstanbul, Turkey
[3]Eurasia Institute of Earth Sciences, İstanbul Technical University, İstanbul, Turkey
[4]Department of Geological Engineering, Fırat University, Elazığ, Turkey

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Abstract: North of İstanbul, the thick Upper Cretaceous volcanic and volcanoclastic sequence of the Yemişliçay Group is nonconformably overlain by the neritic clastic and carbonate sequence of the Zekeriyaköy Formation. This unit, either placed within the volcanic sequence or interpreted to overlie it, was studied near Zekeriyaköy for its larger foraminifera, previously recurrently referred to as the Maastrichtian. The basal epiclastic sandstone beds of the Zekeriyaköy Formation immediately above the volcanic sequence contain *Praesiderolites dordoniensis* and rare rudist shells. The higher sandstone and limestone beds comprise assemblages of *Lepidorbitoides campaniensis*, *Orbitoides megaloformis*, *Vanderbeekia catalana*, *Siderolites* gr. *calcitrapoides*, *Sirtina orbitoidiformis*, *Praestorrsella roestae*, *Lenticulina rotulata*, *Planorbulina* sp., agglutinated and rotaliid foraminifera, rudist fragments, bryozoans, and red algae. *Lepidorbitoides*, the most abundant foraminifera in the studied material, has predominantly *L. campaniensis*-type embryons with a single auxiliary chamberlet, and rarely, *L. bisambergensis*-type embryons, characterized by having 2 such chamberlets. The *Praesiderolites dordoniensis*-*Lepidorbitoides campaniensis*-*Vanderbeekia catalana* assemblages, recorded for the first time in Turkey, suggested a late Campanian age for the Zekeriyaköy Formation, with the implication that Late Cretaceous volcanism terminated in the İstanbul region during or prior to the late Campanian. The fauna shows a great resemblance to those from the Late Campanian type-section in Aubeterre (SW France) and Late Campanian fauna of the Pyrenean Basin (N Spain), and correspond to the most eastern record of the European Faunal Province of the Tethys.

Key words: Larger benthic foraminifera, Late Campanian, northwestern Turkey, systematics

1. Introduction

The Pontide Upper Cretaceous magmatic belt in northern Turkey, extending along the Black Sea region, marks an extensive phase of arc volcanism in the Late Cretaceous (Şengör and Yılmaz, 1981; Okay and Nikishin, 2015). Development of the volcanogenic sequence occurred in an extensional arc setting related to oceanic spreading in the western Black Sea Basin (e.g., Tüysüz, 2018). Throughout the Pontides, the arc volcanism decreases in the Late Campanian, and is replaced generally by the deposition of pelagic limestones and calciturbidites, and shallow marine clastics and carbonates, which continues into the Paleocene (e.g., Okay and Şahintürk, 1997; Consorti and Köroğlu, 2019; Özcan et al., 2019). Upper Cretaceous volcanic rocks also crop out north of İstanbul on both sides of the Bosporus, where limited outcrops of a shallow marine sandstone-limestone sequence of the Zekeriyaköy Formation were recorded near Zekeriyaköy (Chaput and Hovasse, 1930; Chaput, 1936) (Figure 1). The age of the unit was invariably reported as Maastrichtian based on the supposed occurrence of key Maastrichtian larger benthic foraminifera (LBF), that had been identified by routine thin-section studies, which did not necessarily reveal diagnostic details. Herein, the aim is to show the relationship of the volcanogenic sequence and the Zekeriyaköy Formation via new field observations and document the LBF from the latter unit based on investigation of the isolated specimens, supplemented by thin-section studies, for a proper documentation of its fossil content. This provided more accurate age constraints for the termination of the main phase of volcanism in the İstanbul region. The findings were discussed from a paleogeographic perspective, since some LBF assemblages of the Zekeriyaköy Formation were documented for the first time in this part of the Tethys.

* Correspondence: ercanozcan034@yahoo.com

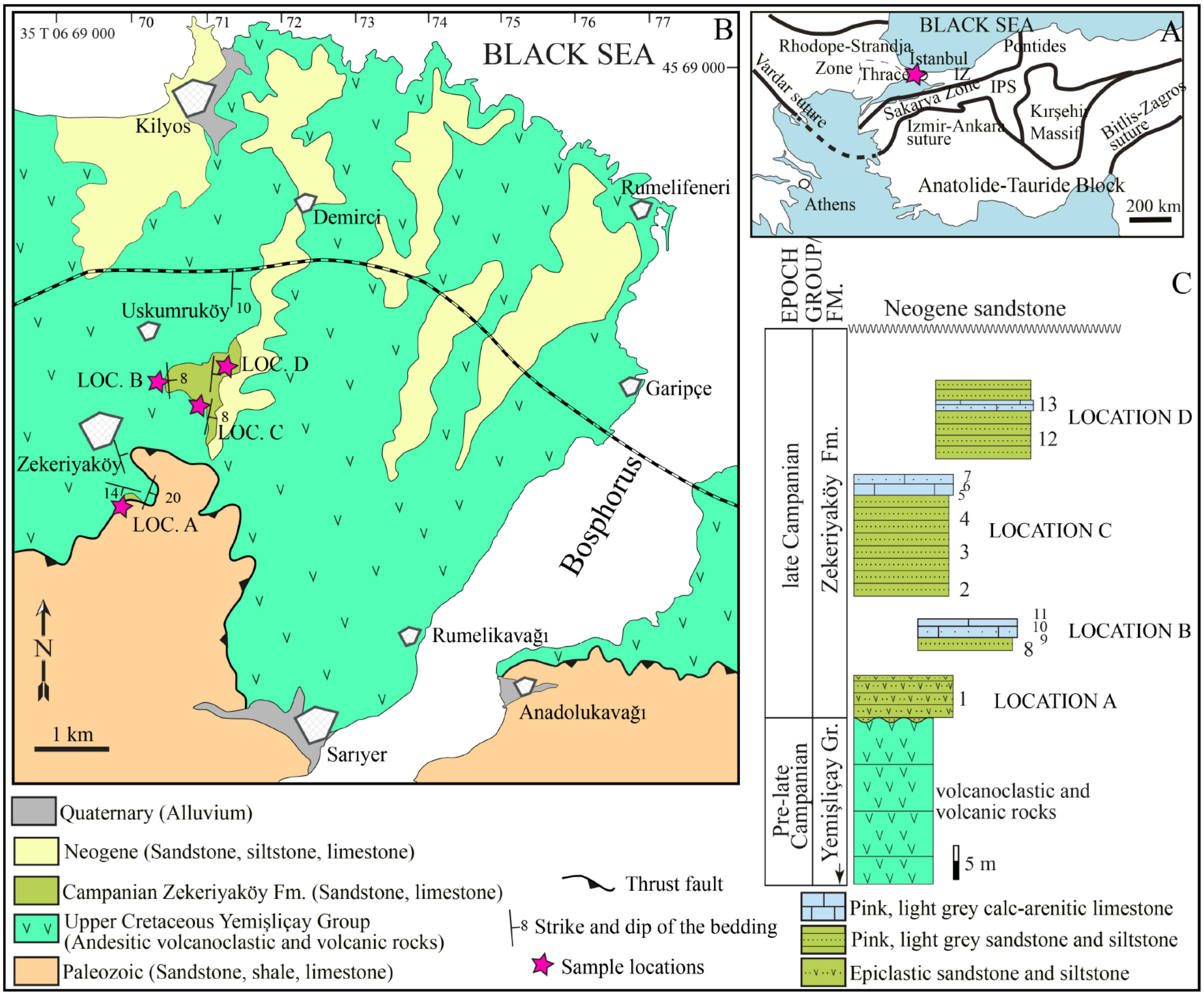

Figure 1. (A) Tectonic map of the northeastern Mediterranean region showing the major sutures and continental blocks and the location of the study area near İstanbul, NW Turkey (map simplified from Okay and Tüysüz, 1999). (B) Geological map of the Zekeriyaköy region and location of the samples (modified from Özgül, 2011). (C)Simplified lithostratigraphic column of the Zekeriyaköy Formation and positions of the samples.

2. Geological setting and stratigraphy

Upper Cretaceous volcanic rocks form a semicontinuous belt along the southern margin of the Black Sea, extending from Georgia through Turkey, to Bulgaria, and beyond. The volcanism was a consequence of the subduction of the Tethyan oceanic lithosphere northward under the Pontides, which also resulted in the opening of the Black Sea as a backarc basin in the Late Cretaceous (e.g., Nikishin et al., 2015). The arc volcanism ranged in age from Turonian to Campanian and resulted in the deposition of several kilometers thick volcanic and volcanoclastic sequences in the intraarc basins, which were assigned to the Yemişliçay Group in the Pontides (Okay and Şahintürk, 1997; Tüysüz et al., 2004; Gallhofer et al., 2015; Kandemir et al. 2019). The volcanoclastic and volcanic rocks are locally interbedded with pelagic limestones, which constrain the age of volcanism (e.g., Keskin and Tüysüz, 2017; Boehm et al., 2019). In the Pontides, the arc volcanism wanes towards the end of the Campanian and is succeeded by the deposition of carbonates, which range in age from late Campanian to the Paleocene, and locally into the Eocene (e.g., Sarı et al., 2014; Boehm et al., 2019; Özcan et al., 2019). Locally, there are minor volcanic horizons in the Maastrichtian limestones.

The Upper Cretaceous volcanic rocks crop out north of İstanbul on both sides of the Bosporus (Figure 1). They form a more than a 500-m-thick sequence of andesitic and basaltic-andesitic volcanoclastic rocks, lavas, and dykes (Keskin et al., 2010; Aysal et al., 2017). In the south, they are tectonically overlain by Paleozoic rocks along an Eocene thrust (Chaput and Hovasse, 1930; Akartuna, 1963). The precise age of the Yemişliçay Group north of İstanbul is poorly constrained since there are no limestone intercalations within the volcanoclastic sequence. On

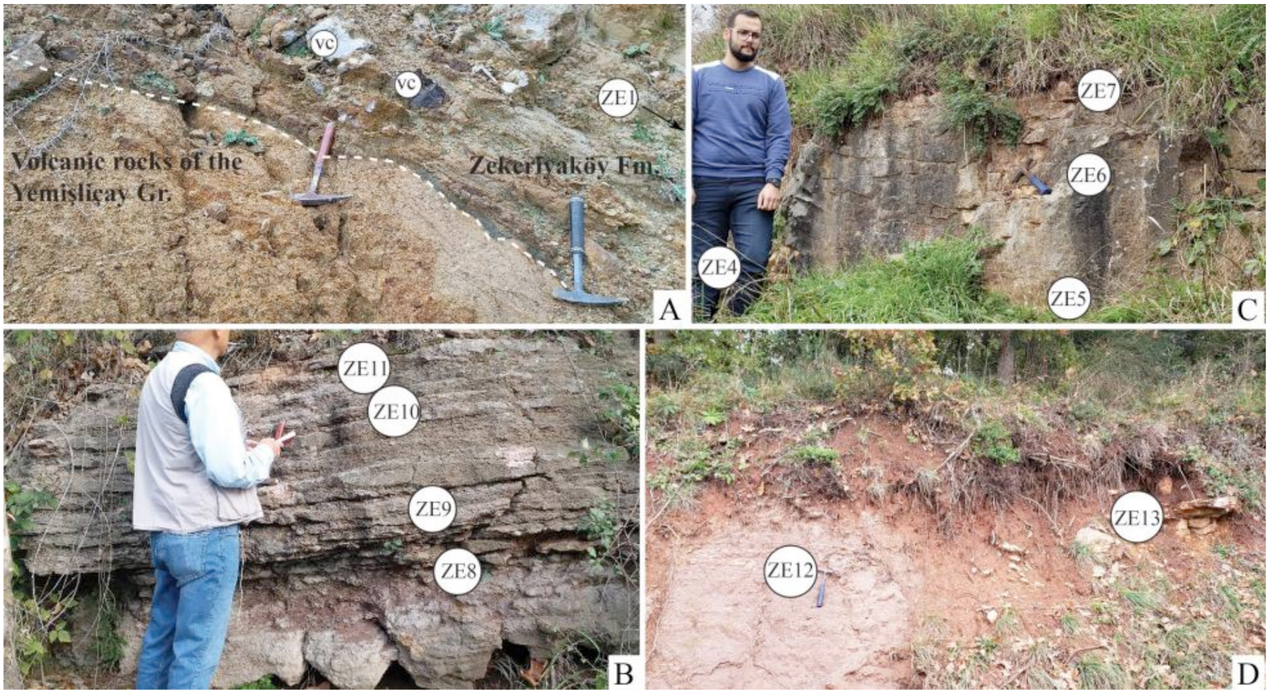

Figure 2. Field photographs of the studied outcrops with the sample locations.(A) Volcanic rocks of the Yemişliçay Group and unconformably overlying basal clastic rocks of the Zekeriyaköy Formation with *Praesiderolites dordoniensis* and rare rudist shells. (B–D) Stratigraphically higher sandstone-limestone beds with *Lepidorbitoides campaniensis*, *S.* gr. *calcitrapoides*, and *Vanderbeekia catalana* assemblages.

the European part of İstanbul in the Zekeriyaköy region, a thin (<50 m) shallow marine limestone-sandstone sequence was first described within the Upper Cretaceous volcanoclastic rocks by Chaput and Hovasse (1930) and Chaput (1936). They reported *Orbitoides socialis*, *Orbitoides apiculatus*, and *Hippuritescornu-vaccium*, and assigned a Maastrichtian age to the limestones. Kaya (1971) regarded the bioclastic limestones as intercalations within the Upper Cretaceous volcaniclastic rocks and named them the Sarıyer limestone. He reported *Lepidorbitoides minor* (Schlumberger), *Orbitoides medius* (d'Archiac), and *Siderolites calcitrapoides* Lamarck, from the limestones and also assigned a Maastrichtian age to this unit. Gedik et al. (2005) included the limestone-shale sequence within the Akveren Formation, the general name for the mostly deep marine Campanian to Paleocene carbonates in the Pontides, which stratigraphically overlie the Upper Cretaceous volcanic rocks. The Upper Cretaceous volcanic rocks on both sides of the Bosporus were named the Sarıyer Group[1], whereas the Upper Cretaceous limestones were regarded as a stratigraphic horizon within the volcanic rocks and were named the Zekeriyaköy member. With the possible exception of Gedik et al. (2005), all previous studies have regarded the Upper Cretaceous limestones as part of the volcanic sequence, and assigned a Maastrichtian age. As discussed below, the field studies herein showed that the Upper Cretaceous limestones and sandstones lie above the Upper Cretaceous volcanic rocks and are unconformably overlain by Neogene sediments (Figure 1). They form a distinct stratigraphic unit named herein as the Zekeriyaköy Formation.

