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Research Article

Planktonic Foraminiferal Biostratigraphy and Correlation Across the Cretaceous-Paleogene Transition at the Tethyan and the Atlantic Realms

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Based on high-resolution planktonic foraminiferal biostratigraphical analysis at El Kef stratotype section (GSSP for the K/Pg boundary), Ellès section in Tunisia, and Agost and Caravaca sections in Spain (Tethyan realm), we attempt to compare biozones and subzones with those of the Bidart section (SW France) (Atlantic realm). The *Abathomphalus mayaroensis* zone of the upper Maastrichtian corresponds to the taxon range interval of the nominate species. We have identified the *Plummerita hantkeninoides* subzone. This species is present and associated with *Pseudoguembelina hariaensis* at the Tethyan realm. However, this species is absent at the middle latitude of the Atlantic realm (Bidart section, SW France). The *Pseudoguembelina hariaensis* species had larger paleogeographic spread, as it was present in both the Tethys and the Atlantic paleoceans. It is more relevant to be considered as the biomarker of a nominate uppermost Maastrichtian subzone instead of *Plummerita hantkeninoides*. The Danian stage is characterized by the *Gt. cretacea* zone, *Pv. eugubina* zone, and the *Parasubbotina pseudobulloides* zone. The deposition thickness of the zones and subzones at El Kef stratotype section and Ellès section is more expanded than at Agost and Caravaca sections (Spain) and Bidart section (France). They would be controlled by the sedimentary basin morphology.

1. Introduction

At the K/Pg boundary, with most of the Heterohelicids, the Globotruncanids suffered mass extinctions. These extinctions affecting many other biological groups of vertebrates and invertebrates induced a major crisis considered as the most severe and catastrophic biological event in the history of our planet. This crisis documented in many research on the foraminifers groups ([4–6], among others) became more accurate until the specialists began to use the high resolution biostratigraphical analyses ([7–16], among others).

The extinction model of planktic foraminifers groups, at the K/Pg boundary, is very controversial. Some authors consider that the lower Danian assemblages include reworked specimens of Maastrichtian taxa [17–19], whereas others have suggested that at least a substantial part of the latest Maastrichtian species survived into the earliest Danian [20, 21]. Deep-water benthic foraminifers were less influenced by the K/Pg boundary event, but their diversity and abundance decreased temporarily [15, 22, 23].

After these K/Pg boundary mass extinctions, small and new planktic foraminiferal species began to appear following an "explosive" adaptive radiation pattern. Consistent debates on the upper Maastrichtian-lower Danian interval based on planktic foraminiferal zonations and biochronology for the middle and lower latitudes are documented ([7, 8, 10, 12–16, 24–26], among others).

In general, the authors are disagreeing about the extinct species at the upper Maastrichtian than about the appeared species at the lower Danian. The estimate evolution and diversification of planktic foraminifers before and after the K/Pg mass extinctions depend firstly on the resolution sampling across the K-Pg transition interval and secondly on problems concerning mainly the planktic foraminiferal taxonomy of the pioneer Globigerinids originated at the Danian.

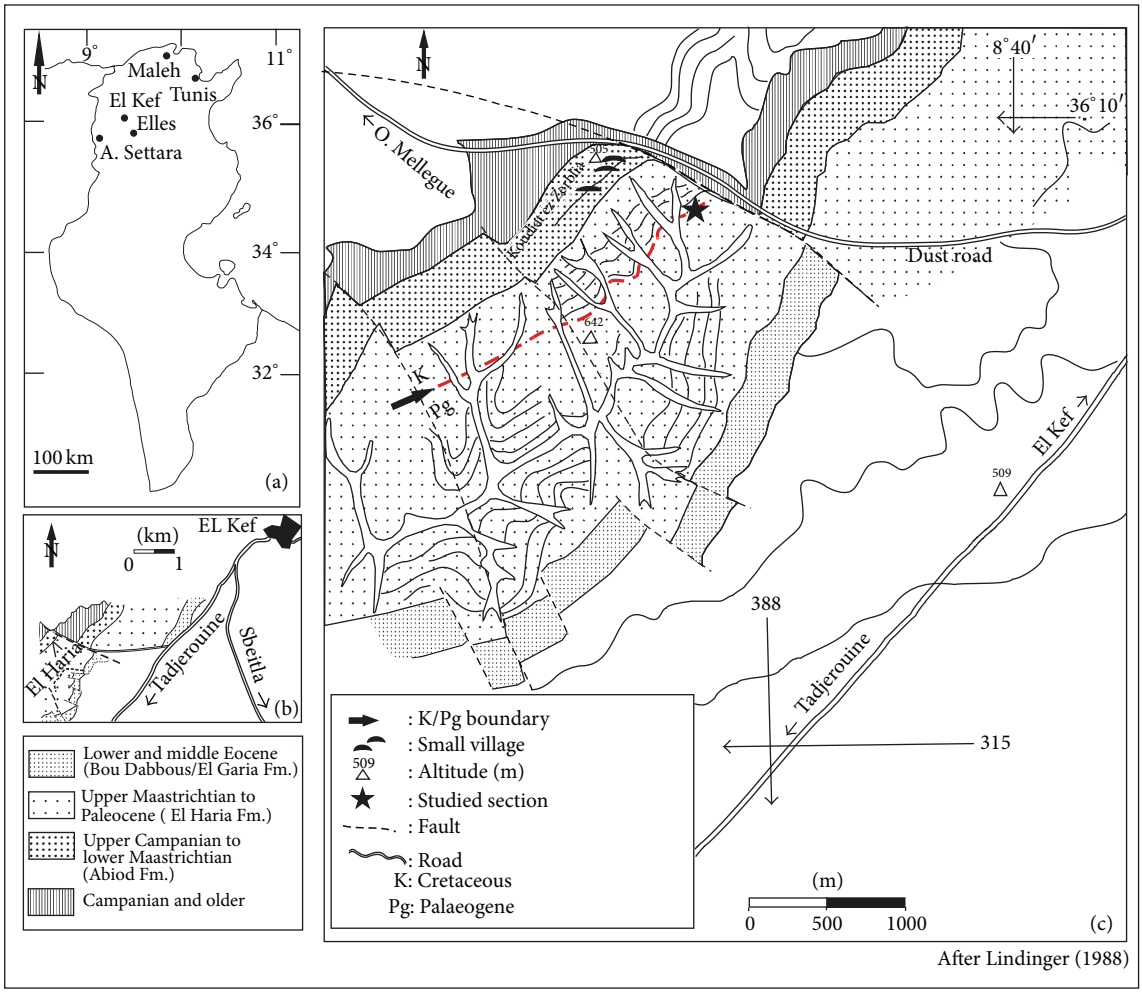

FIGURE 1: Geographical and geological location of the El Kef section in Tunisia, modified from Lindinger [1]. (a) General map of Tunisia, (b) map of El Kef area, and (c) detailed map of the section.

Consequently many species are proposed; other species are emended or discussed.

The planktic foraminiferal zonations and biochronology of the upper Maastrichtian-lower Danian of the middle and lower latitudes are still hotly debated. Whereas the *Abathomphalus mayaroensis* zone is used as a standard subdivision in the upper Maastrichtian, the proposed Danian zonation is still highly controversial. The suggested evolutionary pattern and diversification of planktic foraminifers across the K/Pg boundary interval depend on the sampling resolution and the taxonomy of the early globigerinids that originated at the base of the Danian.

In order to elucidate the biostratigraphy at the K/Pg boundary in tropical, subtropical, and temperate latitudes and to correlate between these different area, we have studied several sections across these latitudes. The most expanded and continuous sections studied are El Kef and Ellès in Tunisia, Agost and Caravaca in Spain, and Bidart in France.

These sections are among the best documented and most complete and continuous sections known to date. The principal features of the K/Pg event (Ir anomaly, spinels, etc.) and the expanded lower Danian planktic foraminiferal zones and subzones are recorded in them [13, 15]. The Global Stratotype Section and Point (GSSP) for the base of the Danian was defined near El Kef, Tunisia [15, 27]. The sections of Ellès (Tunisia), Caravaca and Agost (Spain), and Bidart (France), in which the K/Pg boundary event is well recorded, have been proposed to be auxiliary sections for the definition of the K/Pg boundary [13, 14, 28].

In this paper, based on high-resolution biostratigraphy, we attempt to check if these sections are complete, to present our contribution to the general discussion on the standard biozonation of the uppermost Maastrichtian and Danian stratigraphic interval [5, 7–10, 16, 17, 24–26, 29–32] and to correlate between these different standard biozones and subzones.

2. Materials and Methods

2.1. El Kef Stratotype Section. The GSSP site is located at a distance of between 5 and 6 km from the crossroad of the El Kef city. It can be reached by taking the exit towards

