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Re-Evaluation of the Ionian Basin Evolution during the Late Cretaceous to Eocene (Aetoloakarnania Area, Western Greece)

Elena Zoumpouli [1,*], Angelos G. Maravelis [2], George Iliopoulos [3], Chrysanthos Botziolis [1], Vasiliki Zygouri [4] and Avraam Zelilidis [1]

[1] Laboratory of Sedimentology, Department of Geology, University of Patras, 26504 Patras, Greece; cbotziolis@upnet.gr (C.B.); a.zelilidis@upatras.gr (A.Z.)
[2] Department of Geology, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; angmar@geo.auth.gr
[3] Laboratory of Palaeontology and Stratigraphy, Department of Geology, University of Patras, 26504 Patras, Greece; iliopoulosg@upatras.gr
[4] Laboratory of Structural Geology, Department of Geology, University of Patras, 26504 Patras, Greece; zygouri@upatras.gr
* Correspondence: zoumpouel@gmail.com

Abstract: Field investigation, Microfacies analysis, and biostratigraphy have been carried out in the central parts of the Ionian Basin (Aetoloakarnania area, Western Greece) in order to decipher the depositional environments that developed during the accumulation of the Upper Cretaceous to Eocene carbonate succession. Three different Standard Microfacies types (SMF) have been observed, corresponding to two different depositional environments (Facies Zones or FZ) of a platform progradation. The three SMF types which occur in the study area during the Upper Cretaceous to Eocene are: 1. SMF 3 that includes mudstone/wackestone with planktic foraminifera and radiolaria, corresponding to toe-of-slope (FZ: 3), 2. SMF 4, which can be classified as polymict clast-supported microbreccia, indicating a toe-of-slope-slope environment (FZ: 4) and 3. SMF 5 which is characterized by allochthonous bioclastic breccia and components deriving from adjacent platforms and which reflects a slope environment. Microfacies analysis provided evidence of a change in the origin of sedimentary components and biota showing the transition from toe-of-slope to slope, as well as a change in organism distribution.

Keywords: microfacies; Ionian basin; Upper Cretaceous; Eocene; Aetoloakarnania area

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1. Introduction

The Ionian zone has been the focus of numerous studies for a long time now—most dealing with its biostratigraphy and lithostratigraphy—providing an abundance of information on the palaeogeographical evolution of the Ionian basin [1–4]. The Ionian zone was first described by Philippson in 1890 [5]; however, the main stratigraphy and its geotectonic position were presented by Renz in 1955 [6]. The main Ionian zone, in general, has been studied by Aubouin [7], IGRS-IFP [8], Bornovas [9], Bernoulli and Renz [10], BP [11], Karakitsios and Tsaila Monopolis [12], Karakitsios et al. [13], Skourtsis-Coroneou et al. [14] and Zelilidis et al. [3,15]. Nevertheless, only a few studies have dealt with microfacies analysis combined with the overall architecture of the depositional system of the Ionian basin [16–19]. Specifically, according to Karakitsios [2,20] and Zelilidis et al. [3] the depositional system of the Ionian basin was subdivided into three successions: the pre-rift succession, consisting of lower to middle Triassic evaporites and Upper Triassic to Lower Jurassic limestones, the syn-rift succession, consisting of Lower to uppermost Jurassic deposits and the post rift succession, consisting of Cretaceous to Eocene deposits, and which was further subdivided into two sub-stages, the Lower

Cretaceous and the Upper Cretaceous to the lower Eocene sub-stage, respectively. However, according to Bourli et al. [16], due to the regional tectonic activity, the syn-rift and post-rift stages should be considered as parts of the same Jurassic to early Eocene syn-rift episode.

The studied section is located in south Aetoloakarnania, Western Greece. The succession is mainly composed of carbonate rocks of the Ionian zone, ranging in age from the Cretaceous to the Eocene [2,19–22]. The more than 400 m thick Kato Retsina-Kato Mousoura stratigraphic succession has been studied in order to describe both the sedimentological characteristics and fossil assemblages of these Upper Cretaceous-Eocene carbonate deposits through microfacies analysis. Microfacies criteria identify the depositional environments as well as the energy levels of the respective depositional environment, as they are reflected by sedimentary structures [23].

Microfacies analysis was based on the study of thin sections, and it provided an invaluable source of information on the depositional constraints and environmental controls of these carbonates, as well as on the properties of the respective rocks. Additionally, microfacies analysis assists in understanding the stratigraphic patterns of the respective sequence. These criteria are based on constituent analysis and on the distribution patterns of specific grain types, which are valuable tools in the reconstruction of palaeoenvironmental controls and depositional settings. Microfacies analysis allowed the recognition of three microfacies types and their depositional characteristics. Additionally, lithofacies combined with the study of microfossil assemblages (biofacies) are the key for the interpretation of the depositional environments that allowed distinguishing long-term as well as short-term environmental changes [23].

The scope of this paper is primarily to determine the depositional and palaeoenvironmental settings of the studied Upper Cretaceous-Eocene deposits and provide more data on the evolution model of the carbonate succession of the Ionian basin during this time interval through microfacies analysis. The new data will contribute to completing the picture of the evolution of the Late Cretaceous to Eocene sedimentary system of the Ionian basin, including a discussion of the palaeoenvironmental interpretation.

For this reason, a biostratigraphic subdivision has been considered based mainly on the recorded planktic foraminifera assemblages, to improve the environmental interpretation, and consequently define the palaeoenviromental evolution of the Late Cretaceous-Eocene carbonate sequence of the Ionian zone.

2. Geological Setting

The study area is located in south Aetoloakarnania, Western Greece, and belongs to the Ionian zone which is one of the external geotectonic zones of the Hellenides fold-and-thrust system, namely the pre-Apulian, Ionian, Gavrovo, Pindos and Parnassos zones, respectively (Figure 1) [3,4,20,24,25].

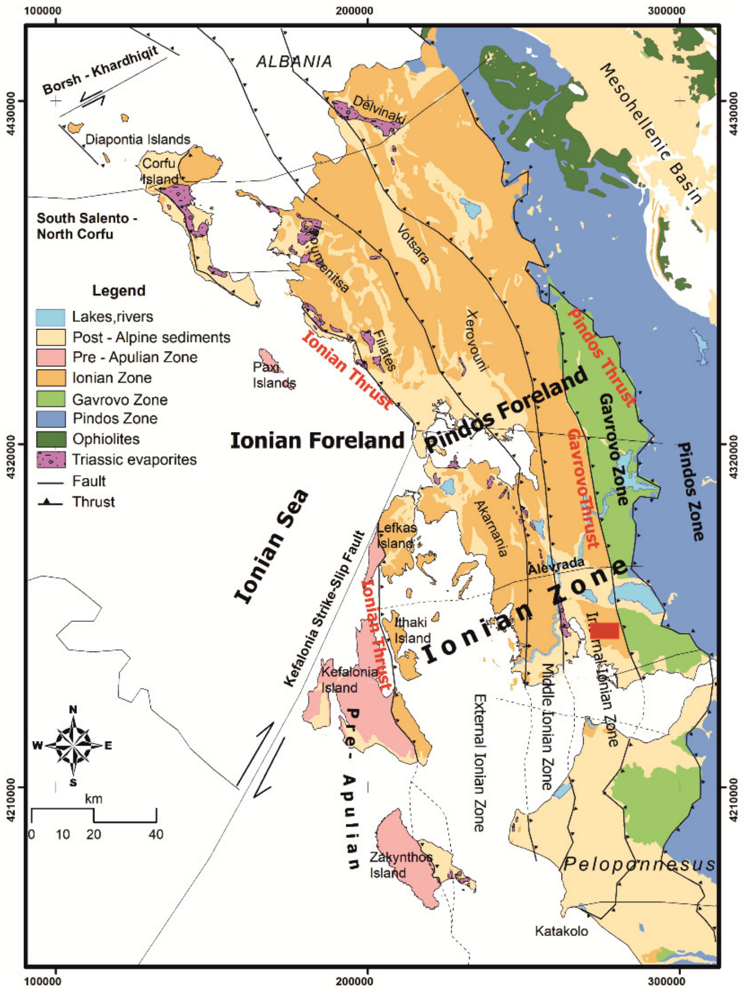

Figure 1. Geological map of the external Hellenides in NW Greece illustrating the principal tectonostratigraphic zones: Pindos, Gavrovo, Ionian, and Pre-Apulian Zones ([3,22]). Red square indicates the studied area at Aetoloakarnania, in the Ionian zone.

The Ionian zone extends from Albania to the north, dominating most of Epirus region and parts of the Ionian Islands, and continues southwards to Central Greece, the Peloponnese, Crete, and the Dodecanese Islands. According to Aubouin [7], the Ionian basin was subdivided into the internal, central, and external Ionian sub-basins (Figure 1) and consists of sedimentary rocks ranging from Triassic evaporites to Jurassic–upper Eocene carbonates and minor cherts and shales, overlain by Oligocene clastic submarine fan deposits [2,3,20] (Figure 2).