The contact between the Zekeriyaköy Formation and Yemişliçay Group is observed only in one locality, where epiclastic rocks of the Zekeriyaköy Formation with volcanic clasts lie nonconformably over the volcanic rocks of the Yemişliçay Group (locality A). The Zekeriyaköy Formation crops out at the top of the NNE trending ridges, where it is unconformably overlain by Neogene sediments (Figure 1). This outcrop pattern, along with low bedding dips in the Zekeriyaköy Formation and Yemişliçay Group, indicate that there are no other volcanic rocks above the Zekeriyaköy Formation. The Zekeriyaköy Formation is not a horizon within the Yemişliçay Group, but lies nonconformably above it, and marks the termination of the main phase of arc volcanism. It can be correlated with the basal part of the Akveren Formation.

3. Materials, methods, and repository

Outcrops of the Zekeriyaköy Formation are small and isolated (Figures 1 and 2). The samples were collected at

[1] Özgül N (2011). İstanbul il alanının jeolojisi. İstanbul Büyükşehir Belediyesi Deprem Risk Yönetimi ve Kentsel İyileştirme Daire Başkanlığı Deprem ve Zemin İnceleme Müdürlüğü (unpublished) (in Turkish).

4 localities around Zekeriyaköy on the western side of Bosporus (İstanbul, NW Turkey). The GPS coordinates of samples are given in Table 1. A stratigraphic log was formed from the isolated outcrops based on their relationship in the study area.

Locality A: Late Cretaceous volcanic rocks of the Yemişliçay Group and nonconformable epiclastic rocks of the Zekeriyaköy Formation crop out along a 6-m-thick road-cut section in Zekeriyaköy (Figure 2A). The relationship of both units is observed only at this locality. Sample ZE1 was collected from a sandstone bed with volcanic clasts from the lowerpart of the Zekeriyaköy Formation.

Locality B: An almost horizontal limestone bed crops out along the main road between Zekeriyaköy and Kilyos, about 2.1 km NNE of Locality A (Figure 2B). Poor exposures of pinkish/brownish sandstones are observed immediately below a limestone bed. The thickness of the outcrop does not exceed several meters. Sample ZE8 was collected from a transitional stratigraphic position between clastic beds below and limestone above, and contained free tests of LBF. The other 3 samples (ZE9–ZE11) were from the hard limestone bed.

Locality C: Samples ZE2–ZE7 were collected from a road-cut section along the main road between Zekeriyaköy and Kilyos, about 0.75 km SE of the Locality B (Figure 2C). Isolated specimens of LBF were collected from samples ZE2–ZE4, which were collected from unindurated sandstone/siltstone beds, whereas samples ZE5–ZE7 were from a limestone bed.

Locality D: This outcrop is located on the highest elevation in the area, 550 m NNE of Locality C (Figure 2D). Pinkish sandstone beds (sample ZE12) and a ca. 30–40-cm-thick limestone intercalation (sample ZE13) with abundant LBF and other fossils crop out along a road section. They are overlain by Neogene sediments.

The material consists of isolated specimens of *Lepidorbitoides*, *Orbitoides*, *Vanderbeekia*, *Praesiderolites*, *Siderolites*, and *Sirtina*, extracted from the sandstone and limestone beds, and were investigated through equatorial and axial sections of the test, supplemented by thin-sections. The measurements and counts used in the morphometry of these taxa are shown in Tables 2 and 3. All of the specimens were deposited in the paleontological collections of the Geological Engineering Department of İstanbul Technical University and prefixed EO/.

4. Revising the stratigraphy, depositional environments, and age of the Zekeriyaköy Formation

Due to dense vegetation and extensive urbanization, the Zekeriyaköy Formation can only be observed in small (< 10 m) and isolated outcrops, as there are no continuous sections. Based on the topography and gently dips, the thickness of the Zekeriyaköy Formation is estimated to be about 50 m. The relationship of the Yemişliçay and Zekeriyaköy formations is observed only at Locality A, where the volcanic rocks are overlain by friable, cream to yellowish pebbly sandstone beds, with volcanic clasts reaching up to 15 cm in diameter (Figure 2A). The gently dipping sandstones beds contain relatively abundant *Praesiderolites dordoniensis* Wannier, 1983 and rare rudist fragments representing the oldest fossil assemblage of the Zekeriyaköy Formation. This part of the sequence is succeeded by almost horizontal pinkish sandstones, and a 1.5-m-thick limestone bed (samples ZE8–ZE11). The limestone bed displays *Lepidorbitoides*-bryozoan packstone/grainstone facies (Figures 3B and 3C). Fossils belong to *Lepidorbitoides campaniensis* van Gorsel, 1973b; *Orbitoides megaloformis* Papp and Küpper, 1953; *Vanderbeekia catalana* Hottinger and Caus, 2007; *Siderolites* gr. *calcitrapoides* Lamarck, 1801; and *Sirtina orbitoidiformis* Brönnimann and Wirz, 1962, agglutinated and rotaliid forminifera, rudist fragments, echinoids, gastropods, bryozoans and red algae (Figure 4). In this section, alternations of cream to pinkish/

Table 1. Coordinates and types of samples (free specimens vs. thin sections).

Locality	Sample	Coordinates	Type of sample
A	ZE1	N41°11′56.30″, E29°1′38.80″	Free specimens
B	ZE8	N41°12′49.20″, E29°2′2.10″	Free specimens
B	ZE9–ZE10–ZE11	N41°12′49.20″, E29°2′2.10″	Thin sections
C	ZE2	N41°12′32.20″, E29°2′25.20″	Free specimens
C	ZE3	N41°12′32.20″, E29°2′25.25″	Free specimens
C	ZE4	N41°12′33.00″, E29°2′25.30″	Free specimens
C	ZE5–ZE6–ZE7	N41°12′32.50″, E29°2′25.25″	Thin sections
D	ZE12	N41°12′50.36″, E29°2′30.11″	Free specimens
D	ZE13		Thin section

Table 2. Morphometric data of *Lepidorbitoides*, *Orbitoides*, and *Vanderbeekia* from the Zekeriyaköy Formation. N: number of specimens. P and D: innercross diameter of protoconch and deuteroconch, D/P: their ratios, Y: number of spiral chambers with single stolon, ps and ds: number of spiral chambers in *Lepidorbitoides*; Li+li and E: embryon size and total number of principal and accessory epiauxiliary chamberlets of *Orbitoides*, Di: diameter of the test (see van Gorsel, 1975; Caus et al., 1996; Hottinger and Caus, 2007 for the parameters and illustrations of the test structure and nomenclature).

Sample	N	Di	P	D	D/P	Y	ps	ds	Li+li	E	Species
		mean (mm)	range (μm) mean±SE (μm)	mean (μm)			mean (μm)	mean (μm)	mean (μm)	mean (μm)	
ZE2	21	2.52	60.0–150.0 97.70 ±5.21	138.5	1.42	1.80	7.55	6.27			*L. campaniensis*
ZE3	17	1.54	65.0–130.0 92.06±4.46	134.7	1.46	1.82	6.86	6.0			
ZE4	83	1.78	65.0–200.0 94.57±2.25	127.9	1.35	1.92	7,42	5.95			
ZE8	27	2.55	70.0–115.0 86.11±2.52	111.1	1.29	2.00	7.50	5.50			
ZE12	53	2.35	70.0–110.0 90.66±1.44	122.1	1.35	2.00	7.09	6.10			
ZE13	5		80.0–120.0 99.00±6.39	129.0	1.30						
ZE2	3	2.3							680.0	6.5	*O. megaloformis*
ZE3	2	1.75							630.0	7.5	
ZE8	1								770.0		
ZE12	1								840.0		
ZE12	6	2.63	75.0–110.0 87.50 ±5.15	98.0	1.12						*V. catalana*
ZE13	2	2.77									

Table 3. Morphometric data of the *Praesiderolites* and *Siderolites* from the Zekeriyaköy Formation. N: number of specimens. p and d: innercross diameter of proloculus, d: second chamber, Di, Ti, Ti/Di: diameter and thickness of the test and their ratios, nw: number of whorls, r1 and r2: number of chambers in the first half whorl and 1.5 whorls [see Robles-Salcedo et al. (2018) for tabulation of the parameters of the *Siderolites* from Pyreenes].

	Sample	p(μm)		d(μm)	Di (mm)		Ti (mm)		Ti/Di	nw	r1 (μm)	r2 (μm)
		N	Mean(range)	Mean(range)	N	Mean(range)	N	Mean(range)				
P. dordoniensis	ZE1	24	70.6 (30–100)	82.5 (60–110)	53	1987.9 (1100–3000)	6	753.3 (650–880)	0.38	2.3–3.2	294.0 (250–340)	658.0 (560–810)
S. gr. calcitrapoides	ZE12	3	50.0 (45–55)	57.5 (55–60)	5	1540.0 (1125–2000)	1	1050.0			150	400
	ZE13	6	65.8 (50–80)	69.2 (60–95)	9	1367.2 (1175–1680)	9	890.0 (800–1000)	0.65	2.2–2.8	225.8 (185–260)	414.0 (390–430)

brownish friable epiclastic sandstones and siltstones, and a 1.5-m-thick prominent limestone bed with a lateral extent of only several meters occur along a 15-m-thick cliff (samples ZE2–ZE7). The limestone bed is a calcarenite with *Lepidorbitoides-Siderolites* packstone/grainstone facies (Figure 3A). This part of the succession yielded assemblages of *Lepidorbitoides campaniensis*, *Orbitoides megaloformis*, *Vanderbeekia catalana*, *Siderolites* cf. *calcitrapoides*, *Sirtina orbitoidiformis*, *Planorbulina* sp., agglutinated foraminifera, rotaliids, rudist fragments, gastropods, bryozoans, and red algae (Figure 4). The visible upper part of the Zekeriyaköy Formation is represented by