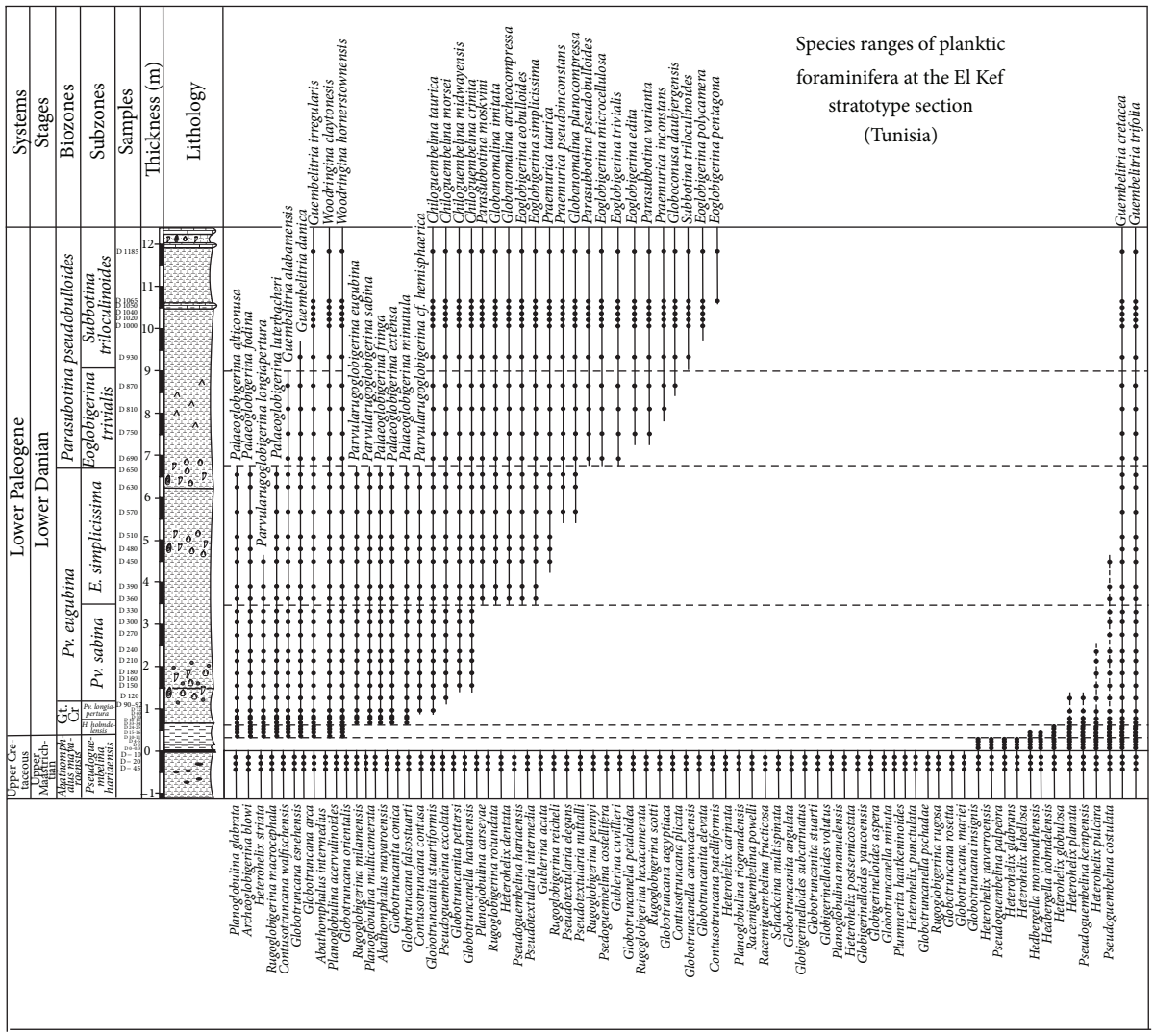

Figure 2: Species distributions of planktonic foraminifera in the El Kef stratotype section (Tunisia).

the town of Tajerouine and following the road which leads to Hammam Mellegue between a small village and a recent artificial lake. The GSSP lies in the upper Maastrichtian to Paleocene El Haria Formation, which is underlain by the upper Campanian/lower Maastrichtian Abiod Formation and overlain by the lower and middle Eocene Bou Dabbous/El Garia Formation (attributed to the Metlaoui Formation in the original proposal) (Figure 1).

The precise coordinates were measured with a GPS; Lambert coordinates calibrated from Carthago point: N36°09′ 13.2″, E008°38′ 54.8″, UTM coordinates: N32, N4001314, E468675. Consequently, the Global Stratotype Section and Point for the base of the Danian, which by def-inition is also the base of the Paleocene, the Paleogene, the "Tertiary" and the Cenozoic, has been officially reestablished at the base of the boundary clay (see [27]).

The GSSP for the base of the Danian was defined in the El Kef section (Tunisia) and ratified by the IUGS in 1991. However, this GSSP was not officially published in a prestigious stratigraphical journal of wide distribution. Only a short note was published in Episodes by Cowie et al. [33], in a report on activities of the ICS from 1984 to 1989. Since then, certain problems have arisen as the detailed proposal was unknown to many scientists working on the K/Pg boundary, new sections in Mexico were found, and controversial interpretations were proposed. Therefore, in order to resolve these problems, the ICS has required the ISPS to finally publish the proposal. On the 6th of April 2006, the chairman of ISPS (E. Molina) in collaboration with our Tunisian group visited the GSSP at El Kef again, in order to put in place an artificial marker ("golden spike") and to request the Tunisian authorities to protect the site. At the same time, the present status of the site has been documented by a series of photographs. Finally, it was officially published, see Molina et al. [27, 28].

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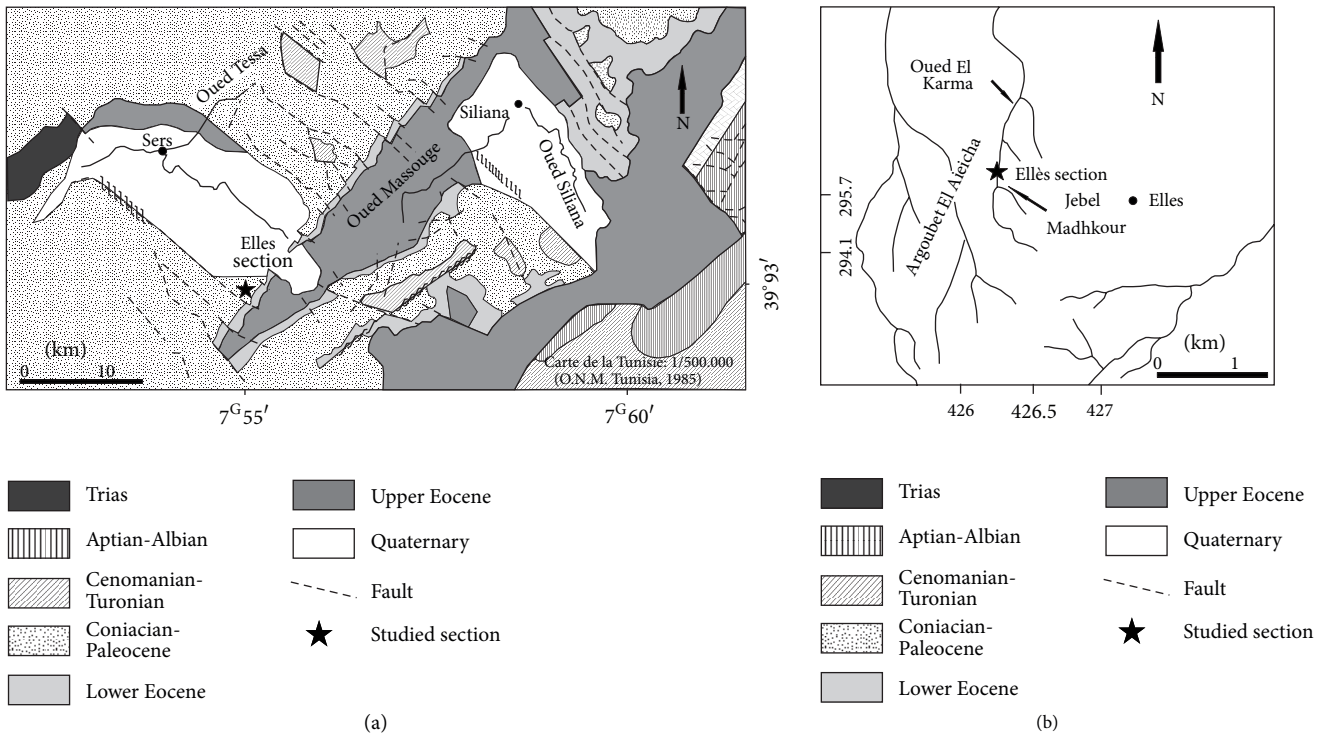

Figure 3: Geographical and geological location of the Ellès section (Tunisia). (a) Geological setting of the studied section, (b) geographical location of Ellès area.

by the lower and middle Eocene Bou Dabbous/El Garia Formation (attributed to the Metlaoui Formation in the original proposal).

In order to detail the Cretaceous-Paleogene (K-Pg) transition interval at the El Kef stratotype section, 41 samples are picked across 12.5 m thick interval deposition; 0.5 m of this interval are from the uppermost Maastrichtian (D-45 - D0-0,3) and 12 m from the lower Danian (D3-D1185). The samples D160, D180, D510, and D650 of lower Danian interval are very rich in corals, brachiopods, and bivalve of millimetric size [15].

The uppermost 0.5 m of the Maastrichtian is characterized by white-gray marls with abundant jarosite; the lower Danian is characterized by 2-3 mm of rusty layer (D0-0,3) superposed by 0.5 m of black clay, which corresponds to the boundary clay [15, 27], 0.5 m of dark gray clay, 1 m of gray, and 10 m of white-gray clayey marls.

2.2. Ellès Section (Tunisia). This section is located in Central Tunisia, 75 km southeast of El Kef K/Pg GSSP, between Houch El Balti and the village of Ellès, and 3 km east of Ellès (Figure 2). Its geographical coordinates are latitude 35°56′ 40.4″ N and longitude 9°4′ 49.9″ E. The K/Pg transition is continuous and well exposed along the northwestern side of the Ellès syncline and is included into the El Haria Formation marls (Figure 3).

In 1978, Said-Benzarti described the Ellès section in her doctoral thesis, studied the upper Maastrichtian and Paleocene microfossils (planktic and benthic foraminifera and ostracods) and concluded that the K/Pg transition is continuous. Karoui-Yaakoub et al. [34] pointed out that the thin layer of the K/Pg boundary is rich in microscopic glassy spheres. In 1998 these authors confirmed, with the collaboration of Rocchia and Robin, that the rust-colored layer is rich in Ir and Ni-rich spinel crystals. In 1999, a high-resolution sampling was carried out by Karoui-Yaakoub in her doctoral thesis. The author detailed the K/Pg transitions and confirmed that the K/Pg transition at the Ellès section is continuous. The ostracods were studied by Said-Benzarti [35] and the nannofossils by Gardin [19].

The K/Pg planktic foraminifera were also studied by Arz et al. [36]. The section was also studied in detail by Zaghbib-Turki et al. [32, 37], recognizing the relevant event of the K/Pg boundary and proposing it as parastratotype. Furthermore, Karoui-Yaakoub et al. [38] revised this section and concluded that the K/Pg interval is complete and similar to the El Kef section. Another section (Ellès II), located at 100 m toward the south, was described by Keller et al. [39], who analysed the paleoecology of the K/Pg boundary mass extinction based on planktic foraminifera.

The planktic foraminifera at this section were studied in detail by Gallala [15]. To detail the planktic foraminiferal species ranges at Ellès section, 58 samples are picked across 16.5 m thick interval deposition. 1 m of this interval is from the uppermost Maastrichtian (EN-90-EN-2-0), and 15.5 m are from the Danian (EN5-EN1550).