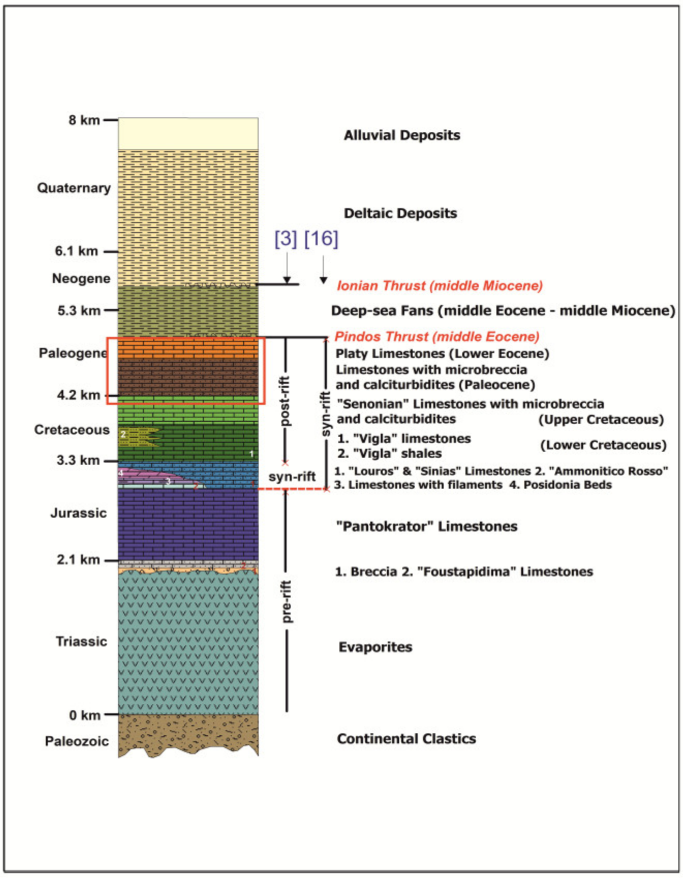

Figure 2. Synthetic lithostratigraphic column of the Ionian zone, NW Greece ([3,16,17]). Red square indicates the range of the studied stratigraphic column. A (Zelilidis et al. [3]) and B (Bourli et al. [16]) refer to the two works on which the starting point of the Ionian Thrust was based on.Specifically, the Ionian basin is part of the external Hellenides orogeny, bounded westwards by the Pre-Apulian platform and eastwards by the Gavrovo platform [2,3,26–29] (Figure 1). The Pre-Apulian zone to the west of the Ionian basin is regarded as the eastern margin of the Apulian platform, in Albania, Croatia and Italy [3,5,30,31]. The sedimentation of the Ionian basin, according to the new models of evolution, is sub-divided into two different stages [16,17]: (i) the pre-rift stage during the Triassic and Early Jurassic, and (ii) the syn-rift stage during the Middle Jurassic to early Eocene.

From the Early Triassic to the middle Early Jurassic, the Ionian basin was part of an extensive shallow marine platform, during the pre-rift stage, which evolved into a vast basin bounded on both sides by shallow platforms, the Apulia platform on the west as well as the Gavrovo platform on the east [19,32]. The oldest rocks of the zone are Triassic evaporites and carbonates [11] and, more specifically, the lower evaporite layers are of Early to Middle Triassic age [2,3,9,16,19,33] (Figure 2).

These rocks are exposed on the surface only in the highly tectonized zones, where they have been transformed into a brecciated evaporitic dissolution formation known as Triassic breccia and gypsum [33,34]. They are overlain by the "Foustapidima" (Ladinian to Rhaetian) limestones and above them the "Pantokrator" Limestones (Hettangian to Sinemurian) occur [6,8,11] (Figure 2). From the late Early Jurassic (Pliensbachian) begins the syn-rift process when the initial shallow platform was submitted to extension, which caused a structural differentiation (shredding) into small sub-basins and started a general deepening, resulting in the formation of a deep basin [2,3,19,20]. At the base, the syn-rift sequence consists of the upper Lower Jurassic (Pliensbachian) pelagic "Siniais" limestones Formation and their lateral equivalent, the hemipelagic "Louros" limestones

Formation which contain abundant ammonites, brachiopods, and foraminifera. These deposits are overlain by the Lower to Upper Jurassic (Toarcian to Tithonian) "Ammonitico Rosso", "Filamentous limestones" and "Posidonia shales" Formations (Figure 2). The thickness variations across the basin are due to the tectonic shredding, and so different basin depths are observed. The Upper "Posidonia shales" represent the deposition during the Callovian-Kimmeridgian interval [2,18,20].

On top of the latter depositional succession, Cretaceous to Eocene deposits are found. According to Karakitsios [2,20] and Zelilidis et al. [3], this period is characterized as the post-rift stage; whereas the new model proposed by Bourli et al. [16,19] includes this interval into the syn-rift stage as well. The sedimentary succession of this time interval is divided into two parts: The lower part is represented by the Berriasian to Turonian "Vigla limestones" Formation and the laterally equivalent "Vigla shales" Formation (Figure 2). Depositional conditions changed during the uppermost Cretaceous (late Santonian-Maastrichtian), when the basin was supplied with clastic material from the basin margins and the neighboring platform zones, forming "brecciated" or "clastic " limestone beds [2,7,19,29]. Specifically, during the Tithonian-Santonian, pelagic sedimentation occurred, forming the "Vigla limestones" Formation [7]. This Formation consists of thin-bedded pale limestones with nodules or lenses of chert alternating between chert and dark grey to green or red shale intercalations. The upper part of the sequence was deposited on top of the Lower Cretaceous "Vigla limestones" Formation, which is represented by the Upper Cretaceous "Senonian limestones" Formation (Coniacian to Maastrichtian) [2,3,16,18,19] (Figure 2).

Carbonate sedimentation prevailed during the Paleocene and Eocene (lower Eocene rocks comprise the "Platy Limestones" Formation) but changed during the upper Eocene to clastic submarine fans due to the change of the tectonic regime from extension to compression [4] (Figure 2). The transition from the carbonates to the clastic submarine fans is characterized by the presence of marly limestones and marls [14]. The clastic deposits accumulated during the upper Eocene to lower Miocene, as a response to the Pindos Thrust activity, the uplift of the Hellenides Orogen, and the development of a pro-foreland basin at the edge of the Apulian microcontinent [4,8,35–39] (Figure 3).

Within the Ionian Zone, the Upper Cretaceous-lower Eocene carbonates were deformed due to NNW-SSE directed thrust faults (Pindos thrust, Gavrovo thrust, internal Ionian thrust, middle Ionian thrust, and Ionian thrust) that developed in response to the compressional regime [3,16,19,20,22]. This regime is associated with the westward migration of the nappes and the external Hellenides Orogeny that has been active at least since the upper Eocene [38,39].

3. Material and Methods

The studied section is located in a well-exposed road-cut along the local road passing across the villages of Kato Retsina, Ano Mousoura, Kato Mousoura, and Kefalovryso (Figure 3). The geographic coordinates of the first and last sampled intervals are 38°27′26.40″ N, 21°24′49.18″ E and 38°27′30.82″ N, 21°22′23.09″ E, respectively.