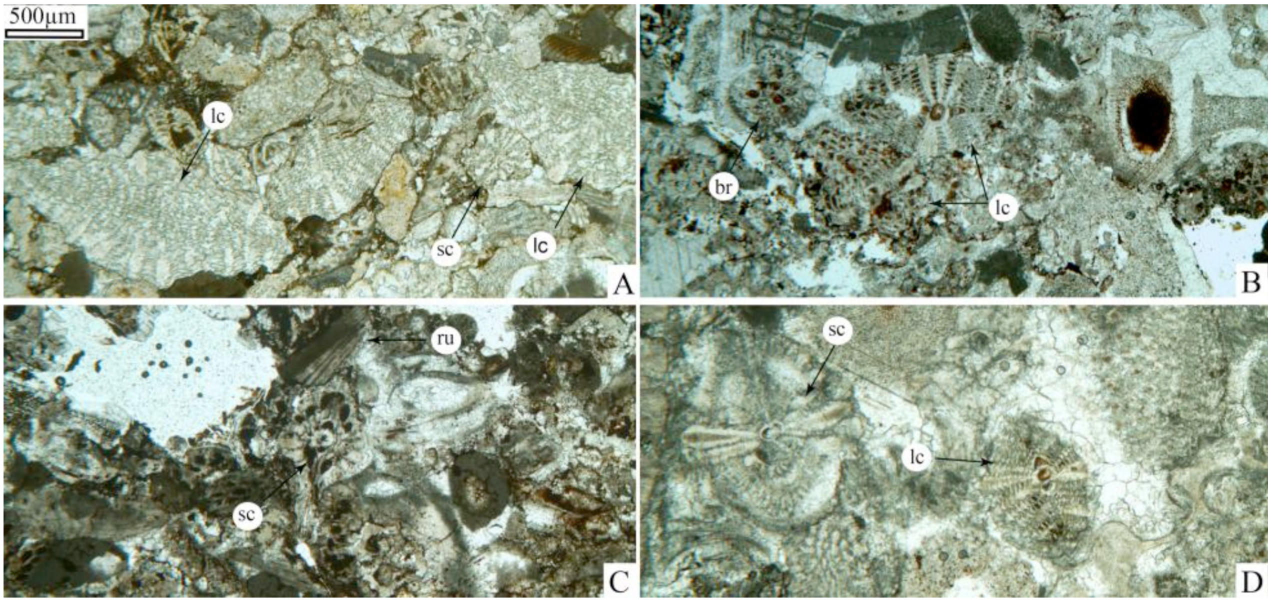

Figure 3. Photomicrographs of thin sections of the limestone beds from the Zekeriyaköy Formation. (A–C) *Lepidorbitoides*-bryozoan packstone/grainstone facies; A: sample ZE5, B: sample ZE9, and C: sample ZE10. (D) *Lepidorbitoides-Siderolites* packstone/grainstone facies, sample ZE13. lc: *Lepidorbitoides campaniensis*, sc: *Siderolites* gr. *calcitrapoides*, br: bryozoans, ru: rudist fragments, vc: volcanic clast.

pinkish sandstones and a ca. 30–40-cm-thick limestone intercalation (Figure 2D) in *Lepidorbitoides-Siderolites* packstone/grainstone facies (Figure 3D). Foraminifera belong to *L. campaniensis*, *O. megaloformis*, *V. catalana*, *S.* cf. *calcitrapoides*, *S. orbitoidiformis*, *Praestorrsella roestae* (Visser, 1951), *Lenticulina rotulata* (Lamarck, 1804), rotaliids, and miliolids, echinoids, bryozoans, and red algae were observed (Figure 4). The Zekeriyaköy Formation is overlain by Neogene sediments, and in one locality it is overthrust by Paleozoic rocks (Figure 1).

Except for the lowest level (sample ZE1), *Lepidorbitoides* is the most common genus, with rare occurrences of *Orbitoides* and *Siderolites*, in the studied material. The absence of porcellaneous taxa is a very characteristic feature of the Zekeriyaköy Formation. The lowest sample containes only *Praesiderolites* and some intact and broken shells of rudists, while the uppermost samples (ZE12 and ZE13) contain abundant *Lepidorbitoides*, subordinate *Vanderbeekia*, and rare *Praestorsella* and *Sirtina* associated with abundant bryozoans. According to Hottinger (1997), *Lepidorbitoides* associated with *Sirtina* and *Hellenocyclina* occurs in low-energy environments in the lower photic zone (ca. 80–120/140 m), while in the lower part of upper photic zone (ca. 40–80 m), it is associated with *Orbitoides*, *Hellenocyclina*, *Omphalocyclus*, *Pseudosiderolites*, and *Arnaudiella*. *Praestorrsella* is considered as an indicator for a deep-neritic environment (Hottinger and Caus, 1993; Caus et al., 2007). In the South Pyrenean margin, Caus et al. (2007) recorded *Siderolites-Omphalocyclus-Orbitoides* assemblages in packstone and grainstone facies with large-scale cross-bedding, indicating a moderate to high-energy shallow marine environment. *Siderolites* is usually confined to the sand-shoal environment or reef (Robles-Salcedo et al., 2013; Caus et al., 2016). *Orbitoides* occur commonly in the upper photic zone (Hottinger and Caus, 1993). In the Zekeriyaköy Formation, the foraminiferal assemblage, dominated by *Lepidorbitoides* with rare *Orbitoides* and *Siderolites*, indicates an open marine environment in the lower photic zone, below the fair-weather wave base, while *Lepidorbitoides-Siderolites* packstone facies of the limestone beds may represent a high-energy shoal environment.

The Zekeriyaköy Formation contains some key late Campanian species, such as *Praesiderolites dordoniensis*, *Lepidorbitoides campaniensis*, and *Vanderbeekia catalana* (van Gorsel, 1973a, 1973b, 1978; Wannier, 1983; Özcan and Özkan-Altıner, 1999a, 1999b; Neumann and Odin, 2001; Hottinger and Caus, 2007). Siderolitids in the Zekeriyaköy Formation were tentatively assigned to *Siderolites* gr. *calcitrapoides*, mostly known from the Maastrichtian (Robles-Salcedo et al., 2018); thus, in this study, this species was not used in the age interpretations. Therefore, the age of the Zekeriyaköy Formation was herein considered as Late Campanian.

5. Systematic description

The systematic descriptions of van Hinte (1976), van Gorsel (1978), Wannier (1983), Hottinger and Caus (2007), and Robles-Salcedo et al. (2018) were followed.

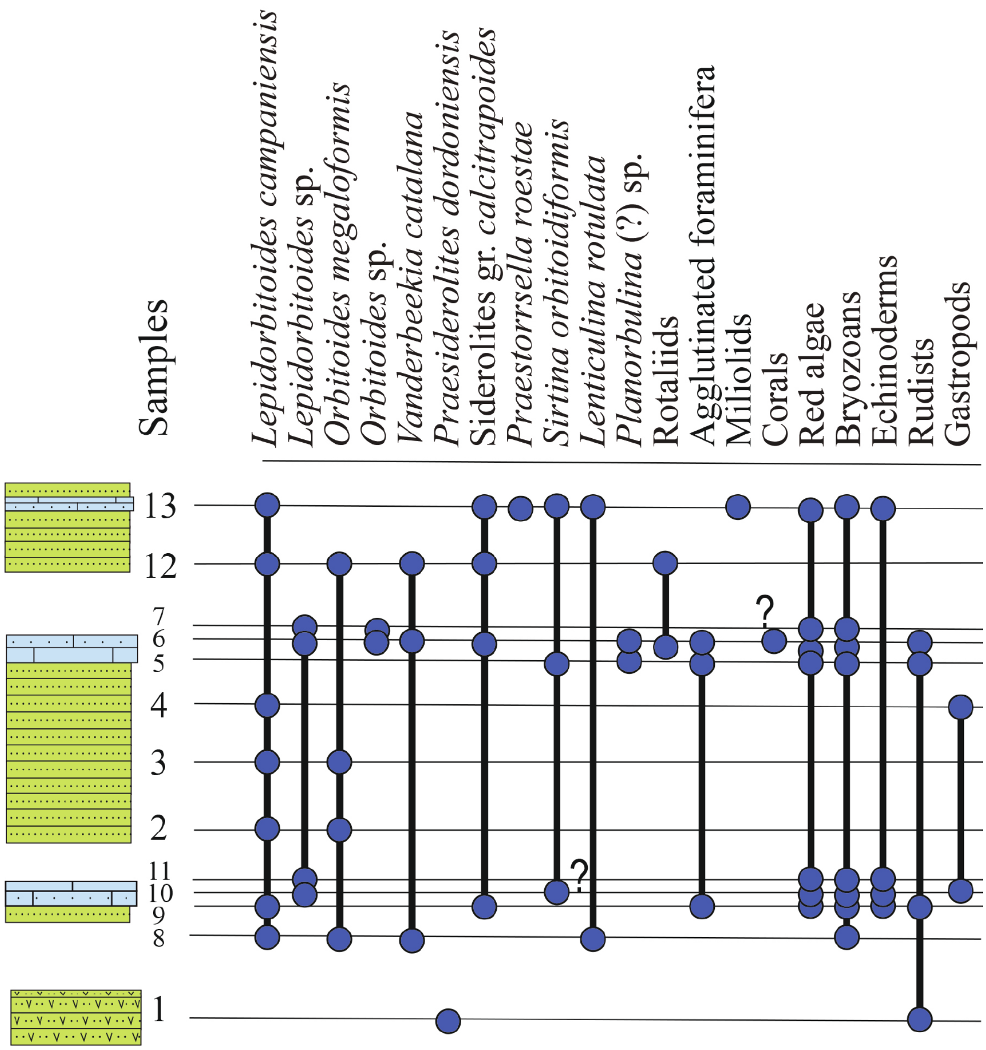

Figure 4. Distribution of the foraminifera and other fossils in the Zekeriyaköy Formation.

Phylum Foraminifera d'Orbigny, 1826

Class Globothalamea Pawloswsky, Holzmann and Tyska, 2013

Order Rotaliina Délage and Hérouard, 1896

Family Lepidorbitoididae Vaughan, 1933

Genus *Lepidorbitoides* Silvestri, 1907

Lepidorbitoides campaniensis van Gorsel, 1973

Figures 5A–5F, 6A–6L, 7, and 9A–9F.

1973b *Lepidorbitoides campaniensis* n. sp.; van Gorsel, p. 263–271, pl. 1, Figures 1–6; pl. 2, Figures 1–4; pl. 3, Figures 1–4; pl. 4, Figures 1–3, and Figure 3.

Description. The test is circular-discoidal in outline, lenticular, and densely granulated (Figures 5A–5B). The test diameter of the megalospheric specimens varies between 1.0 and 3.55 mm, with sample averages of 1.54, 1.78, 2.35, 2.52, and 2.55 mm (Table 2). The granules, ca. 140–150 µm in diameter, in the central part of the test and 50–60 µm near the periphery, are uniformly distributed on the test surface. The embryon consists of a spherical to semispherical protoconch, with an average diameter between 86.11 and 99.0 µm, and a deuteroconch, with an average diameter between 111.1 and 138.5µm (Figures 8A–8B). The embryon is followed by an auxiliary chamber that gives rise to the formation of two spirals ending with a closing chamber (biserial nepionic arrangement of van Gorsel, 1975) (Figure 7). The protoconchal spire (ps) consists of more chamberlets (their average number between 6.86 and 7.55) than the deuteroconchal spire (ds), with an average number between 5.5 and 6.27 (Table 2). Some specimens, on the other hand, rarely possess two auxiliary chambers, resulting in the formation of quadriserial nepionic arrangement with short spirals (Figures 6F, 6L, and 7). It appears that these specimens have larger embryons than specimens with a single auxiliary chamber (Figure 7). The cyclical equatorial chamberlets are arcuate in shape in the nepionic stage and ogival shape in the adult stage (Figure 6A).