The Maastrichtian deposits consist of gray shales and marly shales below the K/Pg boundary. This boundary is well marked by a 2-3 mm thick rusty red layer (EN0-0,2) which contains altered spherules, spinels, and anomalous

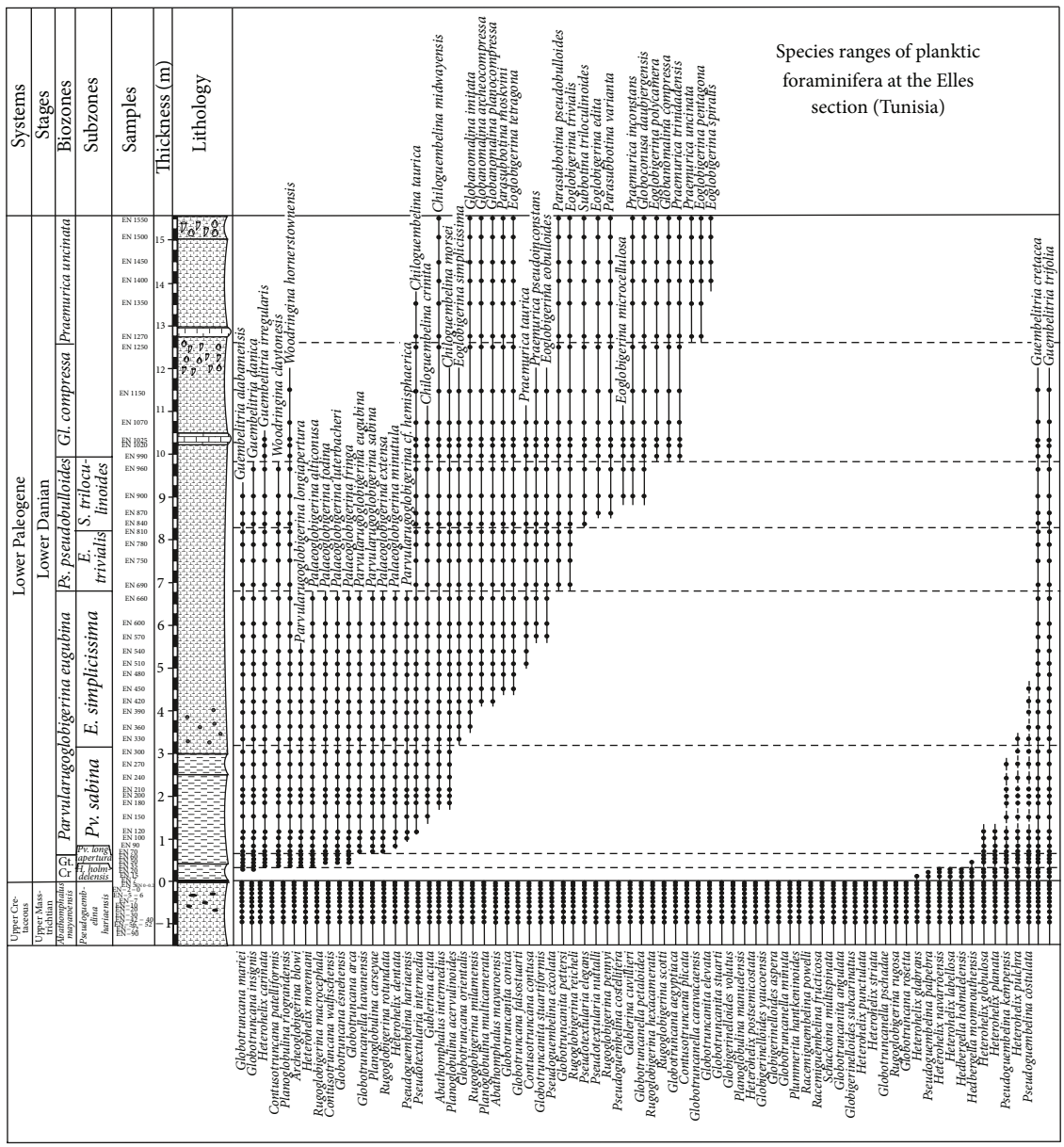

Figure 4: Species distributions of planktonic foraminifera in the Ellès section (Tunisia).

concentrations of iridium [32, 40]. Above this interval, the basal Danian consists of a 50–60 cm thick dark gray to black claystone layer followed by 2.5 m of light gray claystone and 12 m of dark to light gray marls intercalated in the upper part of the Danian interval by 20–30 cm thick of gray limestone. This upper part is rich in corals, brachiopods, and bivalves of millimetric size (samples EN1250 and EN 1550) [15] (Figure 4).

2.3. Agost and Caravaca Section (Spain). The Agost and Caravaca sections are located in the Betic Cordillera of southeastern Spain. The section of Agost is placed about 1 km northeastern of Agost village (Alicante region), at km 13 of the road Agost-Castalla. Its geographical coordinates are latitude 38°27′ N and longitude 0°38′ W. The Agost section is about 100 km to the east of the Caravaca section with a similar lithology (e.g., [9]).

The section of Caravaca is placed about 3 km southwestern of the town of Caravaca (Figure 5). The Caravaca section is located in South Spain (Murcia region), about 3 km south of the town of Caravaca in the Barranco del Gredero ravine (Figure 5). Its geographical coordinates are latitude 39°5′ 19″ N and longitude 1°52′ 26″ W.

The Caravaca section lies in the Betic Cordillera, Subbetic zone, and the K/Pg boundary is in the Jorquera Formation, composed of gray marls and claystone. In 1975, Abtahi initially studied the foraminifera in his master thesis. Smit [41, 42] found that the K/Pg boundary claystone was more

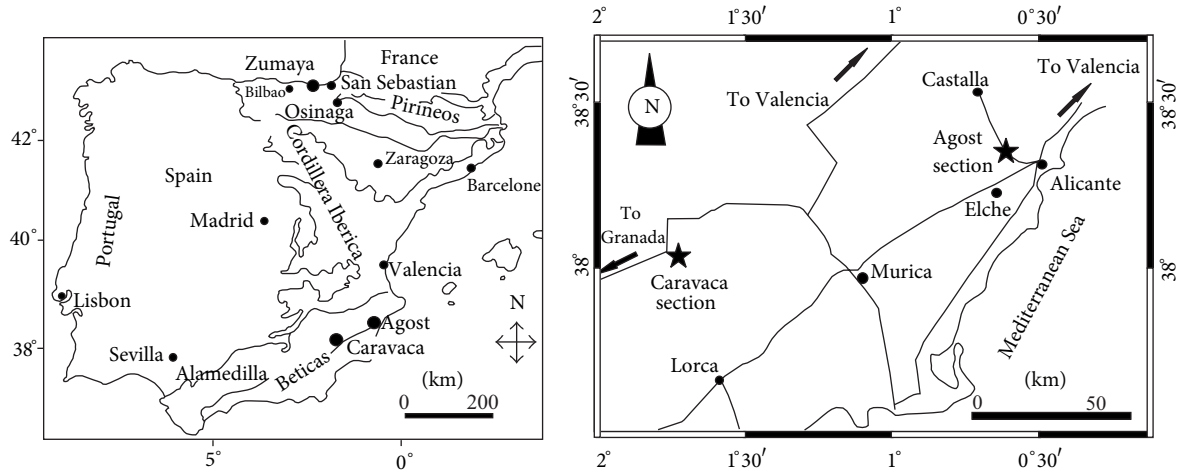

Figure 5: Geographical location of the Caravaca and Agost sections located in Betic Cordillera (Spain).

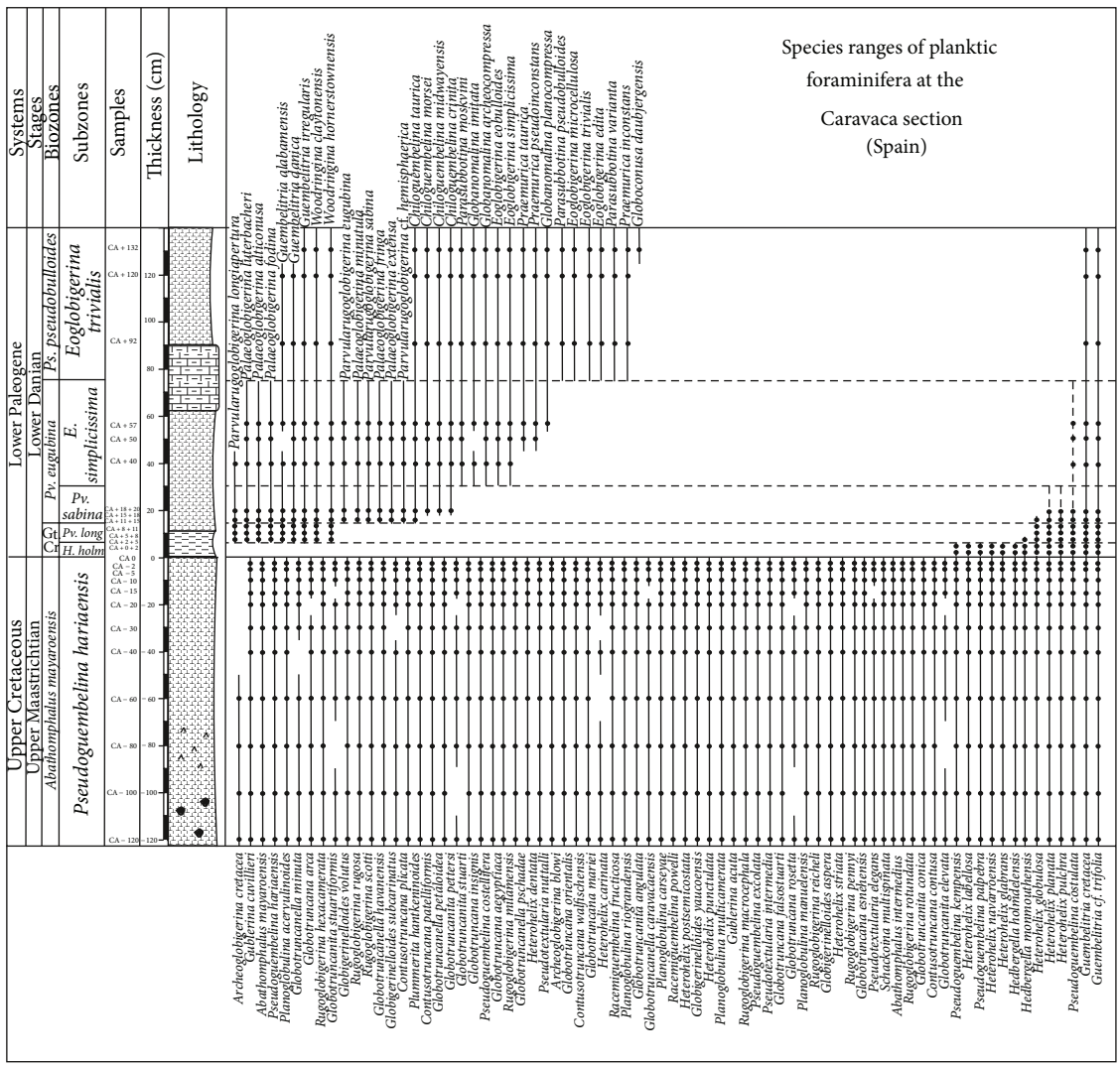

Figure 6: Species distributions of planktonic foraminifera in the Caravaca section (Spain).