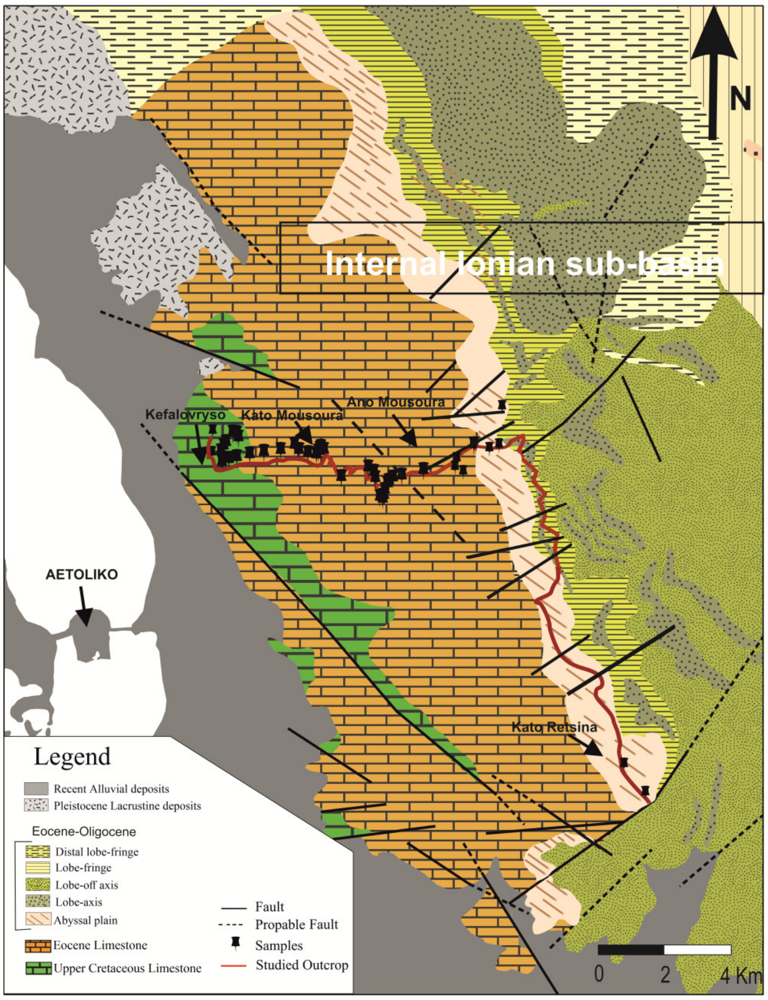

Figure 3. Geological map of the studied area (modified from [4]). Black pins indicate the position of the samples, and the red line indicates the road from Kato-Retsina to Kefalovryso.The present study is based on fieldwork involving the geological study and description of the carbonate rocks of the outcrop as well as the microfacies analysis of Maastrichtian to Eocene limestones. The collected sedimentological data included lithology, texture, sedimentary structures and microfossils content. The section includes a carbonate succession with an average statigraphic thickness of 400 m which was logged and sampled in order to document both the sedimentological characteristics and fossil assemblages. Seventy limestone samples have been collected, thin sectioned and studied under an OPTIKA B293 microscope. Carbonate Microfacies were distinguished according to Dunham's [40] classification modified by Embry & Klovan [41] and Flügel [23] which is also based on the methods of Wilson [42] and Flügel [23]. To determine the respective palaeoenvironmental conditions, the textural characters of Microfacies types (MF) were recorded, which include biogenic and inorganic dominant components, grain types, and fossil assemblages. This determination was based on the SMF types (standard Microfacies types) of the facies zones (FZ) of Wilson's [42] carbonate platform model consisting of twenty-four (24) standard Microfacies (SMF), corresponding to nine (9) standard facies zones (FZ), from open deep-sea basin environments to the slope, the edge of the platform, and the inner platform [24]. The environmental interpretation of carbonate Microfacies and biota follows the existing seminal carbonate-platform models [24]. Finally, mainly planktic foraminifera, when available, were used for the establishment of a biostratigraphic framework and which was mainly based on Boudagher-Fadel [43,44] and Young et al. [45].

4. Biostratigraphy

The biostratigraphic framework is based mainly on planktic foraminifera (Figure 4) and, in a few cases, on characteristic benthic foraminifera.

Maastrichtian (K1-K17 and KM17-KM26 samples, (supplementary material Table S1)): The planktic foraminifera indicating the Maastrichtian are represented by *Abathomphalus mayaroensis*, *Globotruncana bulloides*, *Globotruncana falsostuarti*, *Globotruncana arca*, *Globotruncana esnehensis*, *Globotruncana linneina*, *Globotruncanita pettersi*, *Globotruncana ventricosa*, *Globotruncanita stuarti*, *Euglobigerina* sp., *Globotruncana aegyptiaca*, *Rugoglobigerina* sp., *Globotruncana rosetta*, *Contusotruncana contusa* and *Contusotruncana fornicata* and the benthic foraminifera *Quiqueloculina* sp., *Orbitoides media*.

Paleocene: As the sampling of the studied section was not very dense, unfortunately we were unable to identify the foraminifera assemblage indicating the Danian stage. Hence, the planktic foraminifera indicating the Paleocene Epoch are represented by the following assemblages, respectively: Selandian (KM16-KM12 (supplementary material Table S1)): *Pseudomenardella ehrenbergi*, *Igorina pusilla*, *Miscellanea miscella*, *Morozovella conicotruncana Igorina albeari*, *Morozovella velascoensis Morozovella angulata. Subbotina triloculinoides*, *Parasubbotina varianta*, *Acarinina esnaensis* as well as the benthic foraminifera *Quiqueloculina* sp. and *Discocyclina* sp. Thanetian (KM15-KM7, M21-M17): *Morozovella occlusa*, *Morozovella aequa*, *Igorina albeari*, *Subbotina velascoensis*, *P. varianta*, *Morozovella angulata*, *Subbotina triangularis*, *A. esnaensis*, *Planorotalites pseudomenardi*, *Planorotlites chapmani*, *Morozovella velascoensis*, *Acarinina coalingensis*, *Igorina albeani* and *Acarinina strabocella* and the benthic foraminifera *Alveolina* sp. *Quinqueloculina* sp., *Discocyclina* sp. as well as *Nummulites* sp.

Eocene: The planktic foraminifera indicating the Eocene are represented by the following assemblages, respectively: Ypresian (KM5-KM3 (supplementary material Table S1)): *Acarinina pseudotopilensis*, *Turborotalia* sp. and *Pearsonites broedermanni* and the benthic foraminifera *Nummulites* sp. Ypresian—Lower Lutetian (M16-M12 supplementary Table S1): *Turborotalia frontosa*, *Morozovella* sp., *Acarinina bullbrooki*, *A. esnaensis*, *A. coalingensis*, *Subbotina inaequispira*, *Subbotina linaperta*, *Pseudoglobigerinella bolivariana*, and *Globalomalina planoconica* as well as the benthic foraminifera, *Discocyclina* sp. and *Nummulites* sp. Lutetian (M11-R2 supplementary Table S1): *S. linaperta*, *Subbotina yeguaensis*, *A. bullbrooki*, *P. bolivariana*, *T. frontosa*, *Morozovella lehneri*, *Globigerinatheka* sp., *Morozovella* sp., *A. esnaensis*, *Morozovella caucasica*, *M. lehneri*, *Morozovelloides crassatus*, *T. frontosa*, *Pseudohastigerina micra*, *Subbotina eocenica*, *Pseudohastigerina* sp., *Catapsydrax* cf. *dissimilis*, *Chiloguembelina* sp., *Acarinina collactea*, *Chiloguembelina* sp. and *Acarinina aspensis* as well as the benthic foraminifera *Discocyclina* sp., *Nummulites* sp. and *Orbitoides complanatus.* Lutetian–Bartonian (R1 (supplementary material Table S1)):): *Globigerinatheka* sp., *Morozovella* sp., *A. esnaensis P. micra*, *S. eocenica*, *Truncorotaloides* sp., *Turborotalia* sp., *P. micra*, *Morozovella spinulosa*, *M. lehneri*, *S. inaequispira*, *Planorotalites* sp., *C.* cf. *dissimilis*, *S. linaperta* and the benthic foraminifera *Discocyclina* sp., *Quinqueloculina* sp. and *Orbitoides complanatus.*