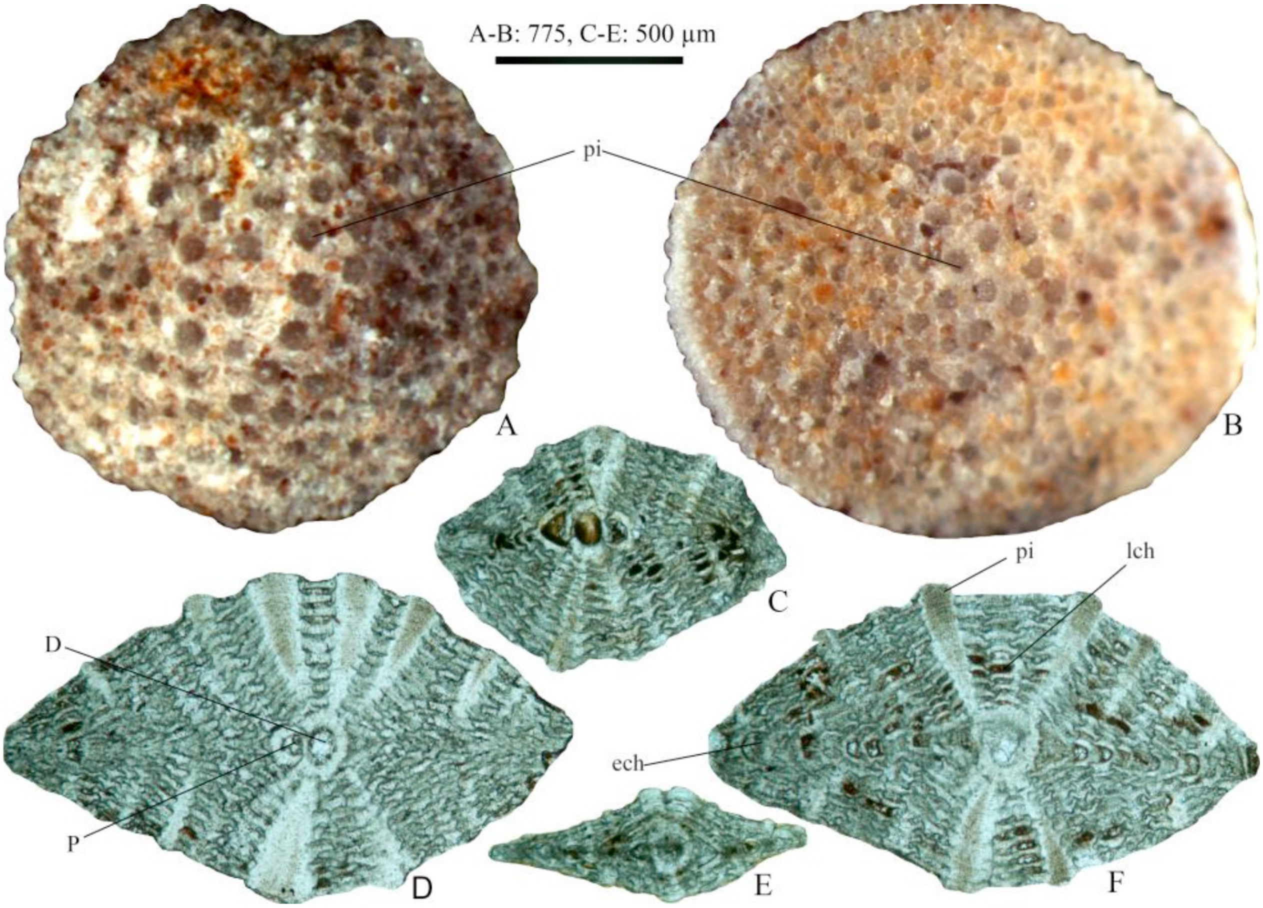

Figure 5. *Lepidorbitoides campaniensis* van Gorsel, late Campanian, from the Zekeriyaköy Formation. (A–B) External views showing the coarse piles at the central part of the test and finer piles at the test margin, A: ZE12–33 and B: ZE12–29. (C–F) Isolated specimens cut in axial sections showing equatorial chamberlets and well-developed lateral chamberlets, ZE13. P: protoconch, D: deuteroconch, pi: piles, ech: equatorial chamberlets, lch: lateral chamberlets.

Remarks. *Lepidorbitoides* has a wide geographic range in the Tethys (Goldbeck and Langer, 2009; Özcan et al., 2019). Van Gorsel (1973b) described *L. campaniensis* for the first time from the Campanian type-section in Aubeterre, SW France, for biserial specimens, which were associated with rare quadriserial ones [also see van Gorsel (1975)]. The Upper Campanian succession in Aubeterre further yielded *Praesiderolites* Wannier (Wannier, 1983) and *Siderolites praecalcitrapoides* at its uppermost levels (Neumann, 1997). The rare quadriserial forms in the current material (10 out of 206 specimens) were assigned to *L. campaniensis* following biometric species discrimination (populations with ca. 80% biserial, ca. 20% quadriserial nepionic arrangement at its type locality). This species was previously recorded from some Campanian deposits in Turkey (Özcan and Özkan-Altıner, 1999a, 1999b).

Family Orbitoididae Schwager, 1876

Genus *Orbitoides* d'Orbigny, 1848

Orbitoides megaloformis Papp and Küpper, 1953

Figures 10A–10F.

1953 *Orbitoides media megaloformis* n. sp.; Papp and Küpper, p. 74, pl. 1, Figures 8A, 8B, and 9.

Description. The test is lenticular with a circular outline and densely granulated outer surface. The diameter of the test ranges from 1.75 to 2.3 mm, based on 5 specimens. The embryon consists of protoconch, deuteroconch, and a tritoconch, producing 4-chambered configurations in the equatorial sections (Figure 10A–10F). The embryon is commonly semispherical in outline. The size of the embryon (Li+li) varies between 460 and 840 µm (based on 7 specimens), with sample averages between 630 and 680 µm in samples ZE2 and ZE3. The embryon is followed by principal and accessory epiembryonic chamberlets (E) and orbitoidal cycles of arc-shaped equatorial chamberlets. The average number of epiembryonic chamberlets is between 6.5 and 7.5.

Remarks. Different species concepts have been applied to *Orbitoides* in the literature, depending on whether

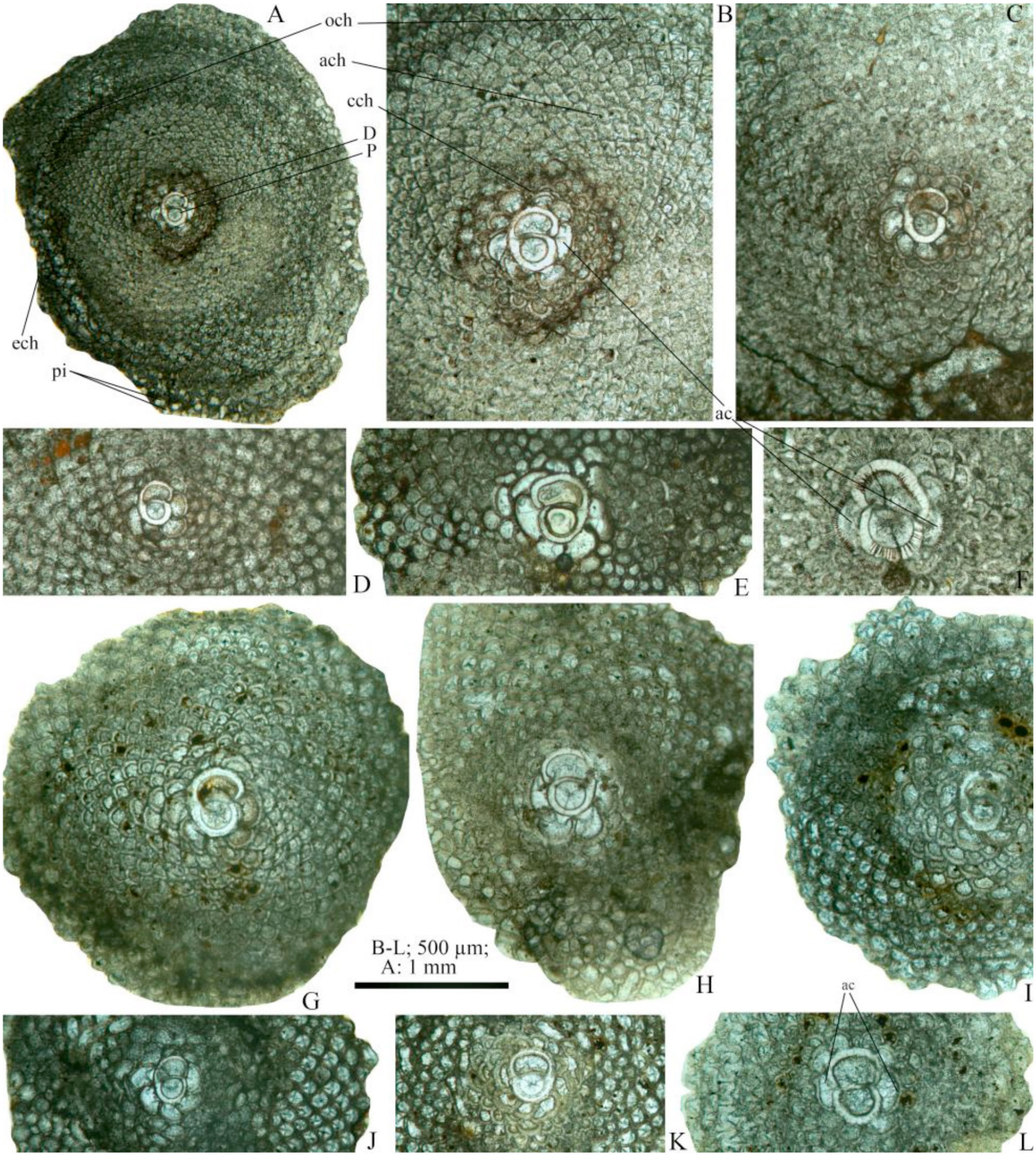

Figure 6. *Lepidorbitoides campaniensis* van Gorsel from samples ZE2 and ZE4, late Campanian, from the Zekeriyaköy Formation. Equatorial sections of the isolated specimens showing the common 'biserial' (A–E, G–K) and rare 'quadriserial' nepionic arrangements (F and L). Note that early arcuate equatorial chamberlets are followed by ogival late chamberlets. A–B: ZE2–8, C: ZE2–10, D: ZE2–11, F: ZE2–6, G: ZE4–67, H: ZE4–24, I: ZE4–65, J: ZE4–109, K: ZE4–21, L: ZE4–69. cch: closing chamber, ach: arcuate equatorial chamberlets, och: ogival equatorial chamberlets, ac: auxiliary chamberlets.

typological or morphometric methods were followed [see van Gorsel (1978) and Baumfalk (1986) for a discussion]. In Europe, the morphometric species discrimination of van Hinte (1976) was based onthe assumption of a single evolutionary lineage of *Orbitoides* from almost Santonian/Campanian boundary to the end of Maastrichtian, and is widely used (van Gorsel, 1978; Caus et al., 1996; Albrich et al., 2014). This concept mainly depends on the increase of

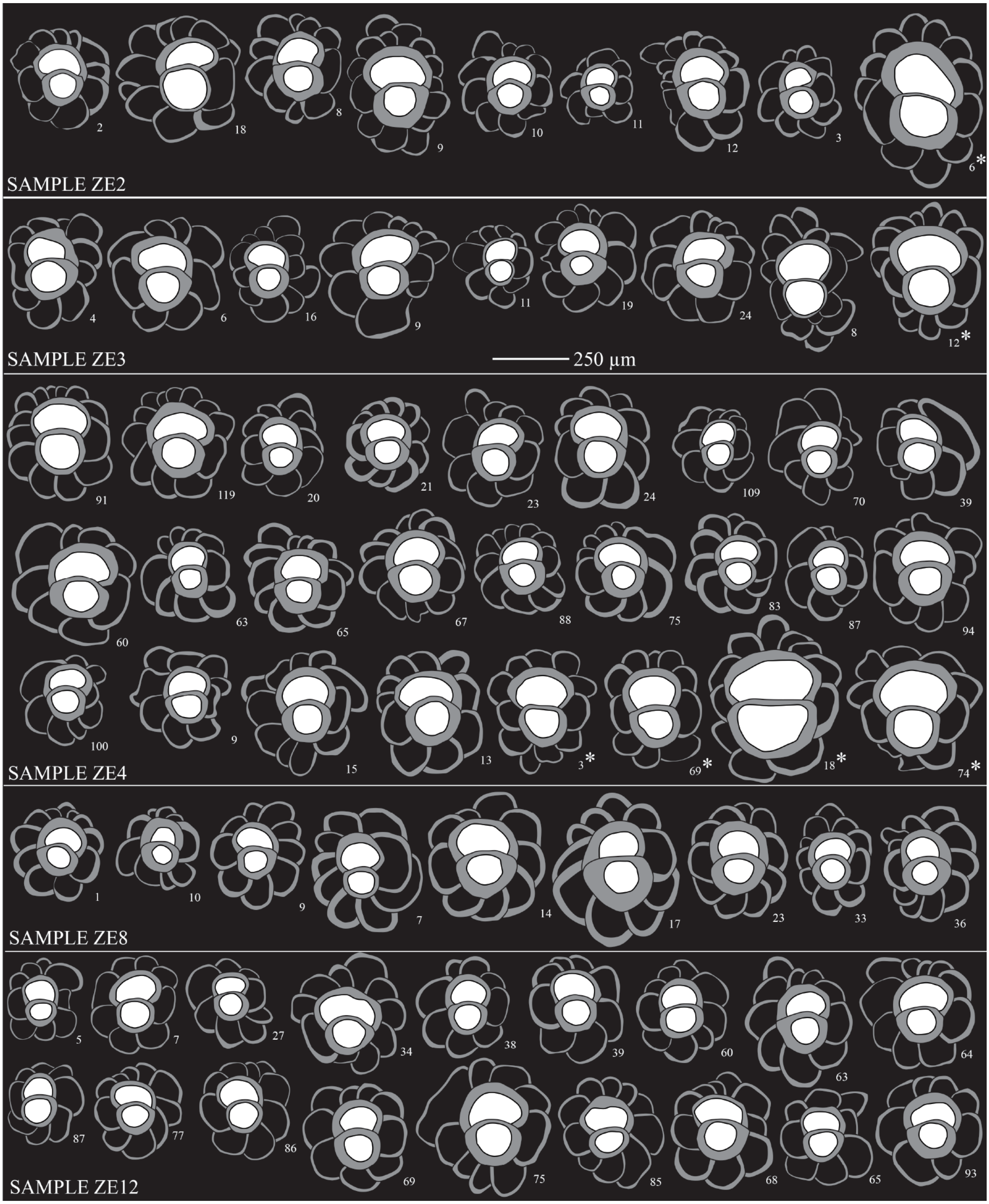

Figure 7. *Lepidorbitoides campaniensis* van Gorsel, late Campanian, the Zekeriyaköy Formation. Drawings of the embryon and periembryonic chamberlets of the isolated specimens showing the variation in the nepionic chamber arrangement. Note the presence of rare quadriserial specimens (shown by asterisk) without adauxiliary chamberlets, a nepionic chamber arrangement distinctive for *L. bisambergensis* Jaeger.