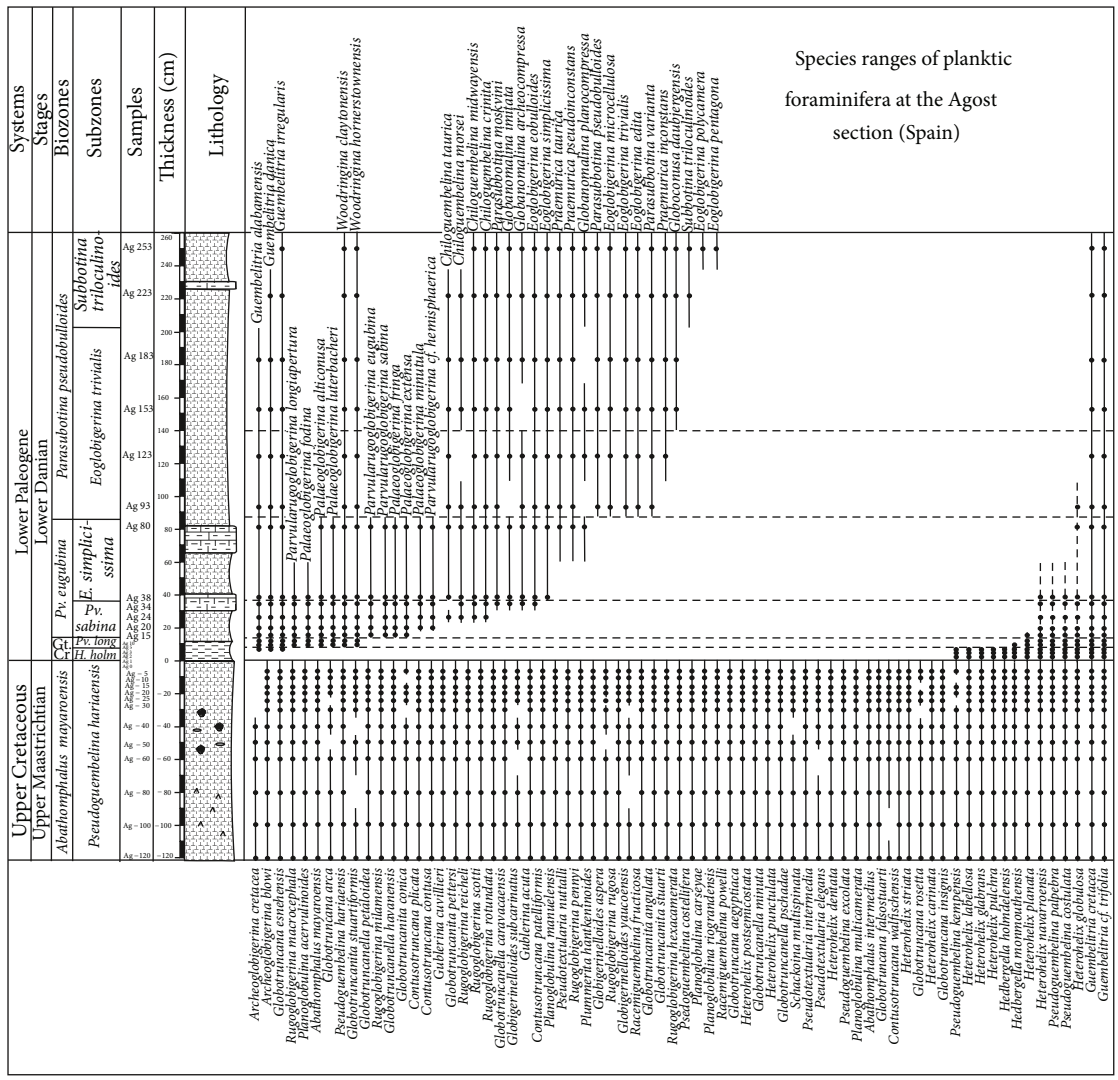

Figure 7: Species distributions of planktonic foraminifera in the Agost section (Spain).

expanded than in the Gubbio section (Italy) and discovered a planktic foraminiferal association between the *Abathomphalus mayaroensis* zone and the *Pv. eugubina* zone, which he called *Gt. cretacea* zone. Later, Smit and Hertogen [43] identified a 2-3 mm thick rusty red layer and the Ir anomaly. Their study was published one month before the seminal paper by Alvarez et al. [44], although they did not claim priority because the theory was previously communicated in a congress in 1979 by the Alvarez team. The red rusty layer also contains altered microtektites [45] as well as anomalous concentrations in Co, Cr, Ni, As, Sb, and Se [46]. Many other mineralogical and geochemical analyses were accomplished finding overwhelming meteoritic impact evidence [47–57].

The planktic foraminifera at this section were studied in detail by Canudo et al. [9], Kaiho and Lamolda [58], Arz et al. [31], and Gallala [15]. A geologically instantaneous extinction event in small benthic foraminifera was also documented at the K/Pg boundary by Coccioni et al. [59] and Coccioni and Galeotti [60] in the Caravaca section. A temporary faunal turnover, consisting of the reorganization of the benthic foraminiferal community structure, but with no mass extinction in the small benthic foraminifera, has been reported from this section [59, 61]. The calcareous nannoplankton was studied by Gardin and Monechi [18] concluding that Cretaceous species occurring after the K/Pg boundary are mainly reworked. Furthermore, bioturbation across the boundary clay has been reported by Rodríguez-Tovar and Uchman [62], which is the cause of the Cretaceous nannofossils and foraminifers reworked in the lowermost Paleogene.

The two Betic sections are similar, although the Caravaca sedimentation rate in the lower Danian is around twice that of Agost. The K/Pg boundary in both sections is marked by a thin 10 cm black clay layer with a basal 2 mm thin rust-red layer containing an Ir anomaly and other impact evidence, such as altered microtektites [7]. The sections of Agost and Caravaca have a similar lithology of gray marls and

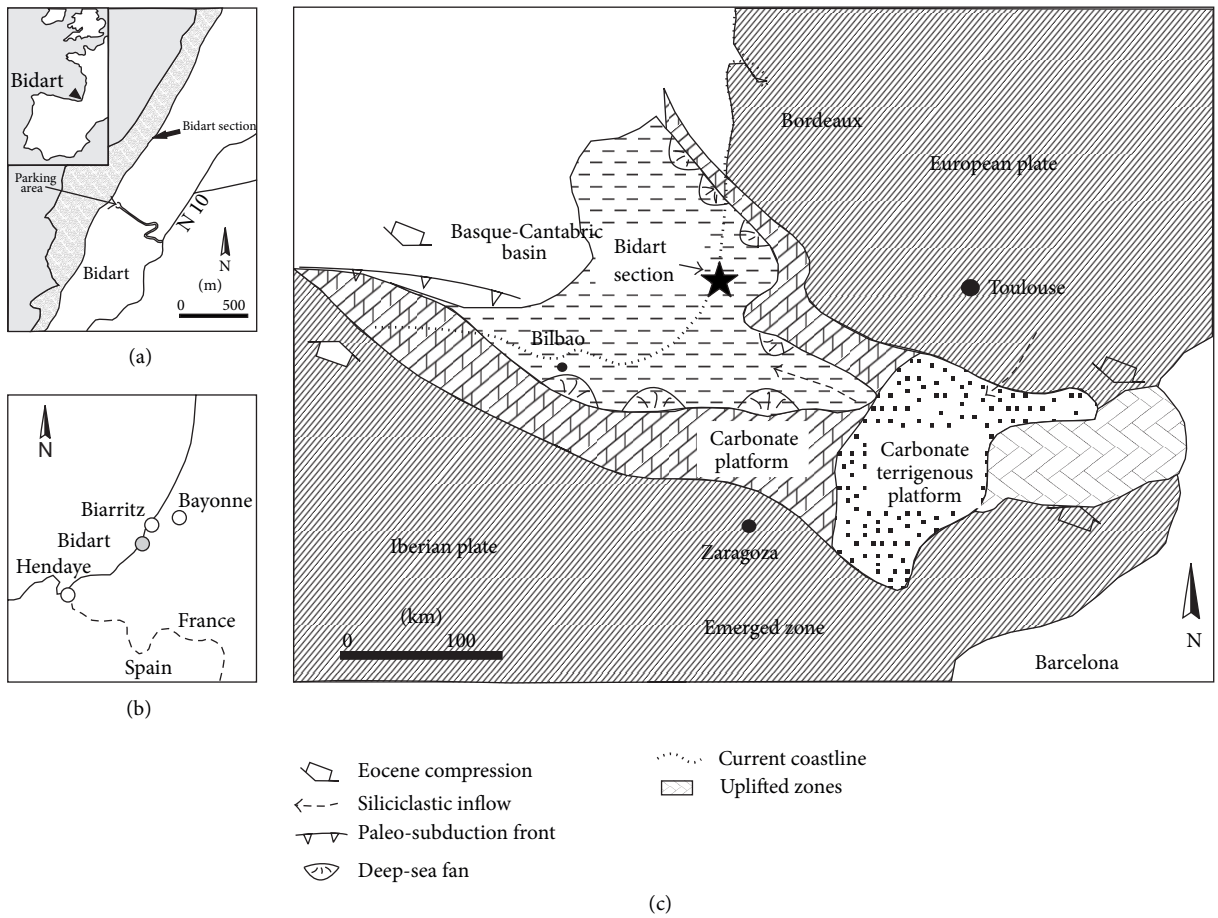

Figure 8: Geographical (a-b) and Paleogeographical setting (c) of the Bidart section located in the Pyrenean domain during the Paleocene (from [2]).

calcareous marls [9] and have been considered as some of the most continuous land-based K/Pg sections (e.g., [20]). The planktic foraminifera at this section were studied in detail by Gallala [15]; 25 samples are picked across 2.6 m thick interval deposition at Caravaca section (Spain). About 1.2 m of this interval corresponds to the uppermost Maastrichtian (CA-120-CA-2) containing abundant tracks of *Zoophycus* [15], the sample CA0 is picked at the K/Pg boundary corresponding to the rusty layer, and 1.4 m was sampled at the lower Danian interval (from the sample CA+0+2 to the sample CA+132) (Figure 6).