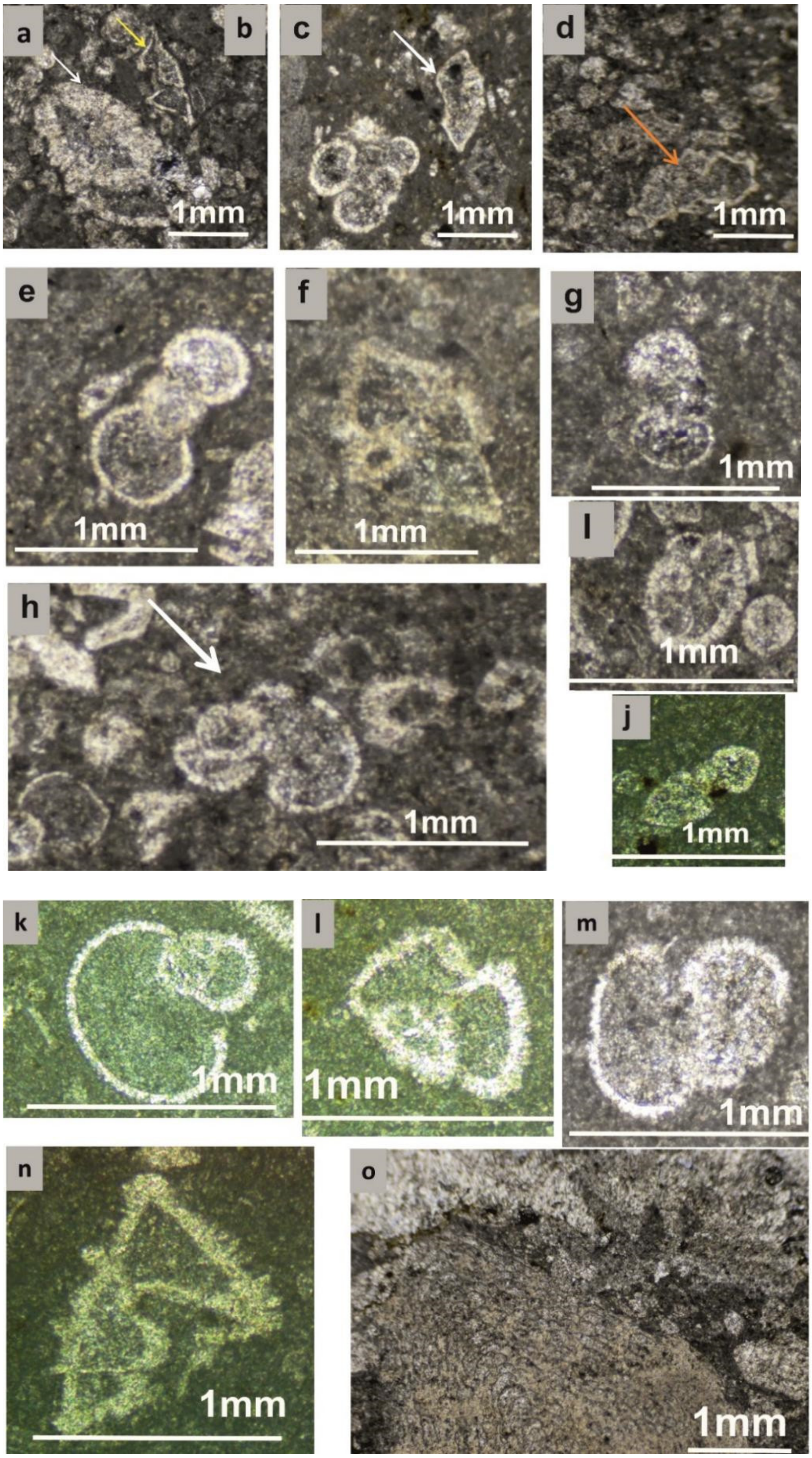

Figure 4. Representative foraminifera species identified from the studied succession. (**a**) *Miscellanea miscella* (white arrow) (**b**) *Morozovella conicotruncana* (Eocene) (yellow arrow), (**c**) *Globotruncana dupeublei*, (**d**) *Globotruncana arca*, (**e**) *Globigerinelloides* sp. (Maastrichtian), (**f**) *Morozovella formosa* (Eocene), (**g**) *Subbotina triangularis* (Paleocene), (**h**) *Turborotalia increbescens* (Eocene), (**i**) *Globigerinatheka* sp. (Eocene), (**j**) *Planorotalites chapmani* (Paleocene), (**k**) *Subbotina linaperta* (Eocene), (**l**) *Acarinina bullbrooki* (Eocene), (**m**) *Subbotina velascoensis* (Paleocene), (**n**) *Morozovella velascoensis* (Paleocene), (**o**) *Orbitoides media*.

5. Facies Analysis and Depositional Environments

Approximately 70 limestone samples were collected and a detailed microfacies analysis of the thin sections was conducted. A total of three Microfacies types (F) corresponding to three Standard Microfacies Types (SMF), could be distinguished, and these facies are generally attributed to two main facies zones/depositional environments (FZ), respectively. The detailed descriptive data are summarized in supplementary material Table S1.

5.1. Discription of the Studied Lithostratigraphic Units and Associated Microfacies Types

Based on biostratigraphy, field observation, and microfacies analysis the following stratigraphic successions have been observed:

The Upper Cretaceous (Maastrichtian) carbonate succession or “clastic limestones” [14], where according to field observations, consists of thick-bedded, white to white-yellow in color brecciated limestones with Rudist fragments and angular and boulder size clasts derived from underlying rocks-beds. Chert nodules have been occasionally observed as well (Figure 5).

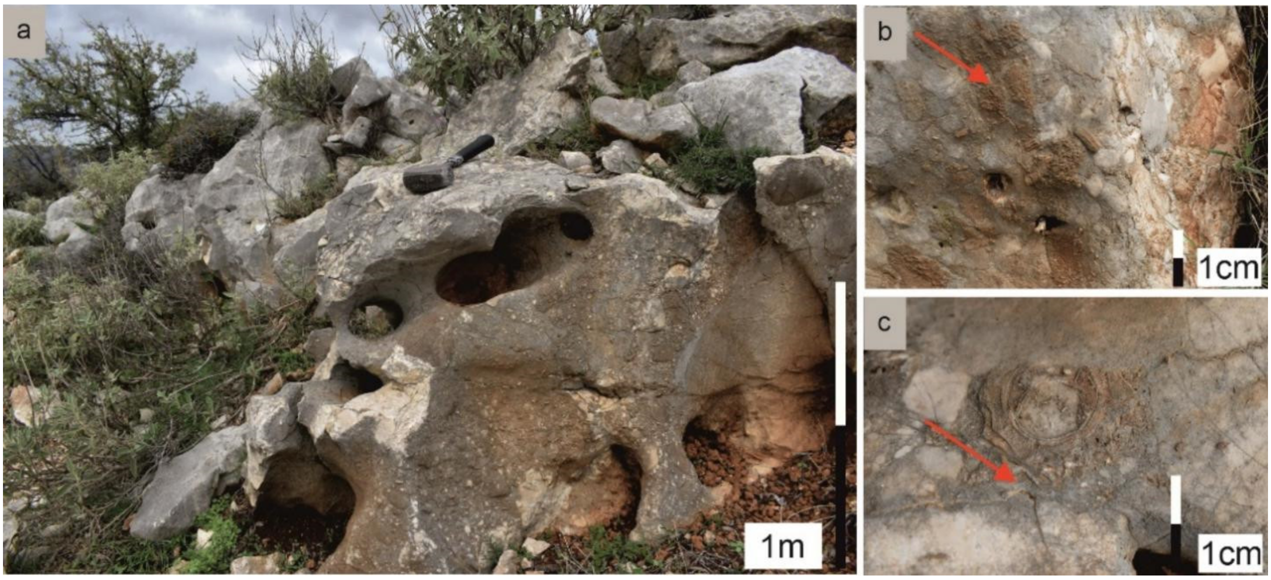

Figure 5. (**a**) General view of the Upper Cretaceous (Maastrichtian) brecciated limestones outcrop with Rudist fragments, (**b**,**c**) Rudist fragments (red arrow).

Microfacies analyses of this succession provided the following microfacies types (F):

F1 Allochthonous, bioclastic-lithoclastic packstone/floatstone microbreccia.

Description

F1 is characterized by densely packed whole fossils and fossil fragments with a high percentage of reef-derived organisms, such as Rudist fragments, algae and very few benthic foraminifera (Miliolidae). The main matrix consists of a wackestone-packstone with planktic foraminifera some of which are recrystallized (Figure 6). In addition, micritic clasts with algae (microproblematica debris), coated bioclastic grainstone clasts, grainstones with peloids and benthic foraminifera clasts as well as oolitic grainstone and pisoids have been also observed.

Interpretation

F1 corresponds to SMF 5 (standard microfacies type) *Allochthonous bioclastic grainstone, rudstone, packstone and floatstone or breccia* [24]. Characteristic criteria of this microfacies are the abundance of reef derived biota, the chaotic fabric and the packstone texture of the matrix indicating high energy depositional conditions.