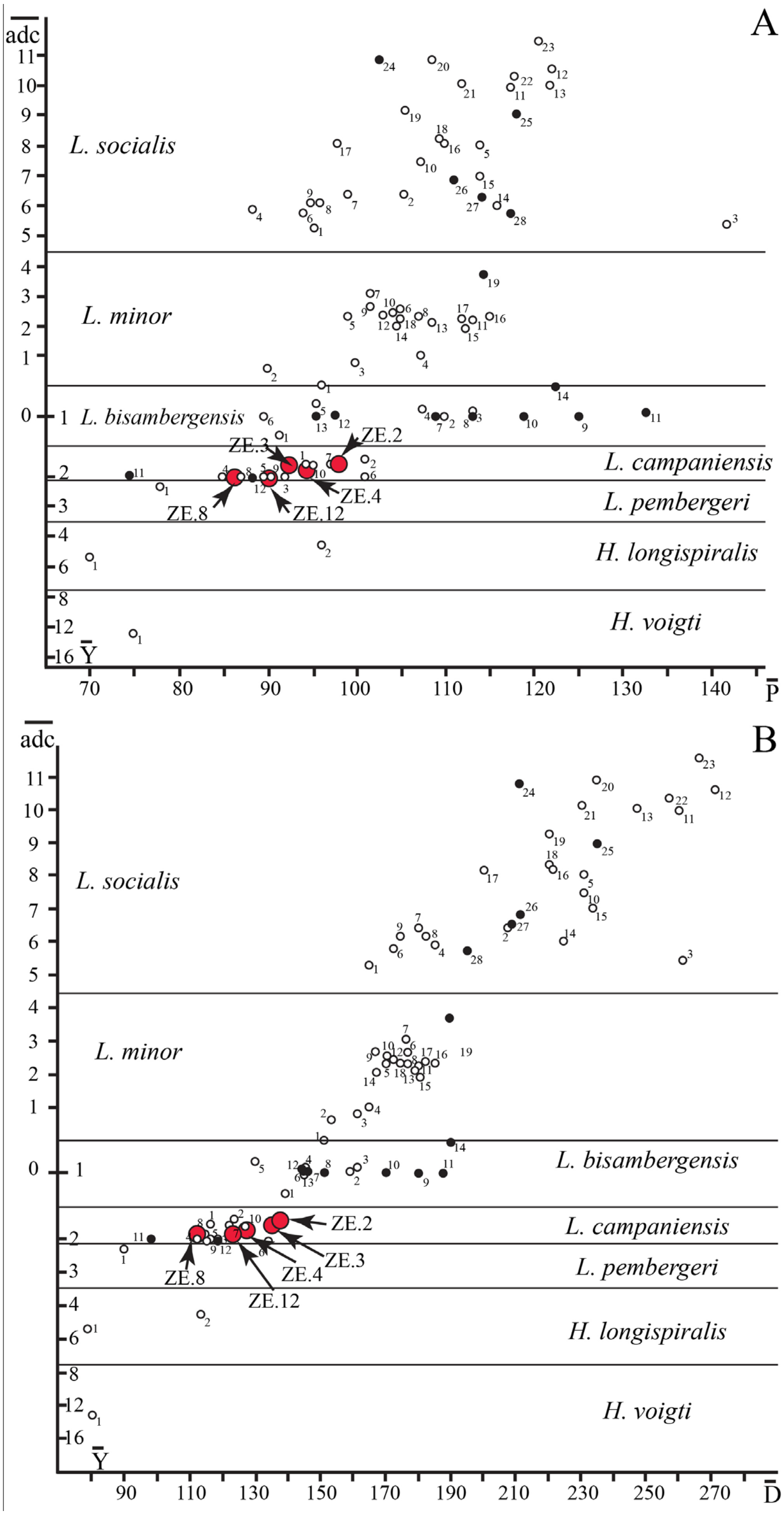

Figure 8. Biometric data of *L. campaniensis* van Gorsel from the Zekeriyaköy Formation in comparison to the previous data from Europe.(A) Relationship between parameters Y and P. (B) Relationship between parameters Y and D. The numbers along the empty circles refer to the code numbers of the samples from Netherlands, France, and Spain studied by van Gorsel (1975). Locations of the samples from Europe were tabulated by van Gorsel (1975). The black circles in A and B refer to the samples from Turkey (Özcan and Özkan-Altıner, 1999a, 1999b). Y: mean number of spiral chamberlets with single basal stolon, adc: number of adauxilary chamberlets. P: innercross diameter of protoconch, D: innercross diameter of deuteroconch.

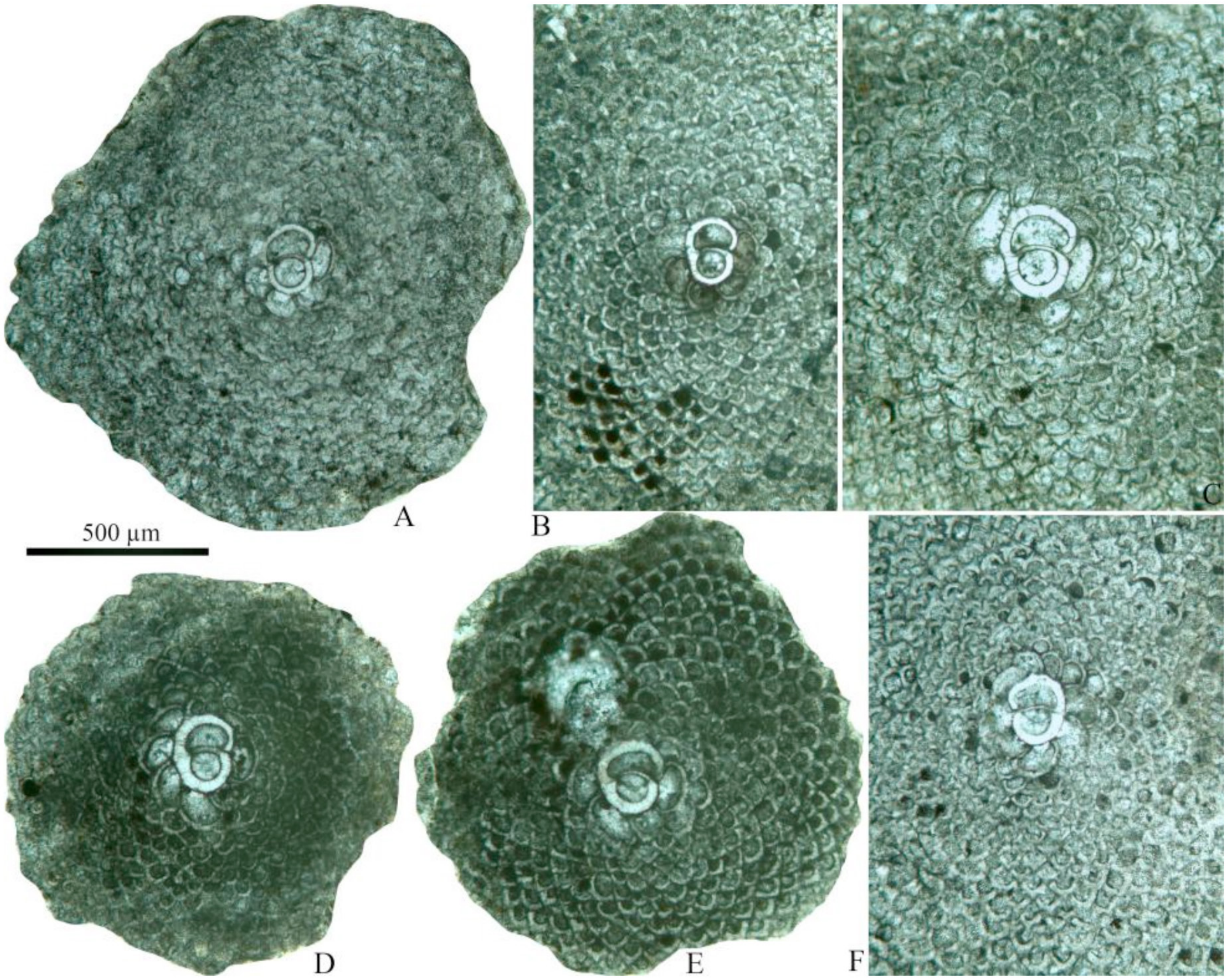

Figure 9. *Lepidorbitoides campaniensis* van Gorsel from sample ZE12, from the late Campanian, Zekeriyaköy Formation. Equatorial sections of the isolated specimens showing the biserial nepionic arrangement. A: ZE12–7, B: ZE12–38, C: ZE12–75, D: ZE12–63, E: ZE12–93, F: ZE12–107.

the embryon size and number of epiauxiliary chamberlets in time. However, occurrences of very small embryons belonging to *O. medius* and *O. apiculatus pamiri* Meriç were also recorded from the Maastrichtian deposits (Meriç, 1974; Özcan, 1993; Özcan and Özkan-Altıner, 1997); hence, the possibility of more than one *Orbitoides* lineage should not be ruled out. This implies that age determinations by *Orbitoides* lineage should be considered with caution. In the current material, *Orbitoides* was extremely rare and the measurements followed only 7 specimens. The morphometric species concept was applied here for the species assignment, and *Orbitoides* specimens were assigned to *O. megaloformis* following species limits of $600 < Li+li_{mean} < 750$ and $5.5 < E_{mean} < 10$, proposed by van Hinte (1976).

Subfamily Clypeorbinae Sigal, 1952

Genus *Vanderbeekia* Brönnimann and Wirz, 1962

Vanderbeekia catalana Hottinger and Caus 2007

Figures 11A–11E and 12A–12F.

2007 *Vanderbeekia catalana* n. sp.; Hottinger and Caus, p. 387–389, Figure 7; pl. 7, Figures 1–12.

2012 *Vanderbeekia catalana* Hottinger and Caus; Brlek et al., Figures 11C–11D.

Description. The test is circular in outline, typically conical with a convex ventral and almost flat dorsal sides (Figures 11A–11C). The test diameter varies between 2.15 and 3.15 mm, with an average of 2.63 mm in sample ZE12, based on 7 specimens, and the thickness varies between 0.71 and 1.03 mm, with an average of 0.86 mm (Table 2). The average test diameter/thickness ratio is 3.07. The ventral side is ornamented by a large central pile, about 400–420 µm in diameter, and radial ridges, characteristic only for this part of the test (Figures 11D and 11F). The dorsal side is characterized by uniformly distributed fine piles (Figure

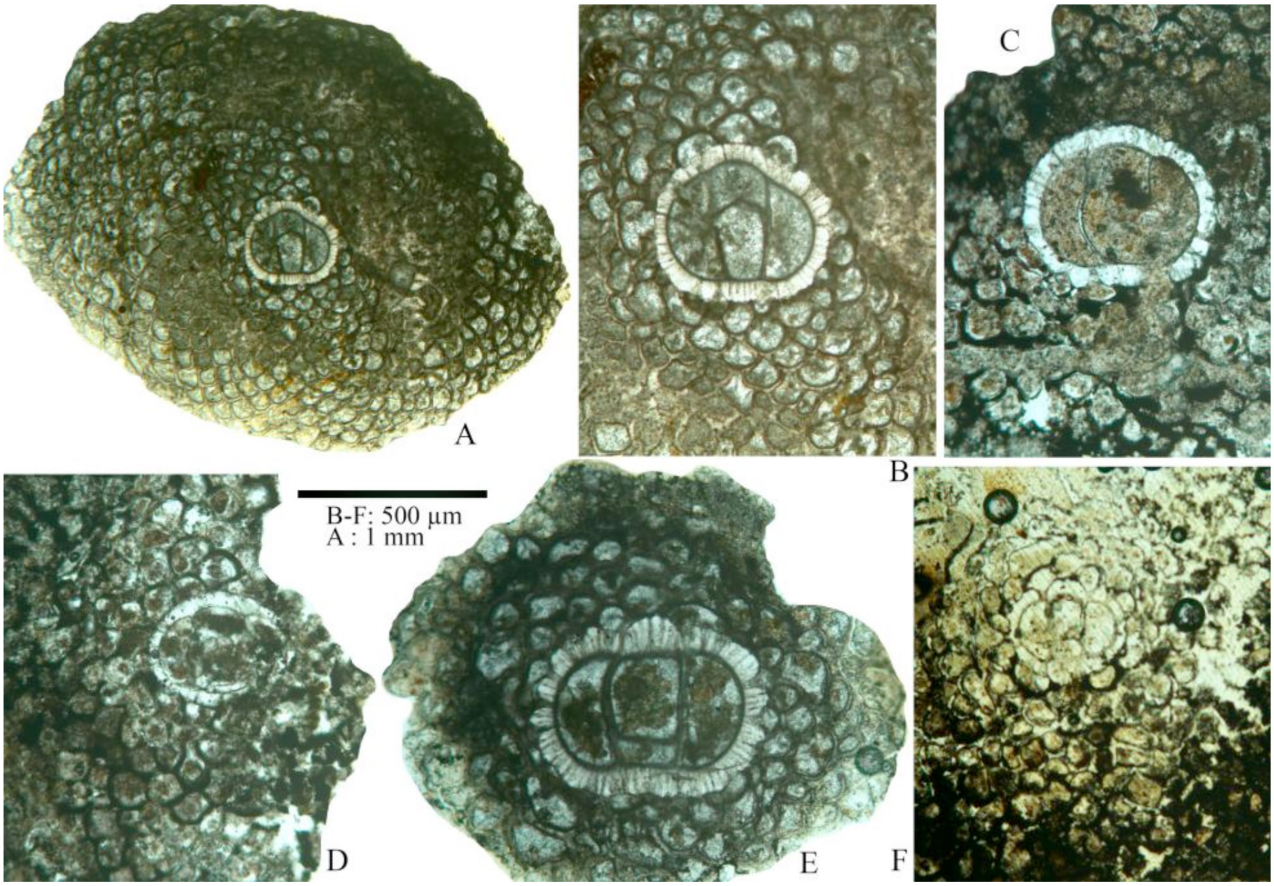

Figure 10. Equatorial sections of *Orbitoides megaloformis* Papp and Küpper from samples ZE2 and ZE3, from the Zekeriyaköy Formation. A–B: ZE2–5, C: ZE2–17, D: ZE2–20, E: ZE3–7, F: ZE3–3.