The Agost section was first described by Leclerc [63], who documented the planktonic foraminiferal faunas and argued that the sedimentation was essentially continuous from Santonian to Eocene. Since then, the Agost section has been studied by numerous authors (e.g., [10, 15, 64–67]) who analysed the biostratigraphy of planktonic foraminifera. Most of these authors are of the opinion that planktonic foraminifera underwent a catastrophic mass extinction at the K/Pg boundary [10, 66, 68], but some interpret the extinction as more gradual [9, 67]. The benthic foraminifera was studied by Pardo et al. [67], Alegret et al. [69], and Gallala [15].

The Maastrichtian deposits consist of pelagic gray massive marls with interbedded calcareous marls; the latter are rare or absent in the uppermost Maastrichtian. These marly deposits which contain abundant ostracodes and foraminifera belong to the upper part of the Quipar-Jorquera Formation, originally described by van Veen [70]. The Quipar-Jorquera Formation is Cenomanian to Eocene in age [71] and shows similar characteristics across the Inner Prebetic. The K/Pg boundary lies within Chron 29R [65] and is marked by a sharp contact between the Maastrichtian marls and a 10 cm thick layer of black claystone (Ag0-Ag10), with a 2-3 mm thick, red, ferruginous level at its base. This layer marks the K/Pg boundary at Agost [10]. Twenty-nine samples are picked, in this work, across 3.8 m thick interval deposition at Agost section (Spain). About 1.2 m of this interval was picked from the uppermost Maastrichtian (sample Ag120 to Ag5) containing zoophycus tracks [15], Ag0 from the rusty layer, and 2.6 m thick from the lower Danian (Ag1-Ag253) (Figure 7).

2.4. Bidart Section (France). The Bidart section is located in southwestern France, within the Basque-Pyrenean Basin between Hendaye and Biarritz villages, on the Bidart beach named Pavillon Royal or Caseville, where the upper Cretaceous-Eocene outcrops are well exposed on the beach of Bidart (Figure 8). This section is easily accessible by

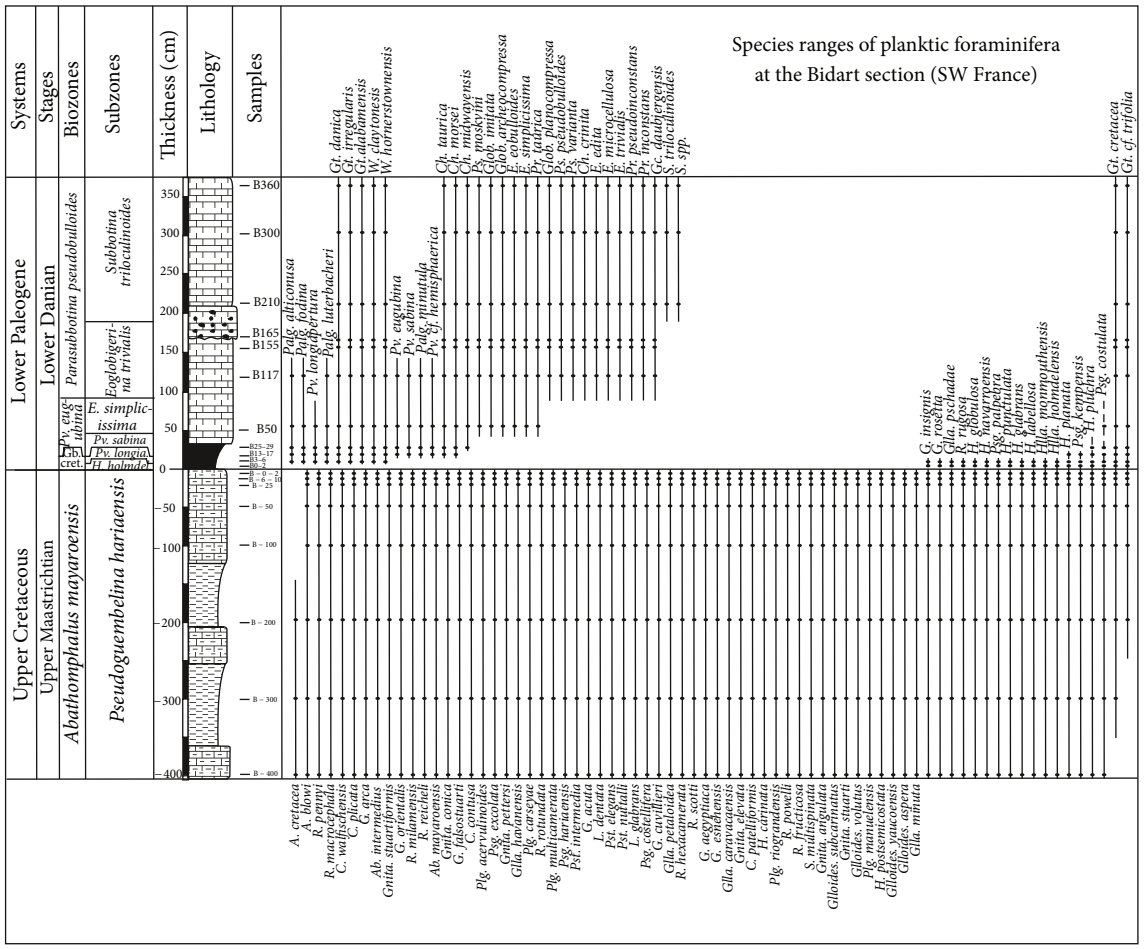

Figure 9: Species distributions of planktonic foraminifera in the Bidart section (France).

the national road n° 10, at about 2 km north of the Bidart village. Its geographical coordinates are latitude 43° 26′ 54″ N and longitude 1° 35′ 16″ W.

The Bidart section (located in southwestern France) together with the Zumaya section (northern Spain) is one of the most complete European K/Pg boundary sections exposed in the Atlantic margin [72, 73].

The well-exposed Cretaceous-Paleogene nearby the Bidart beach has interested many authors. The Bidart section was initially investigated by means of calcareous nannofossils by Martini [74] and by Lézaud in his doctoral thesis in 1967. It has been also studied by numerous authors from different points of view such as stable isotope analysis [75–77], Ir content [46, 78], biostratigraphy (e.g., [13–15, 78–80]), sedimentology [81], magnetostratigraphy [82, 83], geochemistry [76, 78, 84], and chronostratigraphy [83]. Detailed biostratigraphical studies across the K/Pg interval were based on calcareous nannofossils (e.g., [72, 85, 86]), confirming the continuous deposition record at the Bidart section, and on planktic foraminifera [13–15, 73, 87, 88]. Its macrofaunal content (ammonites and inoceramids) was studied by Ward [89] and Ward and Kennedy [90]. Benthic foraminiferal assemblages across the K/Pg boundary indicate deposition in the upper-middle part of the slope and reflect mesotrophic conditions during the late Maastrichtian and a strong decrease in the food supply to the sea floor coincident with the K/Pg boundary [15, 22].

The uppermost Maastrichtian deposits at the Bidart section consist of metric thick marls and clayey limestones alternations containing abundant foraminifers and scarce echinoids. The uppermost 2 cm Maastrichtian deposits are gray soft marls. The K/Pg boundary is marked by a 2 mm thick rusty layer. The lowermost Danian deposits which contrast with those of the Maastrichtian consist of 6 cm dark clays. The overlying rocks consist of brownish claystone, thin laminated dark gray marls, and pink and white limestones. Into these limestones, a mass flow deposits with a clear erosive basal surface and breccia occur between 1.6 m and 2.10 m above the K/Pg boundary rust layer.

Below and above the K/Pg boundary layer, the marls contrast sharply. Those of the uppermost Maastrichtian are light gray marls, and those of the lowermost Danian (6 cm thick) are dark clays. The K/Pg boundary layer corresponds to a 2 mm thick of rust deposits with a positive Ir anomaly [46, 78, 84] and Ni-spinel enrichment [40]. This rust layer is overlain by 6 cm of brownish claystone which marks