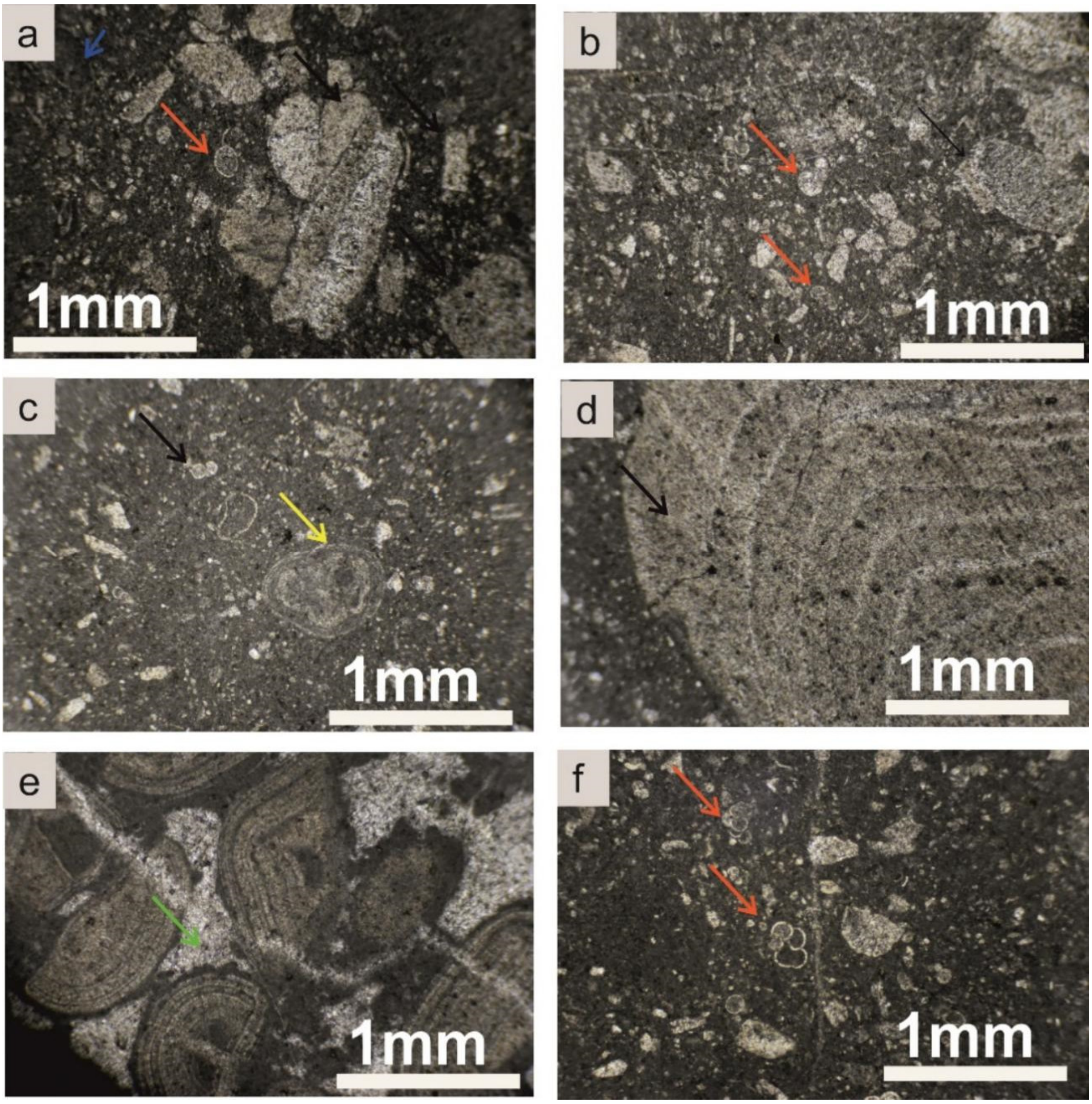

Figure 6. Representive photomicrographs of F1 microfacies type -: Allochthonous, bioclastic-lithoclastic packstone/floatstone microbreccia of Maastrichtian age. (**a**) planktic foraminifera (red arrow), micritic clast (purple arrow), bioclasts (black arrow), sample K17, (**b**) planktic foraminifera (red arrow), bioclasts (black arrow), sample K17, (**c**), bioclasts (recrystallized planktic foraminifera, black arrow), pisoids (yellow arrow), sample K1, (**d**) bioclasts (rudist? black arrow), sample K1, (**e**) ooids (green arrow), (**f**) planktic foraminifera (red arrow), sample KM17.

F2 Polymict clast-supported microbrecia

Description

In other cases, this succession is represented by polymict clast-supported microbreccia, a bioclastic and lithoclastic wackestone-packstone, consisting of grains of various origins. The main matrix is wackestone with recrystallized planktic foraminifera. The identified bioclasts include Mollusk fragments, Miliolidae, and recrystallized planktic foraminifera (Figure 7).

Interpretation

The F2 microfacies type corresponds to SMF 4, *Microbreccia*, *bioclastic-lithoclastic packstone or rudstone* [24]. This microfacies type is characterized by fine grained breccias, consisting of grains of either polymict origin or uniform composition, indicating a relatively high energy depositional environment.

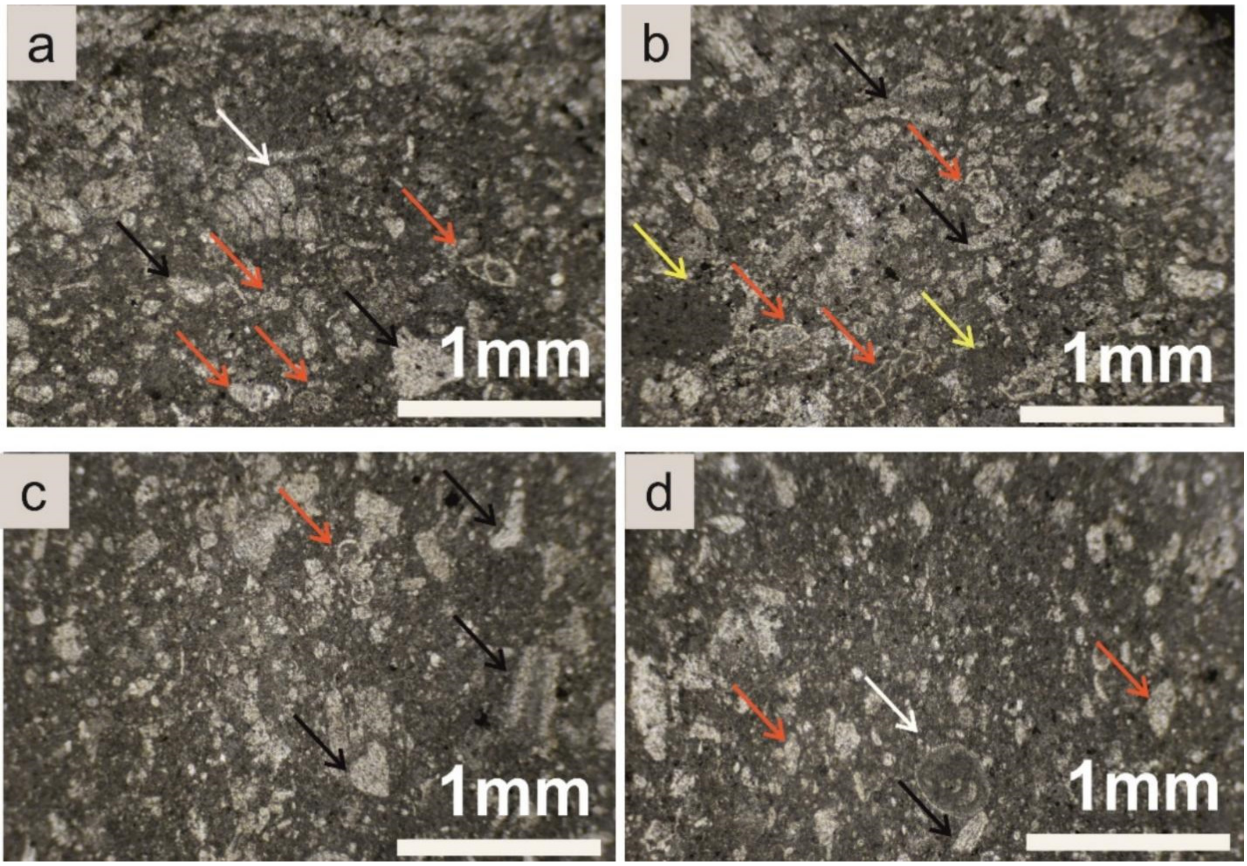

Figure 7. Microfacies typeF2: Polymict clast supported microbreccia of Maastrichtian age. (**a**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), benthic foraminifera (white arrow), sample K13, (**b**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), micritic clasts (yellow arrow), sample K13, (**c**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), sample K6, (**d**) recrystallized planktic foraminifera (red arrow), bioclasts' debris (black arrow), benthic foraminifera (white arrow), sample K2.

Additionally, the Upper Cretaceous (Maastrichtian) carbonate succession consists of micritic limestones of small thickness, where nodules and thin layers of chert locally occur (Figure 8).

Figure 8. (**a**) General view of the outcrop of the Maastrichtian micritic limestones where nodules and thin layers of chert (red arrow) locally occur, (**b**) chert Nodules (red arrow).

F3 Pelagic foraminifera mudstone/wackestone

Description

This part of the succession is classified as micritic to biomicritic limestones represented by F3 mudstone/wackestone with abundant radiolaria and planktic foraminifera such as Globotruncanidae. Many samples are characterized by very small bioclasts of planktic foraminifera and some of them are recrystallized. In addition, in some thin sections we observe microfractures or calcite veins, as well as a smooth lamination or bioturbation of planktic foraminifera. Finally, in some cases very few scattered benthic foraminifera have been observed (Figure 9).

Interpretation

This facies corresponds to SMF 3 [24], which is characterized by a micritic matrix with common to abundant pelagic microfossils, such as planktic foraminifera and radiolaria, showing low energy depositional conditions.