11B). Proloculus is small, with a diameter of 75–110 µm, and is followed by spiral chambers (Figures 12D–12F). In 1 specimen, it was deduced that 2 spirals, arising from the third chamber, met at the apex of the second chamber before the cyclical growth (Figure 12E). The cyclical chamberlets were not well observed, thus their aspects are not known.

Remarks. This species was originally described from the Late Middle Campanian *Lepidorbitoides*-bearing limestone beds of the Arén Formation in the Tremp Basin, northern Spain (Hottinger and Caus, 2007). It was reported from the levels below the beds with *Lepidorbitoides minima*, which might be actually synonymous with *L. campaniensis*, based on its biserial nepiont [see van Gorsel (1972) and Aguilar et al. (2002) for the discussion on *L. minima*], *O.* cf. *megaloformis* and siderolitids. Robles-Salcedo et al. (2018), on the other hand, reported *V. catalana* in association with *L. bisambergensis*, *O. gruenbachensis*, *S. praecalcitrapoides*, *Sirtina ornata*, *Wannierina vilavellensis*, and other less diagnostic benthic foraminifera from the latest Campanian of the Pyrenees. Thus, the stratigraphic range of *V. catalana* may correspond to the *L. campaniensis* and *L. bisambergensis* zones. For the systematic assignment of *Vanderbeekia* specimens from Zekeriyaköy, Hottinger and Caus (2007) were followed, who conducted a detailed study on the architecture of *V. catalana* at its type-locality in the Tremp Basin. Hottinger and Caus (2007) provisionally assigned their specimens from the Arén Formation to *Vanderbeekia*, even though the ventral sides of these specimens did not bear the same features as *V. trochoidea*, the type species of the genus from the Persian Gulf, Iran (Brönniman and Wirz, 1962). According to the only illustration by drawing, the type-species of the genus lacks lateral chamberlets on the ventral side.

Genus *Sirtina* Brönnimann and Wirz, 1962

Sirtina orbitoidiformis Brönnimann and Wirz, 1962

Figures 13A–13E.

1962 *Sirtina orbitoidiformis* n. sp.; Brönnimann and Wirz, p. 521–527, Figures 2–4, and 6, not 5.

Description. The test is small, lenticular, asymmetric, and has a more pronounced ventral side than dorsal side (Figure 13E). Equatorial and axial diameters are about 0.7–0.1.1 and 0.3–0.36 mm respectively. Proloculus is small, about 40 µm in diameter (Figure 13B). Spiral chambers are low trochospiral (Figures 13C–13E), dorsally more

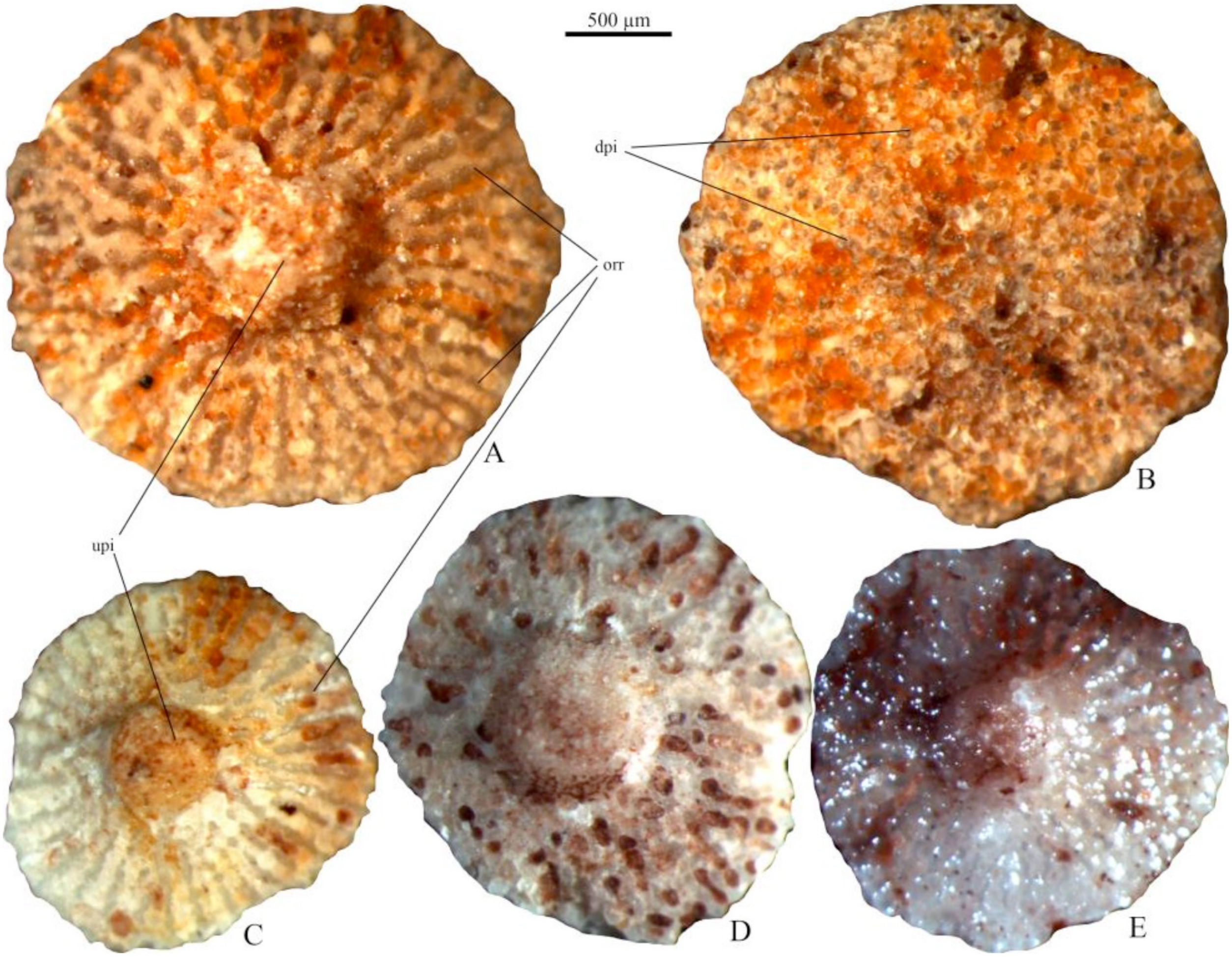

Figure 11. *Vanderbeekia catalana* Hottinger and Caus from sample ZE12, from the late Campanian, Zekeriyaköy Formation. (A, and C–E) Ventral side of the conical shell with thick umbilical pile in the central part of the test and piles appearing as linear radial structures. (B) Dorsal side of the test with uniformly distributed fine piles.A–B: ZE12–42, C: ZE12–48, D: ZE12–15, E: ZE12–45. upi: umbilical pile, orr: ornamental radial ridges at ventral side, dpi: dorsal piles.

involute than ventrally, with radial septa strongly bent backward before reaching periphery of the spire (Figure 13A and 13B). Umbilicus is filled with umbilical piles.

Remarks. The material contains very rare specimens of this species. A very comprehensive revision of the test architecture of this genus was conducted by Hottinger and Caus (2007). According to these researchers, so-called lateral chamberlets [orbitoidal lateral chamberlets in Loeblich and Tappan (1988)] on the dorsal side of the test, in fact, correspond to linear cavities extending from the spiral chamber between the dorsal piles towards the axial zone of shell.

Family Siderolitidae Finlay, 1939

Genus *Siderolites* Lamarck, 1801

Siderolites gr. *calcitrapoides* Lamarck, 1801

Figures 14A–14G.

1986 *Siderolites calcitrapoides*; Neumann, p. 376.

Description. The test is biconvex-lenticular with a rounded periphery, with 4 to 6 spines located in the equatorial plane of the test (Figure 14A). The test diameter varies between 1.12 mm and 2.5 mm, with an average of 1.54 and 1.81 mm in samples ZE12 and ZE13, respectively. The test surface is covered by a dense network of piles reaching up to 170 µm (ranging between 100 and 170 µm) in diameter in the umbilical part and 60–70 µm near the test periphery. The test consists of 2.2 to 2.8 whorls and 22 to 28 chambers (Figures 14D–14G). Proloculus is small, with an inner cross-diameter ranging between 45 and 80 µm, and sample averages of 50.0 and 65.8 µm, and is followed by slightly larger second chamber (Table 3). The first whorl consists of 8 chambers and the second consists of 10 to 11.

Remarks. Identification of *Siderolites* species in thin sections was difficult, since parameters, such as the