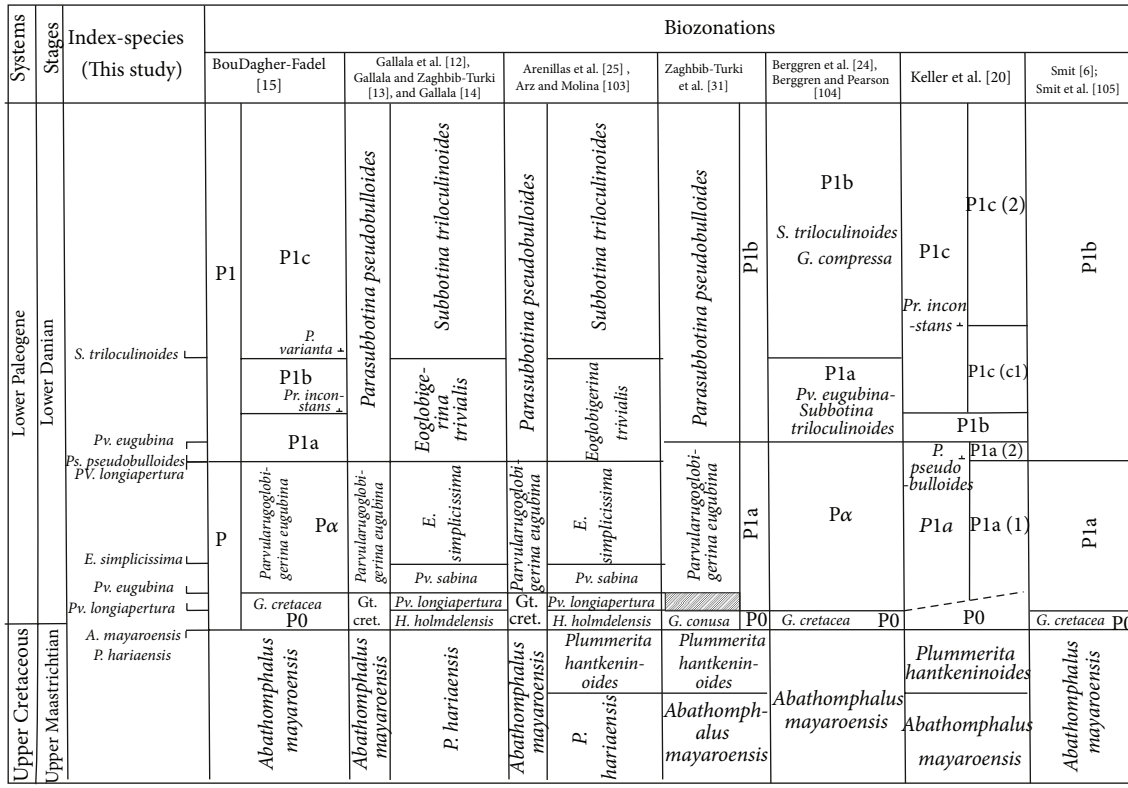

Figure 10: Correlation between the proposed uppermost Maastrichtian and lowermost Danian planktic foraminiferal biozonations.

the boundary layer, then and towards the top, by thinly laminated dark gray claystone. Consequently, across the lowermost Danian, the clays dominate over the carbonates.

For this study, we collected 19 samples in an interval including 4 m of the uppermost Maastrichtian below the K/Pg boundary (samples B 400 cm to B 0-2 cm) and 3.60 m of the lowermost Danian overlying the K/Pg rusty layer (samples B 0-2 cm to B 360 cm).

All the samples picked in the Tethyan and Atlantic sections in this work are irregularly spaced, being a detailed sampling of the upper Maastrichtian and lower Danian and a high resolution sampling across the K/Pg boundary. Close to the K/Pg boundary in the uppermost Maastrichtian-lowermost Danian 50 cm thick interval, the samples are spaced at 2–10 cm intervals, although below and above, the samples are less close and are mostly spaced at 10–50 cm intervals. The preservation of the planktic foraminifers of the studied sections is generally good. All the soft clayey or marly samples were disaggregated in water with diluted H_2O_2, and those of limestone were soaked in acetic acid diluted solution (80%) for 6 hours and then washed through a 63 μm sieve. All the samples were dried in an oven at 50°C. The specimens of the planktic foraminifers identified are equal to 63 μm or larger than this size fraction (Figure 9).

3. Biostratigraphy

At the Tethyan (El Kef stratotype and Ellès in Tunisia and Agost and Caravaca in Spain) and Atlantic sections (Bidart in France), the planktonic foraminifers are often well preserved, very abundant, and diversified. All the biozones and subzones are easily recognized by their biomarkers (Figure 10). Across the K-Pg transition, four standard biozones are recognized. Using high-resolution sampling, these zones are detailed and subdivided in subzones.

3.1. Abathomphalus mayaroensis Zone. As defined by Bolli [5], this biozone corresponds to the taxon range interval of the nominate species. It has been recognized by many authors in the Tethyan area and elsewhere [7, 9, 10, 13–15, 17, 29, 31, 91–98].

This biomarker remains omnipresent up to the top of the Maastrichtian. Moreover, no apparent hiatus exists at the El Kef section (Tunisia), Agost and Caravaca sections (Spain). We have identified the *Plummerita hantkeninoides* subzone which is the most common and persistent species across the uppermost Maastrichtian. This species is absent at middle latitudes: Bidart section (SW France) and Zumaya section (Spain) [13–15, 36, 68]. Previously, several authors used this small-sized species (<150 μm) as the biomarker of the latest Maastrichtian nominate zone [9, 21]. Nevertheless, Keller [99] working on the high-latitude K-Pg transition deposits (sites 738C, 752B, and 690C) noted the absence of *Plummerita hantkeninoides*. Consequently, if this species was considered absent at the middle- and high-latitude areas, it would be restricted to low latitudes [13–15].

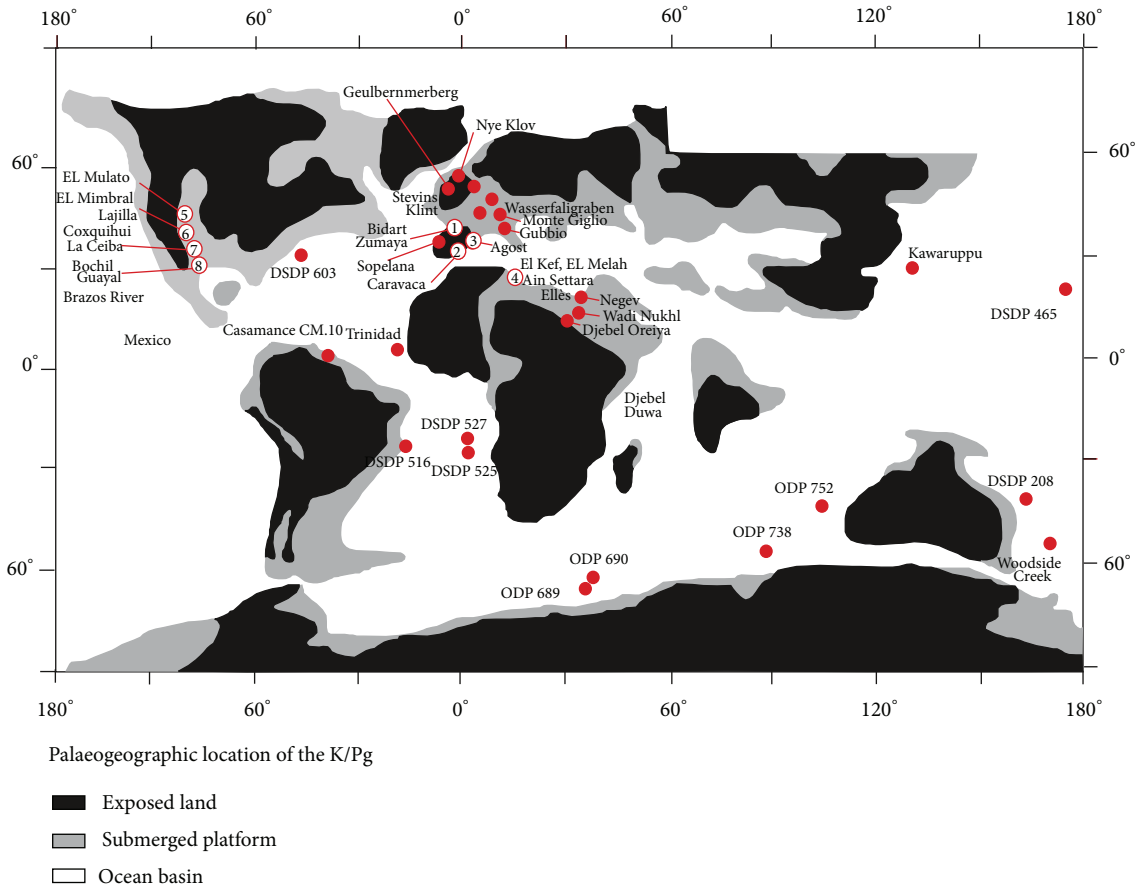

Figure 11: Paleolatitudinal and paleogeographic location of the correlated sections: the El Kef GSSP (Tunisia) and the auxiliary sections, Ellès (Tunisia), Agost, and Caravaca (Spain) located at the Tethys Ocean, and Bidart (SW France) and Zumaya (Spain) located at the Atlantic Ocean (after [3]).

3.2. Guembelitria cretacea Zone. This zone was initially defined by Smit [7, 41]. It spans the biostratigraphic interval characterized by the partial range of the nominate taxon, between the last appearance datum (LAD) of Cretaceous taxa (*Abathomphalus, Globotruncana, Gansserina, Pseudoguembelina,* among others) at the K/Pg boundary as delineated by the essentially global iridium spike and the first appearance datum (FAD) of *Parvularugoglobigerina eugubina*. In this paper, following Arenillas et al. [26, 100], we take in account that *Parvularugoglobigerina longiapertura* and *Parvularugoglobigerina eugubina* are two valid species occurring shift FAD. Its magnetostratigraphy position is in Chron C29r, and its duration is between 65.000 and 64.981 Ma (after [12, 25]: **A**) or between 65.500 and 65.478 Ma (after Röhl et al., 2001 [101]: **B**). At the stratotype K/Pg boundary section and GSSP point El Kef section, Ellès section as well as at Caravaca and Agost sections, and Bidart section, the *Parvularugoglobigerina longiapertura* FAD is prior to the *Parvularugoglobigerina eugubina* FAD [10, 26]. We subdivide the *Gt. cretacea* zone into two subzones: (1) *Hedbergella holmdelensis* subzone, characterising the interval between the K/Pg boundary and the FAD of *Parvularugoglobigerina longiapertura*; (2) *Parvularugoglobigerina longiapertura* subzone, corresponding to the interval between the FAD of *Parvularugoglobigerina longiapertura* and the FAD of *Parvularugoglobigerina eugubina.*

3.3. Parvularugoglobigerina eugubina Zone. This zone was defined by Luterbacher and Premoli Silva [4] and identified as the *Globigerina eugubina* (=*Parvularugoglobigerina eugubina* in this paper) zone. It corresponds to the biostratigraphical interval characterized by the total range of the nominate taxon. It corresponds to the later part of Chron C29r. Its estimate age is between 64.981 and 64.945 Ma (**A**) or between 65.478 and 65.436 Ma (**B**).