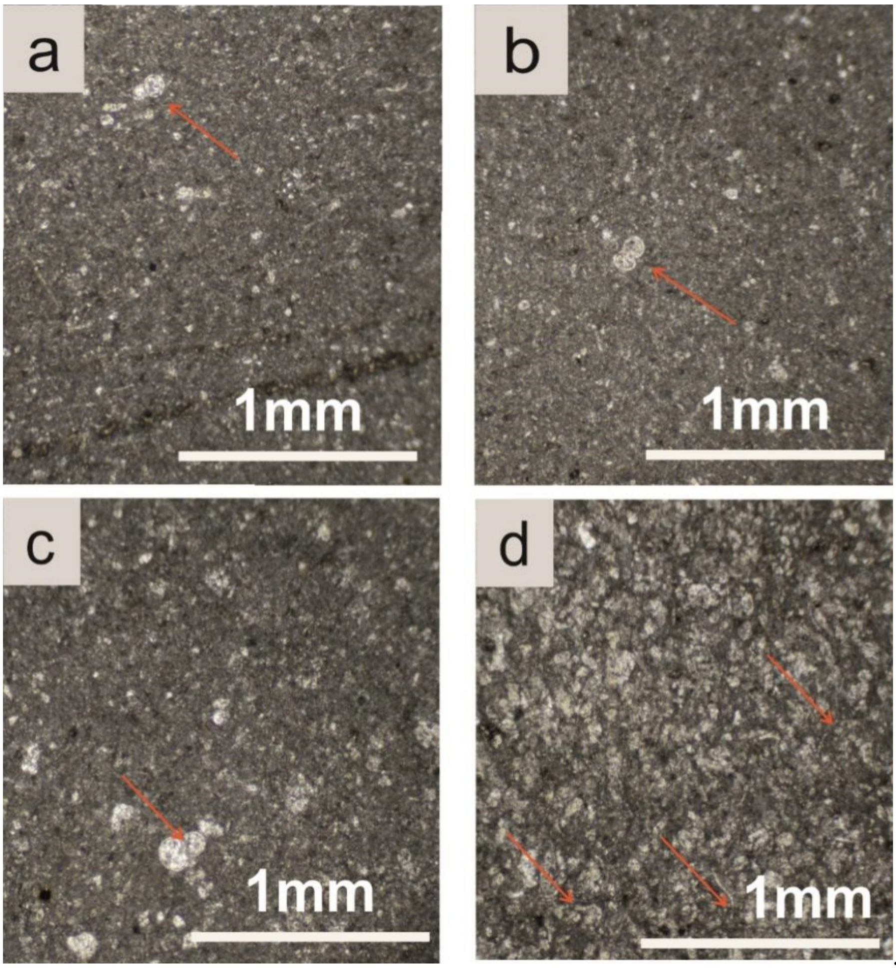

Figure 9. Microfacies type F3: Mudstone/wackestone with planktic foraminifera (red arrow) of Maastrichtian age. (**a**) mudstone with planktic foraminifera (red arrow), sample K9, (**b**) mudstone with planktic foraminifera (red arrow), sample K9, (**c**) mudstone with planktic foraminifera (red arrow), sample K10, (**d**) wackestone with planktic foraminifera (red arrow), sample K11.

The Paleocene-Eocene carbonate succession (known as "Limestones with microbreccia" Formation) is characterized by similar microfacies and lithofacies as the Upper Cretaceous (Senonian Formation) limestones. It consists of thin- to medium-bedded, white to white-yellow in color limestones with chert nodules and thin layers of chert (Figure 10) which represent the same microfacies type F3 as well, containing Globigerinidae, Truncorotaloididae, Globanomalinidae and fragments of benthic foraminifera and other reef organisms (Figures 11–13). Additionally, at some horizons, bedded or nodular cherts were also found. Finally, successions of thick bedded normal graded microbreccia and cobbles with calcarenitic turbidites and alterations of calcite and marly layers of small thickness, representing F2 and F1 microfacies types, occur, respectively.

Figure 10. (**a**) General view of the outcrop of the Paleocene micritic limestones where nodules and thin layers of chert (red arrow) locally occur, (**b**) closer view of a Microbreccia limestone.

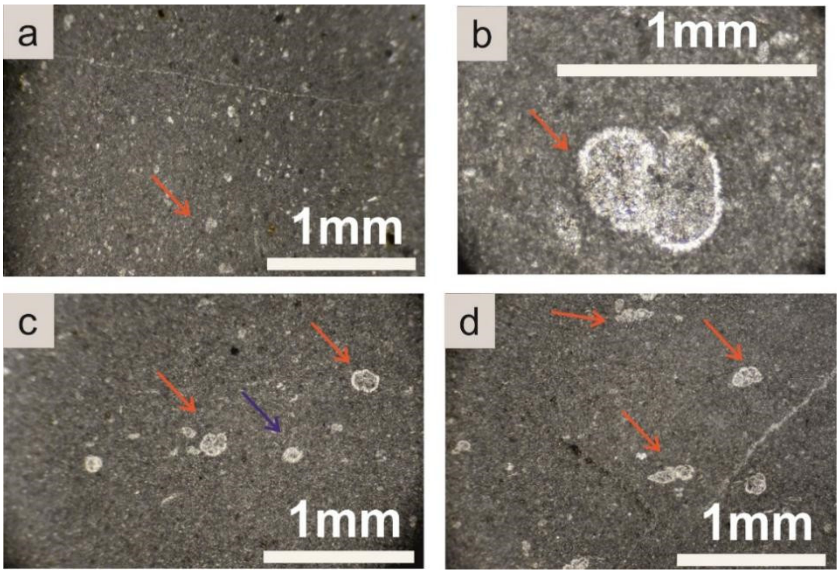

Figure 11. Microfacies typeF3: Mudstone/wackestone with planktic foraminifera (red arrow) of Paleocene age. (**a**) mudstone with planktic foraminifera (red arrow), sample KM11, (**b**) mudstone with planktic foraminifera (red arrow), sample KM11, (**c**) mudstone with planktic foraminifera (red arrow) and radiolaria (purple arrow), sample KM6, (**d**) Mudstone with planktic foraminifera (red arrow), sample KM11.

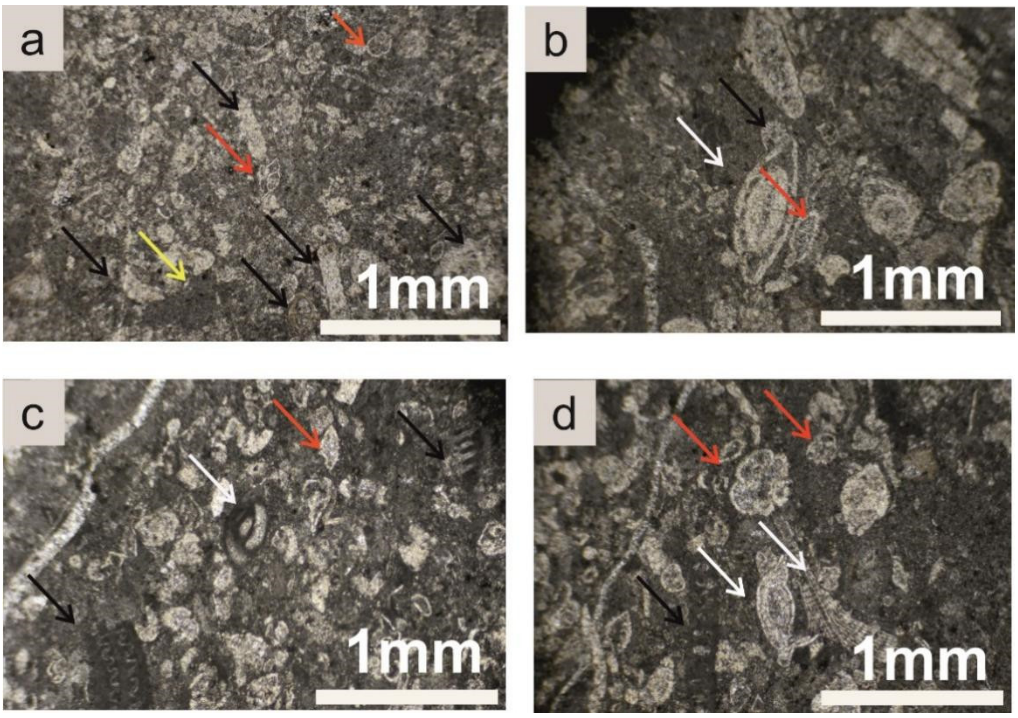

Figure 12. Microfacies type F2: Polymict clast supported microbreccia of Paleocene age. (**a**) planktic foraminifera (red arrow), bioclasts (black arrow), benthic foraminifera (white arrow), micritic clasts (yellow arrow), sample KM10, (**b**) planktic foraminifera (red arrow), bioclasts (black arrow), Miliolidae (white arrow), sample KM9, (**c**) planktic foraminifera (red arrow), bioclasts (black arrow), benthic foraminifera (white arrow), sample KM8, (**d**) planktic foraminifera (red arrow), bioclasts (black arrow), benthic foraminifera (white arrow), sample KM8.