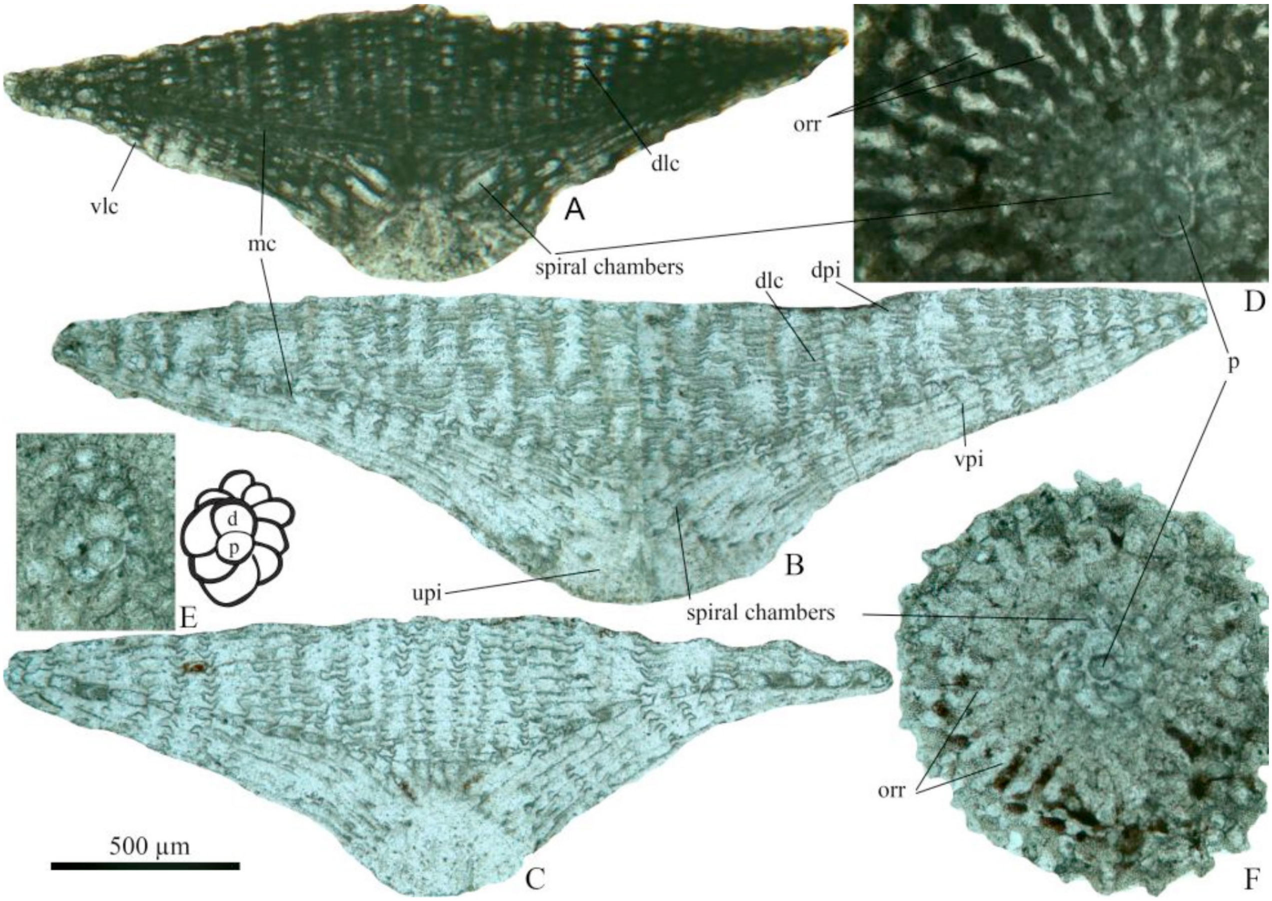

Figure 12. *Vanderbeekia catalana* Hottinger and Caus from samples ZE12 and ZE13, from the Zekeriyaköy Formation. (A) Centered axial section showing the orbitoidiform test with a small proloculus, spiral chambers and poorly developed lateral chamberlets on the ventral side, and well-developed lateral chamberlets on the dorsal side. (B-C) Off-centered axial sections. Note the slightly convex to flat dorsal test surface. (D–F) Horizontal centered sections showing small proloculus, early spiral chambers and radial ridges on the ventral side of the test. Drawing of the chamber configuration in E shows a biserial spiral arrangement around the embryon. Spires meet with a closing chamber. A: ZE12–4, B–C: ZE13, D: ZE12–9, E: ZE12–96, F: ZE12–12. upi: umbilical pile, orr: ornamental radial ridges at ventral side, dpi: dorsal piles, vpi: ventral piles, dlc: dorsal lateral chamberlets, vlc: ventral lateral chamberlets, mc: median chamberlets.

diameter of the test and proloculus size, showed great variability, despite a notable increase in the proloculus diameter from Campanian to the end of the Maastrichtian (Robles-Salcedo et al., 2018; Table 1). Parameters r1 and r2 in the samples range between 185 and 260 μm, and 390 and 430 μm, respectively (Table 3), and were comparable with those of *S. praecalcitrapoides* Neumann, 1986 from the Pyrenees (Robles-Salcedo et al., 2018). The proloculus diameter of the specimens, however, fell within the range of *S. pyrenaicus* Robles-Salcedo et al. (2018). Thus, the specimens showed the features of both species and could not be confidently assigned to a single species. In the presence of only a few specimens, the Zekeriyaköy specimens were herein assigned tentatively to *Siderolites* gr. *calcitrapoides*, being aware that they may belong to early siderolitids in the Campanian.

Genus *Praesiderolites* Wannier, 1983

*Praesiderolites dordoniensis*Wannier, 1983

Figures 15A–15M.

1983 *Praesiderolites dordoniensis* n. gen., n. sp.; Wannier, Figures 3.1–13; Figures 6.1–10; Figure 8.4-5; pl. 3, Figures 1–7.

Description. The test is lenticular, planispirally coiled, and involute, with an irregular circular outline and a sharp peripheral margin, which is usually denticulated (Figures 15A–15C and 15J–15M). Piles are coarser at the umbonal areas (80–160 μm in diameter) and much finer at the test periphery (40–70 μm in diameter). The diameter of the test ranges from 1.1 mm to 3.0 mm, with an average of 1.99 mm (Table 3). The thickness of the test ranges between 0.65 and 0.88 mm, with an average of 0.75 mm. The test consists of 2.3 to 3.2 whorls with a number

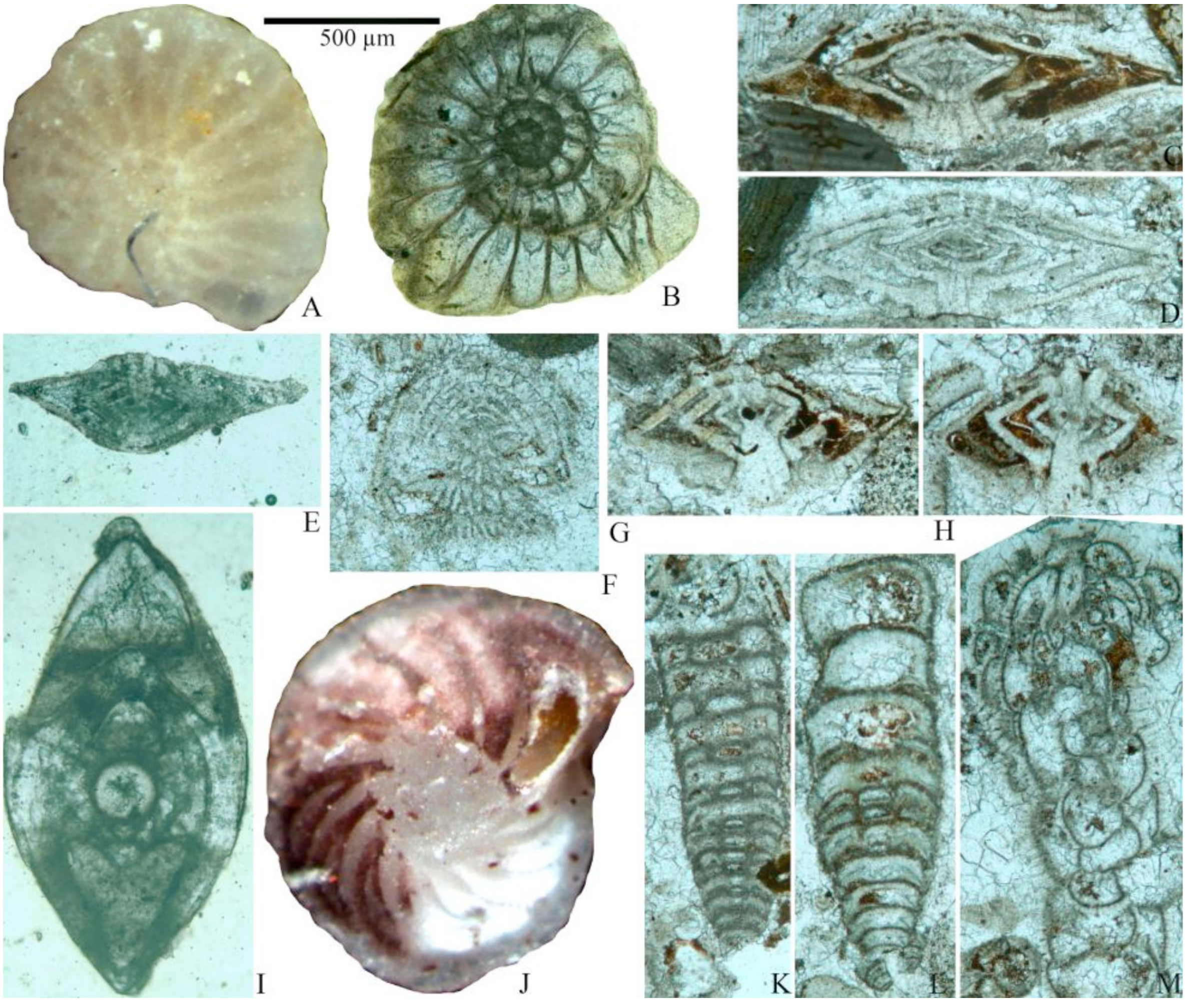

Figure 13. Subordinate foraminifera from the Zekeriyaköy Formation, late Campanian. (A–E) *Sirtina orbitoidiformis* Brönnimann and Wirz, A–B: ZE4–27, C–D: ZE13, E: ZE12–124. (F) *Praestorrsella roestae* (Visser), ZE13. (G–H) Unidentified rotaliid foraminifera, ZE13. (I-J) *Lenticulina rotulata* (Lamarck), J, external view, I, axial sections. I: ZE12–121, J: ZE12–126. (K-L) Unidentified agglutinated foraminifera, K: ZE6, L: ZE13. (M) *Planorbulina* sp., ZE6.

of chambers, ranging between 35 and 52. The first and second whorls consist of 10–11 (including proloculus and second chamber) and 14–18 chambers, respectively. The proloculus is small, with an inner cross-diameter ranging between 30 and 100 µm, and a sample average of 70.6 µm, and is followed by slightly larger second chamber (Figures 15C–15I, Table 3).

Remarks. Siderolitids, especially its primitive members in Santonian and Campanian, are particularly well-known from the Pyrenees (N Spain), Aquitaine Basin (SW France), and southern Italy (Wannier, 1983; De Castro, 1990; Robles-Salcedo et al., 2018). Wannier (1983) differentiated 3 species as *P. santoniensis* ($p \leq 45$ µm), *P. douvillei* ($45 \leq p \leq 55$ µm), and *P. dordoniensis* ($p \geq 55$ µm) in the upper Santonian-Campanian deposits of the Aquitaine and Tremp basins (Catalonia, N Spain). Wannier (1983) suggested an average proloculus diameter of 65 µm for *P. dordoniensis* from the Campanian (late Campanian) type-section in Aubeterre, in association with *L. campaniensis*, *Arnaudiella grossouvrei*, and *O. tissoti/O medius*, and from another late Campanian section in Charente Maritime (SW France) in association with *O. medius*. The specimens herein were assigned to *P. dordoniensis*, mainly based on the proloculus diameter of the type species and heavy denticulation at the test periphery. Robles Salcedo (2015) recognized another species, *P. praevidali*, which filled the gap between *P. santoniensis* and *P. douvillei* during the Middle Campanian. Detailed information on this genus can be found in Robles Salcedo (2015).

Superfamily Glabratellallacea Loeblich and Tappan, 1964

Family Glabratelloidea Loeblich and Tappan, 1964

Genus *Praestorrsella* Gowda

Praestorrsella roestae (Visser, 1951)

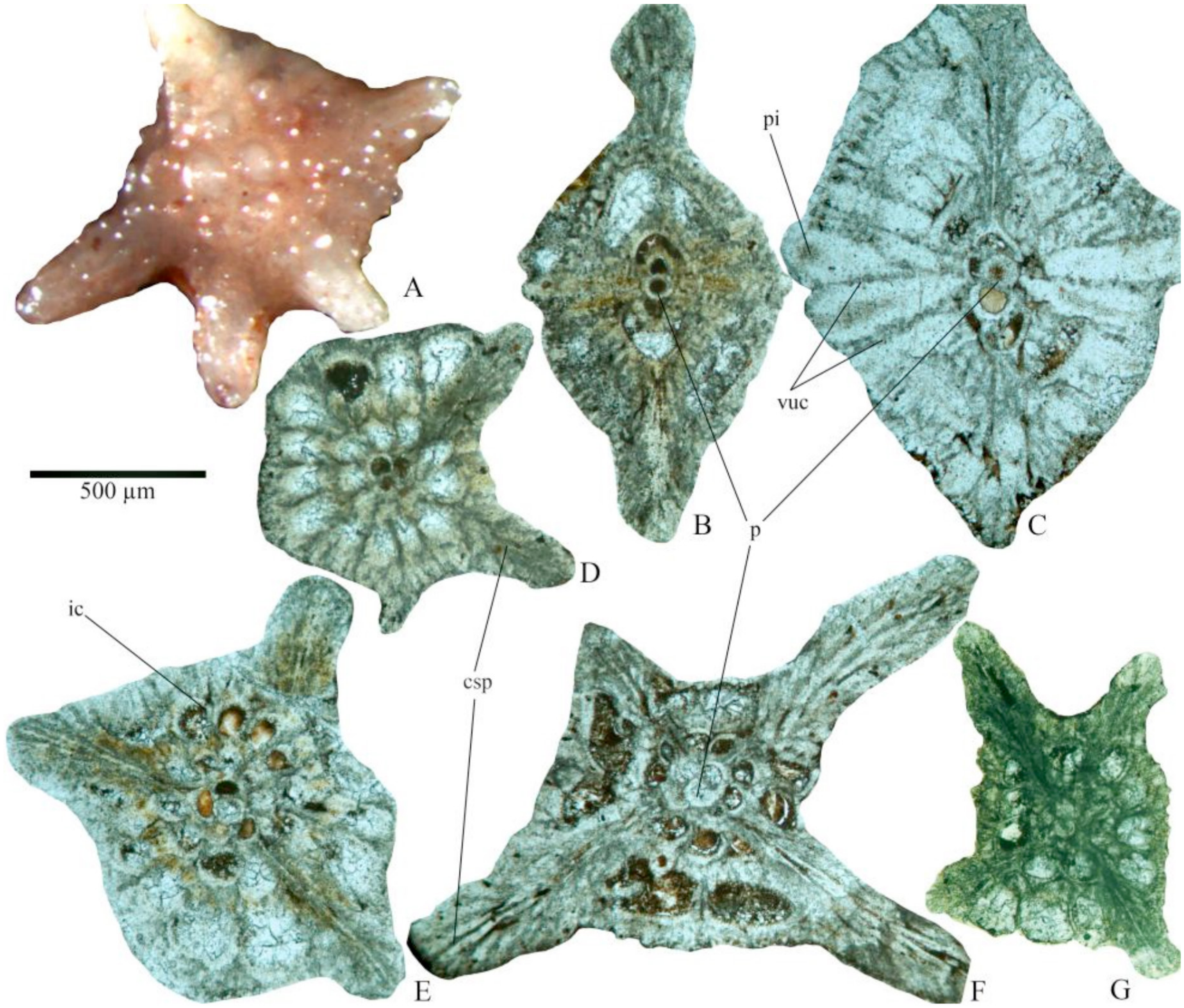

Figure 14. *Siderolites* gr. *calcitrapoides* Lamarck from samples ZE12 and ZE13, late Campanian, from the Zekeriyaköy Formation. (A) External test features of an isolated specimen showing the spines and granules. (B-C) Axial sections showing canaliferous spines and umbilical canals. (D–G) Equatorial sections showing small proloculus and tight spire. A and F: ZE12–127, B–F: 13. p: protoconch, pi: piles, vuc: vertical umbilical canal, ic: intraseptal canal, csp: canaliferous spine.