We subdivide the *Pv. eugubina* subzone into two subzones which are, respectively, the *Palaeoglobigerina sabina* subzone and *Eoglobigerina simplicissima* subzone. The oldest one (i.e., *Parvularugoglobigerina sabina*), as defined previously [26], corresponds to the interval between the FAD of *Parvularugoglobigerina eugubina* and the FAD of *Eoglobigerina simplicissima*. In this paper, we emend the youngest one (i.e., *Eoglobigerina simplicissima*) which becomes corresponding to the interval between the FAD of the nominate taxon to the LAD of the *Pv. eugubina*.

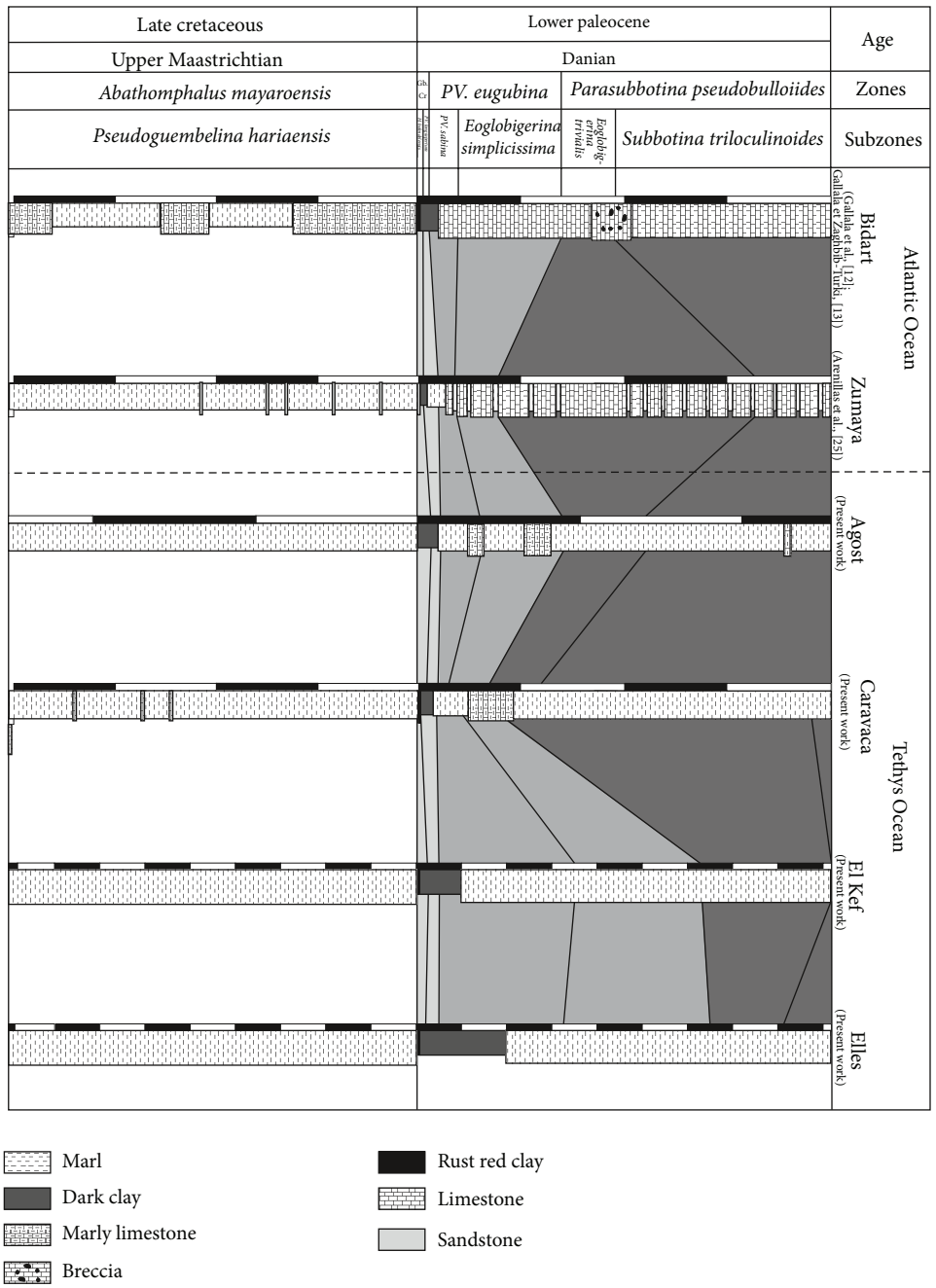

Figure 12: Correlation between complete Cretaceous-Paleogene transition interval low latitude sections: El Kef and Ellès (Tunisia), Caravaca and Agost (Spain) and the middle latitude sections: Bidart (France) and Zumaya (Spain).

3.4. Parasubbotina pseudobulloides Zone. Initially, Leonov and Alimarina [102] proposed *Globigerina pseudobulloides-G. daubjergensis* zone, and then Bolli [5] shortened this name. It corresponds to the interval between the LAD of *Pv. eugubina* and the FAD of *Globanomalina compressa*. It differs slightly from the *Parasubbotina pseudobulloides* proposed by Molina et al. [10] and adopted by Arenillas et al. [17, 26, 100] especially at its base as discussed above. We remind that at the El Kef section (Tunisia), Agost and Caravaca sections (Spain), the LAD of *Parvularugoglobigerina eugubina,* and the FAD of *Parasubbotina pseudobulloides* are simultaneous.

Following Arenillas et al. [26], we subdivide the *Parasubbotina pseudobulloides* zone into the *Eoglobigerina trivialis* and *Subbotina triloculinoides* subzones. The older subzone (*Eoglobigerina trivialis*) corresponds to the interval between the LAD of *Parvularugoglobigerina eugubina* and the FAD of *Subbotina triloculinoides*. The younger one (*Subbotina triloculinoides*) spans the interval between the FAD of *Subbotina triloculinoides* and the FAD of *Globanomalina compressa*.

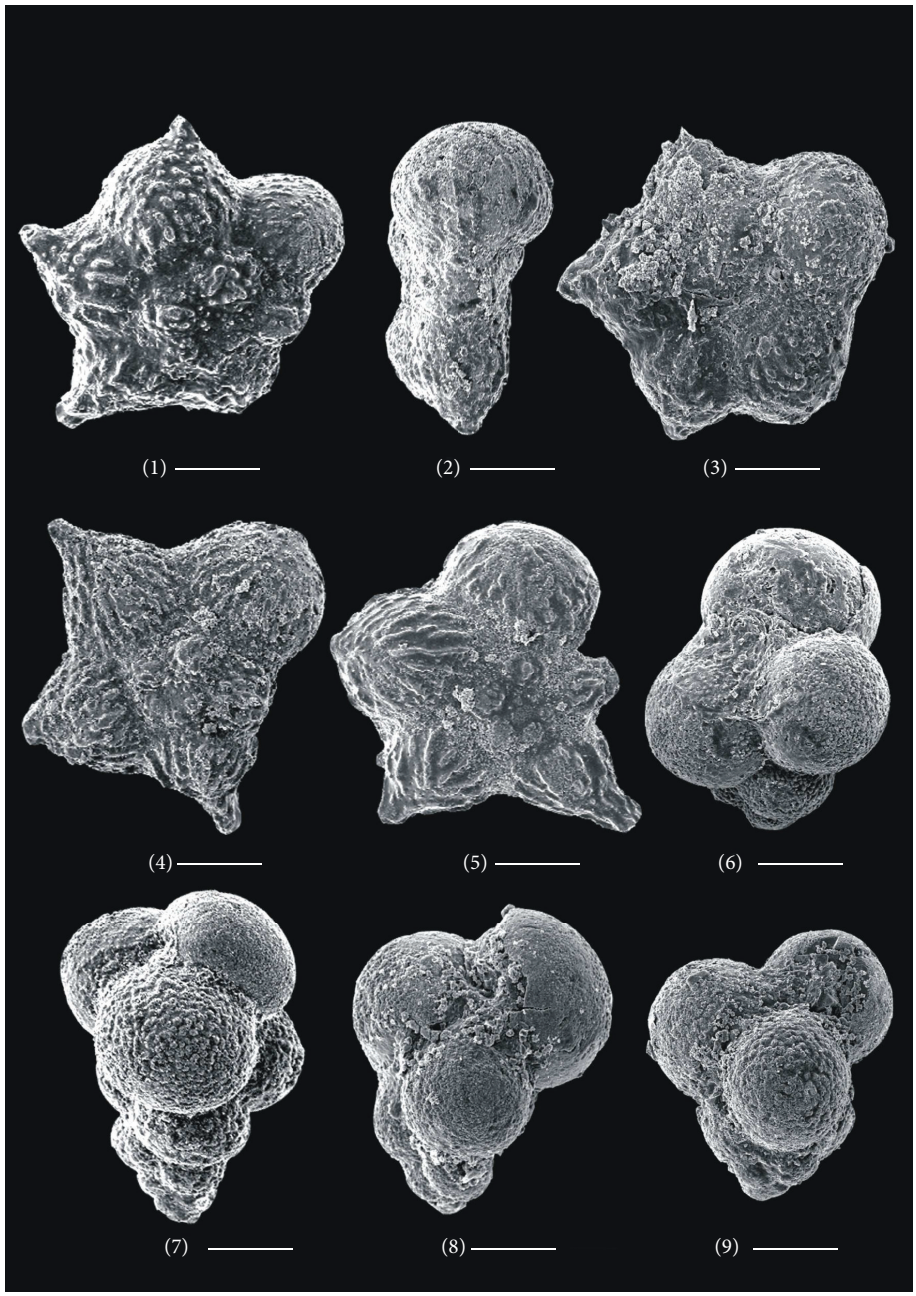

Figure 13: Scale bars = 100 μm. (1–5) *Plummerita hantkeninoides* (Brönnimann), Upper Maastrichtian. (6) *Globoconusa daubjergensis* (Brönnimann), Danian. (7) *Guembelitria irregularis* (Morozova), Danian. (8) *Guembelitria cretacea* (Cushman), Danian. (9) *Guembelitria trifolia* (Morozova), Danian.

4. Correlation

Based on high-resolution biostratigraphy analysis, the El Kef (K/Pg boundary stratotype section and GSSP point) and Ellès sections in Tunisia, the Agost and Caravaca sections (Betic Cordillera, Spain), and the Bidart section (France) have a complete stratigraphic record across the Cretaceous-Paleogene transition. These coeval sections may be compared with their neighbours in the Atlantic and Tethyan realms and may be considered auxiliary sections (Figure 11).