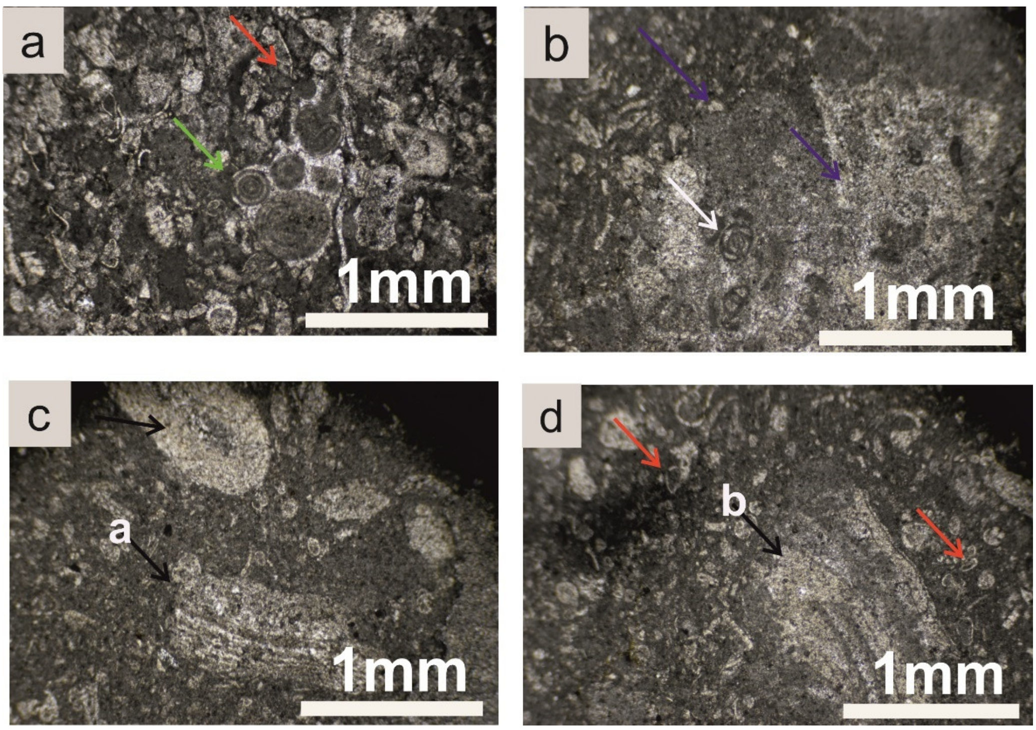

Figure 13. Microfacies type F1: Allochthonous, bioclastic-lithoclastic packstone/floatstone microbreccia of Paleocene age. (**a**) planktic foraminifera (red arrow), oolitic grainstone green arrow), sample KM15, (**b**) grainstone with benthic foraminifera (purple arrow), Miliolidae (white arrow), sample KM15, (**c**), Bioclasts (Mollusk?. black arrow), sample KM16, (**d**) Bioclasts (black arrow),

sample K1, (**a**) ooids (green arrow), (**d**) planktic foraminifera (red arrow), planktic foraminifera (red arrow), sample KM16.

The lower Eocene (Ypresian-Lutetian) rocks comprise the "Platy Limestones" Formation, which lithologically seem to be similar to the "Vigla limestones" Formation with nodular cherts, but they lack bedded cherts (Figure 14). After microfacies analysis these deposits were classified as F3 pelagic wackestones/mudstones with Globigerinidae, Truncorotaloididae and Globanomalinidae (Figure 15).

On the other hand it is important to mention that in the field they also appear as thick-bedded, micro-brecciated limestones, which after microfacies analysis have been classified as F2, clast-supported microbreccia characterized as bioclastic and lithoclastic wackestone-packstone with Mollusk fragments and Miliolidae (Figure 16), and in other cases as F1, floatstones/packstones with complete fossils and fossil fragments such as Mollusk fragments, algae, and very few benthic foraminifera (Miliolidae), clasts with algae (microproblematica debris) and grainstone clasts with peloids and benthic foraminifera as well as oolitic grainstones and pisoids (Figure 17).

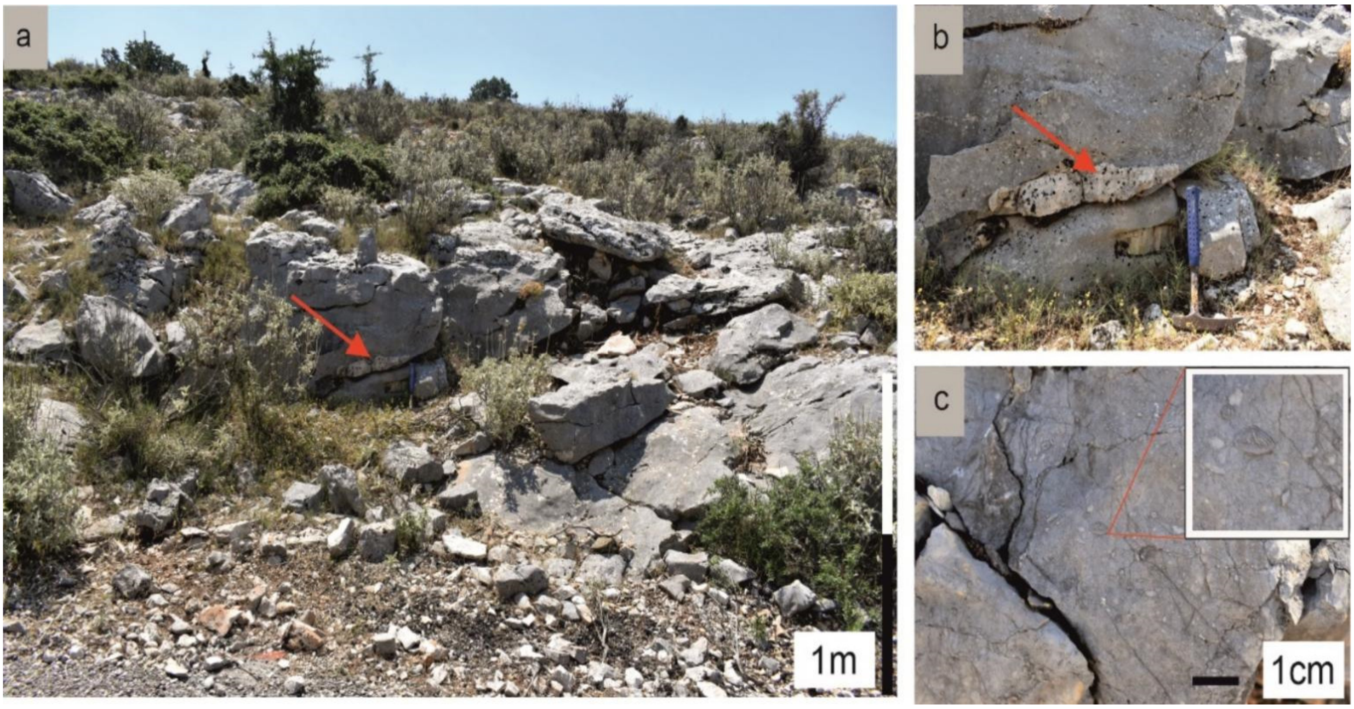

Figure 14. (**a**) General view of the outcrop of the Eocene "Platy Limestones", (**b**) Eocene "Platy Limestones, (**c**) Thick-bedded, micro-brecciated limestones with *Nummulites.*

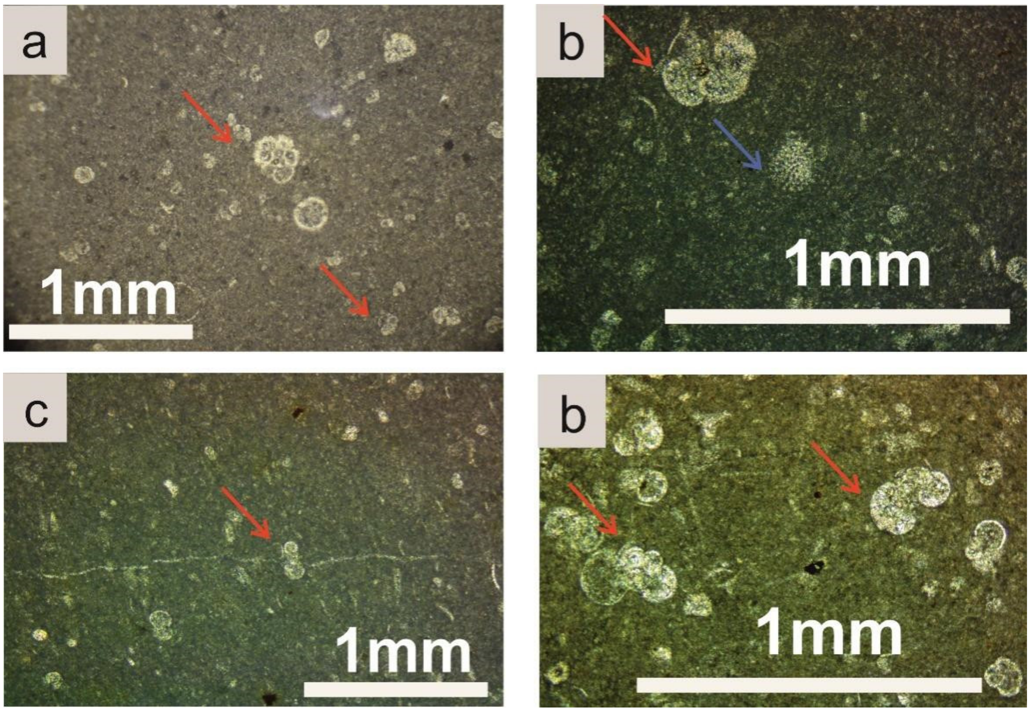

Figure 15. Microfacies typeF3: Mudstone/wackestone with planktic foraminifera of Eocene age. (**a**) planktic foraminifera (red arrow), sample KM1, (**b**) planktic foraminifera (red arrow), radiolaria (blue arrow), sample M20, (**c**) planktic foraminifera (red arrow), sample M4 (**d**) planktic foraminifera (red arrow), sample M4.