Figure 13F.

1951 *Cibicides roestae* n. sp.; Visser, p. 291, pl. 6, Figure 9.

1993 *Praestorrsella roestae* (Visser); Hottinger and Caus, p. 214–215, Figures 1A–1D, pl. 1; Figures 1–19, pl. 2; Figures 1–8.

Description. The test is small, subconical, and inequally biconvex. The dorsal side is hemispherical with thick pillars. The ventral side is almost flat, and the umblical space is filled with piles. Coiling is tight trochospiral.

Remarks. This species was very rare in the material herein and only 1 specimen was recorded. *Praestorrsella roestae* was previously recorded from the Maastrichtian deposits in Turkey (Akyazı and Özgen-Erdem, 2003). Good illustrations of the species can be found in Hottinger and Caus (1993) and Granero et al. (2018). Based on the records by Hottinger and Caus (1993), from the Campanian of Pyreenes and Maastrichtian of India (Gowda, 1978), the species appears to have a wide geographic range in the Tethys.

6. Paleogeography

Most of the stratigraphically important LBF found in the Zekeriyaköy Formation, such as *Lepidorbitoides campaniensis*, *Vanderbeekia catalana*, and *Praesiderolites dordoniensis*, were first described from the Aquitaine and Pyrenean basins in western Europe (van Gorsel, 1973b; Wannier, 1983; Hottinger and Caus, 2007). These species and their assemblages, recorded from several basins in Europe, are considered to represent the European Faunal Province of Goldbeck and Langer (2009) (Figure 16). *Vanderbeekia catalana* was also reported from the late Campanian levels of the Upper Cretaceous carbonate

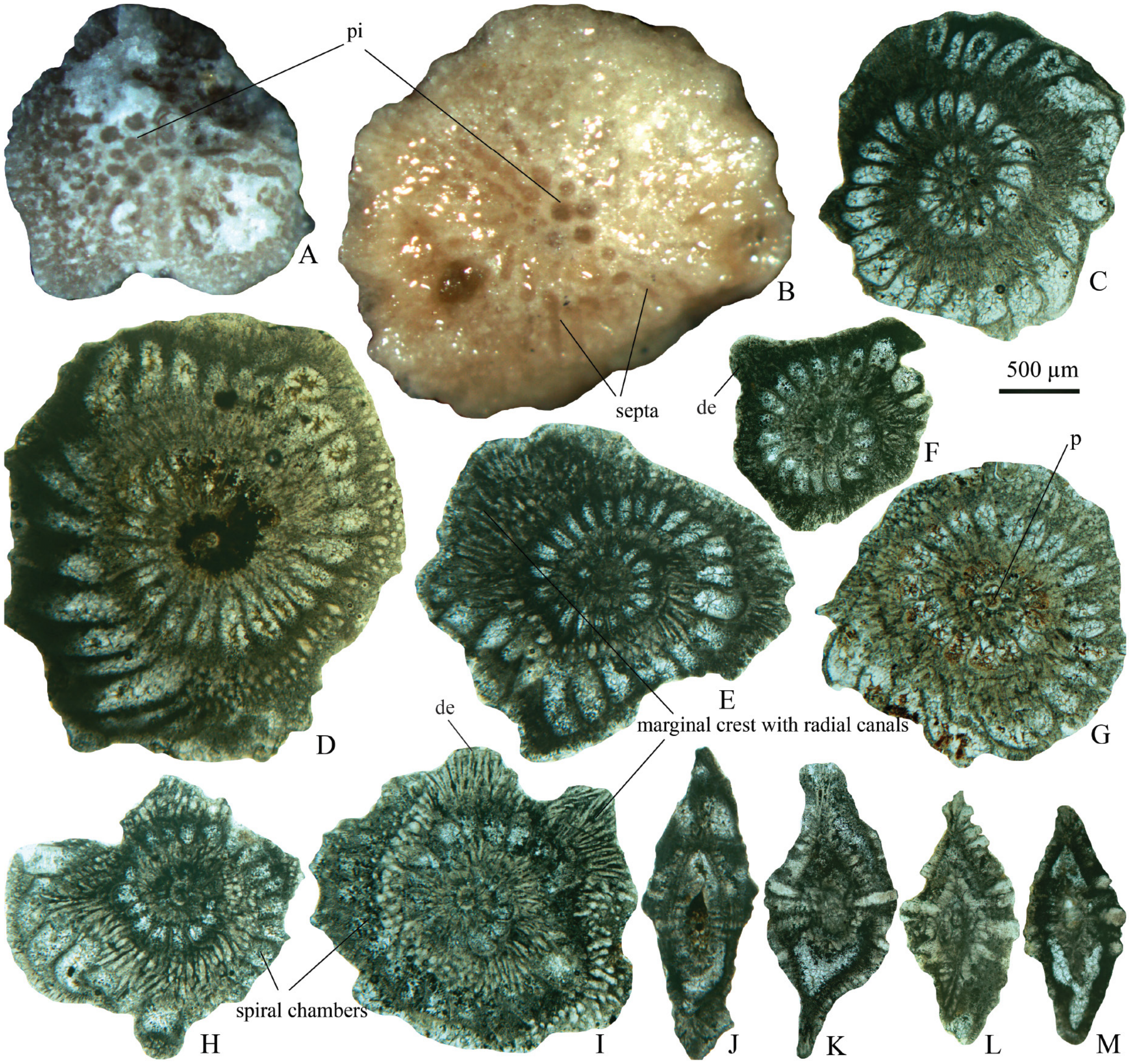

Figure 15. *Praesiderolites dordoniensis* Wannier from sample ZE1, late Campanian, from the Zekeriyaköy Formation. (A–C) External test views showing the denticulated test margin, coarse pile at the central part of the test, and septa. (D–I) Equatorial sections showing the small proloculus, denticulated margin of the test and marginal crest with radial canals. (J–M) Off-centered axial sections showing the simple spinose test. A and L: ZE1–12, B and E: ZE1–18, C: ZE1–5, D: ZE1–1, F: ZE1–15, G: ZE1–25, H: ZE1–24, I: ZE1–19, J: ZE1–29, K: ZE1–27, M: ZE1–4, P: proloculus, de: denticulation.

succession in the central Dalmatia, Adriatic region of Croatia, in association with *Siderolites* and *Orbitoides* (Brleket al., 2013) (Figure 16). The occurrence of this species in the Zekeriyaköy Formation marks the most eastern record of the genus in the Tethys. *Praesiderolites*, known in detail from the Aquitaine and Pyrenean basins, was also reported from the late Campanian of Turkey (Korkmaz et al., 1993; Özcan, 1993; Fenerci and Özer, 1998; Özer et al., 2009). Campanian *Orbitoides*, on the other hand, is widespread, occurring in the tropics and subtropics, from the Caribbean to South Asia (Loeblich and Tappan, 1988; Goldbeck and Langer, 2009).

7. Conclusion

The Zekeriyaköy Formation, commonly interpreted to be within the Upper Cretaceous volcanic sequence, in fact, represents a shallow-marine sandstone and carbonate deposit that nonconformably overlies the Upper Cretaceous volcanic rocks. This unit contains very characteristic late Campanian LBF, with great similarities to those in the Campanian type-section in Aubeterre (SW France) and lower part of the Arén Formation, near Vila-vella in the Tremp Basin (Pyrenees). Based on the assemblages of *Lepidorbitoides*, *Vanderbeekia*, *Praesiderolites*, and *Siderolites*, and in the absence of previously reported typical

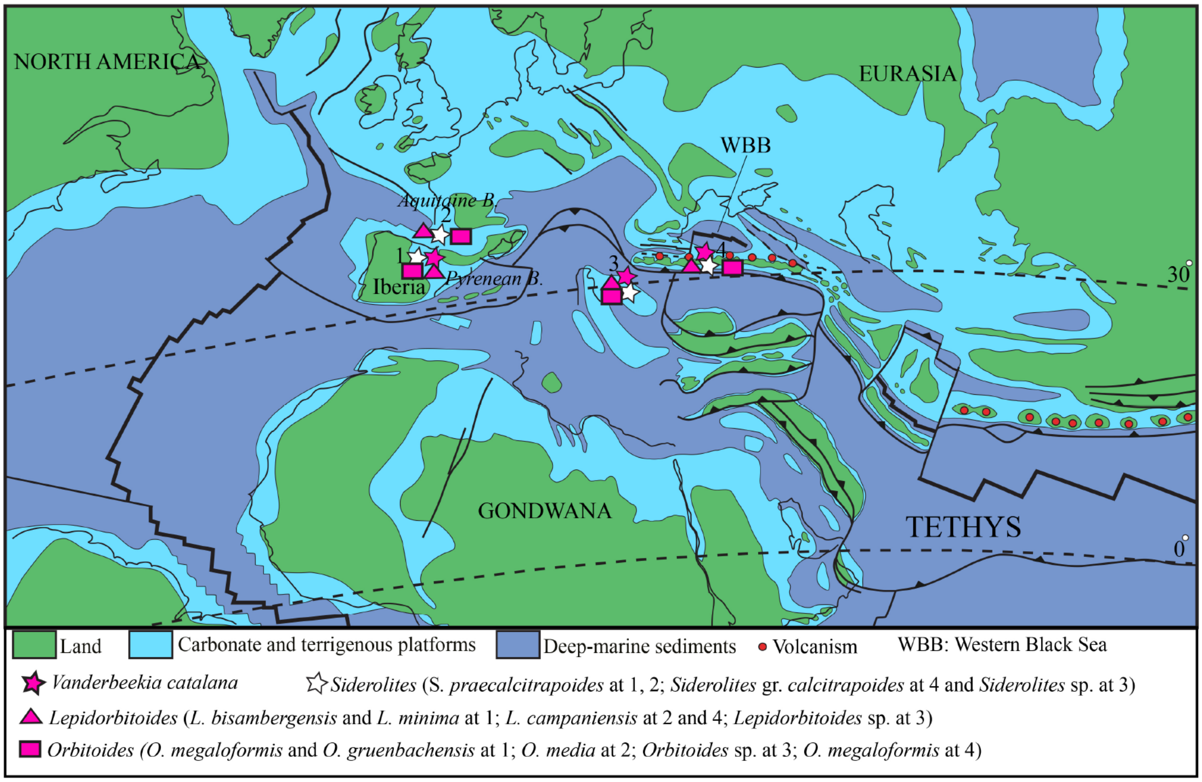

Figure 16. Distribution of the late Campanian *Vanderbeekia-Lepidorbitoides-Praesiderolites-Siderolites-Orbitoides* assemblage in the Tethys (from various sources). (1) Pyrenean Basin (N Spain), (2) Aquitaine Basin (SW France), (3) Central Dalmatia (Adriatic region, Croatia), (4) NW Turkey. Paleogeographic map from Barrier et al. (2018).

Maastrichtian species, the age of the Zekeriyaköy Formation was revised as the Late Campanian. The foraminiferal assemblage and associated fossils indicated an open marine environment in the lower photic zone below the fair-weather wave base, and a high-energy shoal environment, indicated by the deposition of *Lepidorbitoides-Siderolites* packstone/grainstone and absence of porcellaneous foraminifera. The fossil assemblages implied that Late Cretaceous volcanism in the İstanbul region ceased during the late Campanian or earlier. The data herein showed that the reported taxa belong to the European Faunal Province of Goldbeck and Langer (2009), and extend the geographic distribution of the aforementioned taxa from Spain and SW France, to the Black Sea region for the Campanian of the Western Tethys.

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