At the Tethys and Atlantic realms, all the biozones and subzones are easily recognized by their biomarkers (Figure 10). At the Tethyan realm, *Plummerita hantkeninoides*, commonly indicative of the uppermost Maastrichtian, is present, and it is associated to *Pseudoguembelina hariaensis*. However, *Plummerita hantkeninoides* is absent at the Bidart and Zumaya sections located in middle latitudes of the Atlantic realm. The Atlantic realm contains diverse planktonic foraminifers; among them is *Pseudoguembelina hariaensis* which had a larger paleogeographical distribution

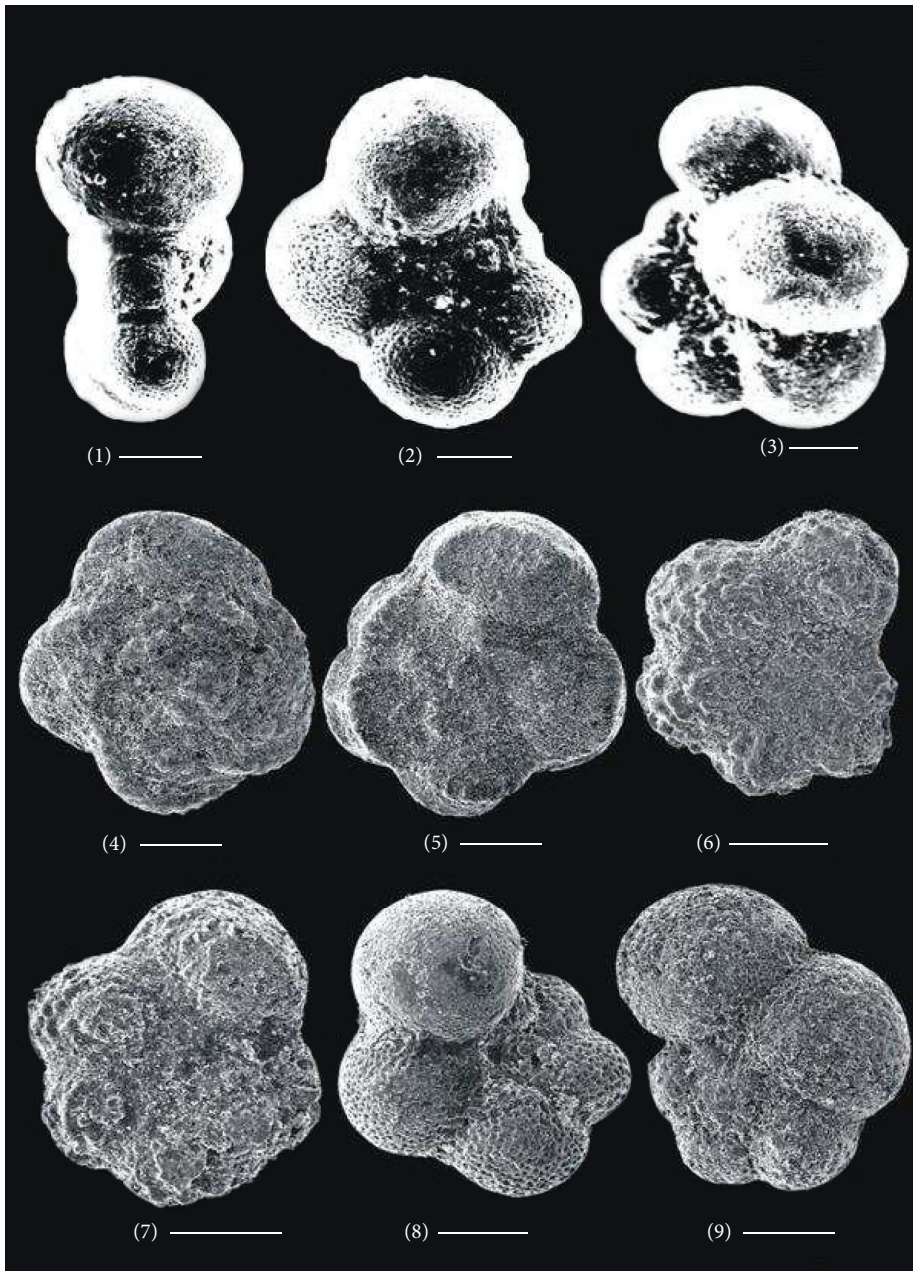

Figure 14: Scale bars = 100 μm. (1-2) *Parasubbotina pseudobulloides* (Plummer), Danian. (3) *Praemurica pseudoinconstans* (Subbotina), Danian. (4-5) *Abathomphalus mayaroensis* (Bolli), Upper Maastrichtian. (6-7) *Hedbergella holmdelensis* (Olsson), Danian. (8-9) *Parvularugoglobigerina sabina* [4], Danian.

being recorded both in the Tethys and the Atlantic paleoceans. It is more relevant to be considered as the marker species of the nominate uppermost Maastrichtian subzone instead of *Plummerita hantkeninoides* (Figure 13).

Consequently, we replaced *Plummerita hantkeninoides* by *Pseudoguembelina hariaensis* as index species. This is recorded both in the Tethys and Atlantic realm; it indicates the uppermost Maastrichtian subzone.

At El Kef section, the *Guembelitria cretacea* biozone spans 55 cm. It is more expanded than at Agost (12,5 cm), Caravaca (15 cm) relative to the Tethys realm, and Bidart (10 cm) [13–15], and Zumaya [26, 100], relative to Atlantic realm. It is nearly as expanded as at Ellès section in Tunisia (65 cm).

In spite of the reduced *Guembelitria cretacea* biozone expansion at El Kef K/Pg boundary stratotype and the auxiliary sections, Caravaca and Agost sections (Spain), like elsewhere (at the Bidart and Zumaya sections), and the Ellès section (Tunisia), the *Parvularugoglobigerina longiapertura* FAD is observed at the upper part of the relevant biozone (Figure 12).

Figure 15: Scale bars = 100 μm. (1-2): *Subbotina triloculinoides* (Plummer). Danian. (3-4): *Eoglobigerina trivialis* (Subbotina). Danian. (5-6): Eoglobigerina simplicissima (Blow). Danian. (7-8): *Praemurica inconstans* (Subbotina). Danian. (9): *Parasubbotina pseudobulloides* (Plummer). Danian.

At the El Kef section, the *Parvularugoglobigerina eugubina* zone spans 5.7 m. It is more expanded than at Caravaca and Agost sections (42 cm and 65 cm, resp.). It is also more expanded than at the Zumaya section (Spain) which spans 63 cm [26, 100] and the Bidart section (SW France), spanning 107 cm [13]. However, it is approximately equivalent to the Ellès section (5.8 m). This zone is subdivided into the *Parvularugoglobigerina sabina* (Figure 14) and *Eoglobigerina simplicissima* subzones (Figures 6 and 15). The deposition thickness of the zones and subzones at the El Kef stratotype section and Ellès section is more expanded than at the ones at Agost and Caravaca (Spain) and at Bidart (France). This would be related to a largest deposition ratio and/or to the sedimentary basin morphology.

In summary, El Kef section (K/Pg boundary stratotype section and GSSP point) and Ellès section in Tunisia, Agost and Caravaca sections (Betic Cordillera, Spain), relative to the Tethyan realm (low latitude), and Bidart section (France) relative to the Atlantic realm (middle latitude) are complete sections containing all the zones and subzones characterizing the upper Maastrichtian-lower Paleogene interval without any hiatus. The Ellès, Agost, and Caravaca sections may

be proposed as auxiliary sections of low latitude like the Bidart section for middle latitude.

5. Conclusion

A high-resolution biostratigraphic analysis carried out at El Kef (K/Pg boundary stratotype section and GSSP point) and Ellès sections in Tunisia, Agost and Caravaca sections (Betic Cordillera, Spain) in the Tethys realm (low latitude), and Bidart section in the Atlantic realm (middle latitude) confirms the completeness and continuity of the stratigraphic record across the K-Pg transition. All the planktic foraminiferal zones and subzones, characterizing the uppermost Maastrichtian-lower Danian interval, are well defined including the *Abathomphalus mayaroensis* zone (ended by *Pseudoguembelina hariaensis* subzone indicating the uppermost Maastrichtian), the *Guembelitria cretacea* zone (subdivided into *Hedbergella holmdelensis* and *Parvularugoglobigerina longiapertura* subzones), the *Parvularugoglobigerina eugubina* zone (subdivided into *Parvularugoglobigerina sabina* and *Eoglobigerina simplicissima* Subzones), and the *Ps. pseudobulloides* zone (subdivided into *Eoglobigerina trivialis* and *Subbotina triloculinoides* subzones) for the lower Danian. These zones and subzones are easily recognized by their well preserved biomarkers.

The *Gt. cretacea* zone in the Bidart section is less expanded than at El Kef and Ellès, but nearly equal to the equivalent zone in the Zumaya, Agost, and Caravaca sections in Spain. Despite its reduced thickness, it is relatively complete, as suggested by the FAD of *Pv. longiapertura* in its upper part, similarly as in the El Kef K/Pg boundary stratotype section and other auxiliary sections. The *Pv. eugubina* zone is 107 cm thick. Although it is thinner than in El Kef (5.7 m) and Ellès (5.8 m), it is thicker than in the Caravaca and Agost sections (42 cm and 65 cm, resp.). The *E. trivialis* subzone of the *Ps. Pseudobulloides* zone is less expanded than in the Agost, Caravaca, El Kef, or Ellès sections. In the Bidart section, only the lower part of the *S. triloculinoides* subzone was studied herein, still below the FAD of *Gl. compressa*. The deposition thicknesses of the zones and subzones at the El Kef and Ellès sections are more expanded than at the Agost and Caravaca sections (Spain) and the Bidart section (France). This could be related to the higher deposition rates and/or to the sedimentary basin morphology.

In summary, these sections (Agost, Caravaca, Bidart, and Ellès) possess a complete uppermost Maastrichtian–earliest Paleogene record, as documented by planktic foraminifers in this work. Although they are much less expanded than the El Kef stratotype section, they may be very useful auxiliary sections of the boundary interval for the Tethyan and the Atlantic realms.

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