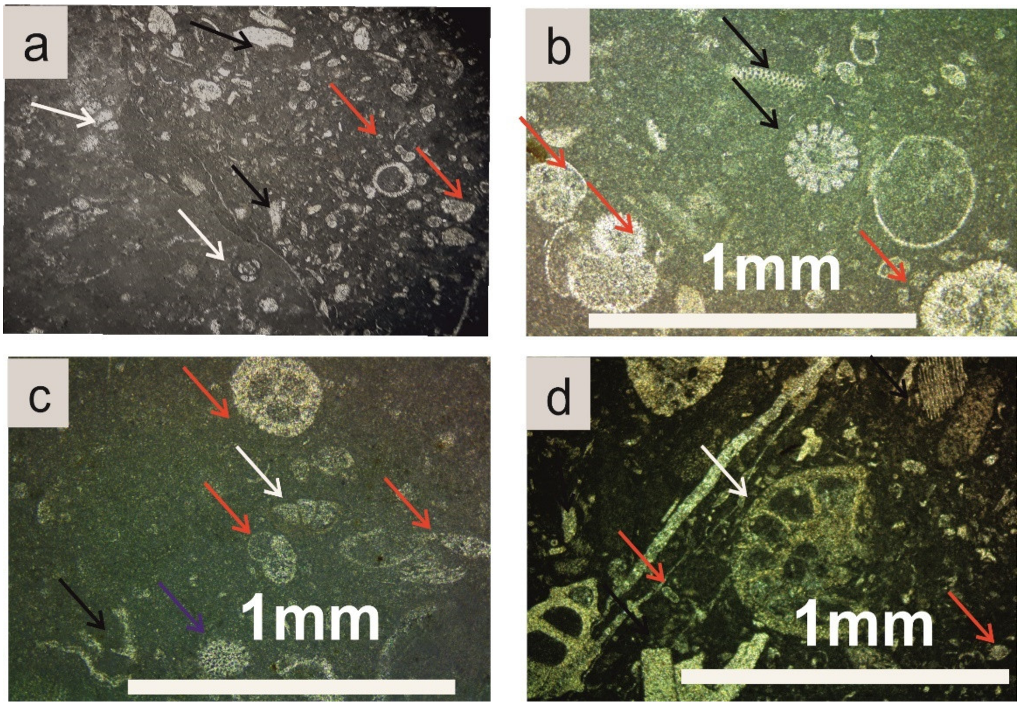

Figure 16. Microfacies type F2: Polymict clast supported microbreccia of Eocene age. (**a**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), benthic foraminifera (white arrow, sample M16, (**b**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), sample M15, (**c**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), benthic foraminifera (white arrow), radiolaria (purple arrow), sample M16, (**d**) planktic foraminifera (red arrow), bioclasts' debris (black arrow), benthic foraminifera (white arrow), sample M17.

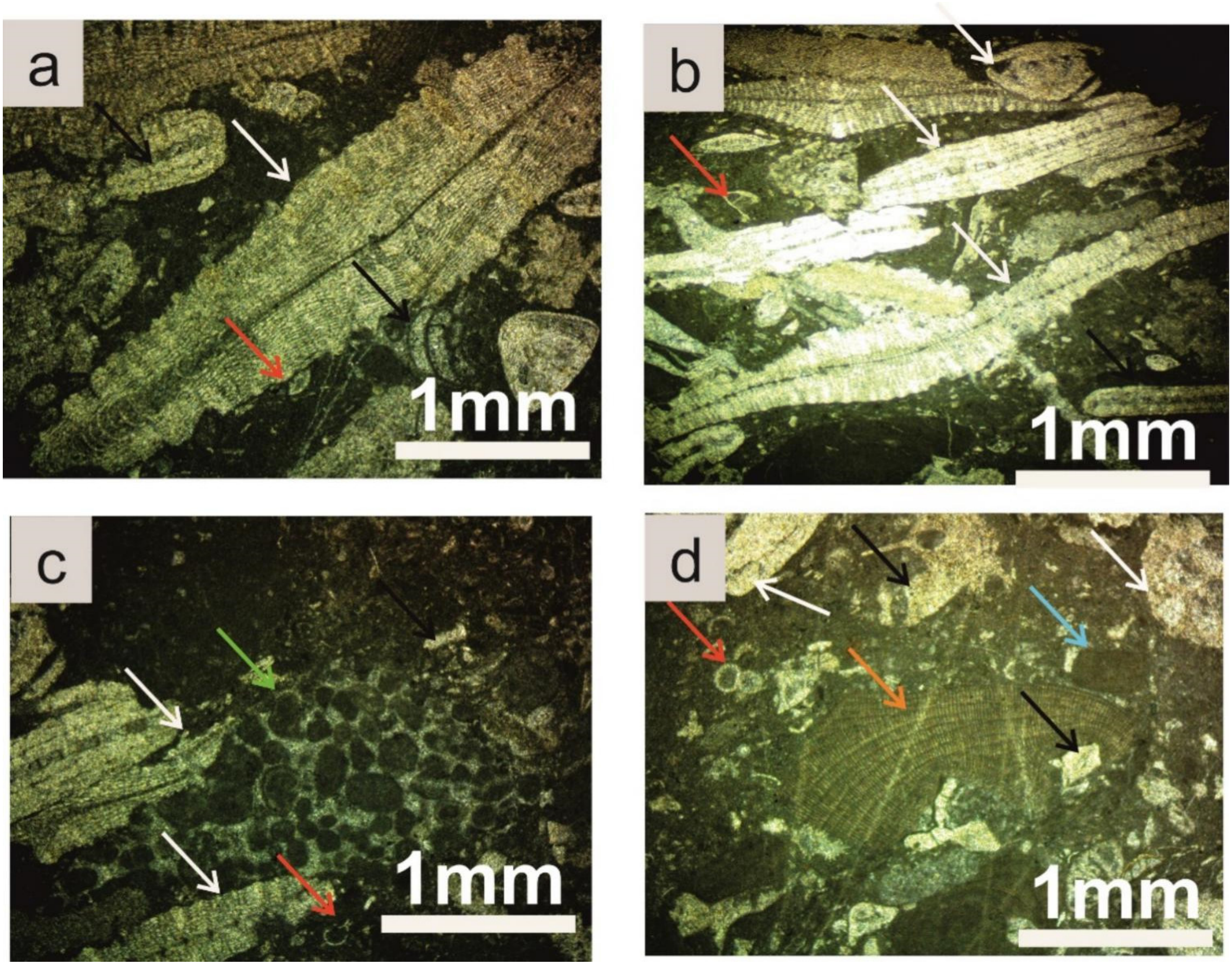

Figure 17. Microfacies type F1: Allochthonous, bioclastic-lithoclastic packstone/floatstone microbreccia of Eocene age. (**a**) bioclasts (black arrow), benthic foraminifera (white arrow), planktic foraminifera (red arrow), sample M6, (**b**) bioclasts (black arrow), benthic foraminifera (white arrow), planktic foraminifera (red arrow), sample M12, (**c**) bioclasts (black arrow), planktic foraminifera (red arrow), benthic foraminifera (white arrow), oolitic grainstone and coated grains (green arrow), sample M6, (**d**) bioclasts (black arrow), benthic foraminifera (white arrow), micritic clasts (blue arrow), algae (orange arrow), sample M5.

Finally, upwards and during the passing from the lower to the upper Eocene (Lutetian to Bartonian), transitional deposits consisting of alterations of carbonates and clastics, show the change in the depositional conditions (Figure 18) characterizing the upper part of the Eocene succession. Additionally, within these transitional deposits synsedimentary deformation structures were observed (Figure 19). In these deposits, microfacies analysis identified only one microfacies type, F3 pelagic wackestones/mudstones with planktic microfossils.

Figure 18. General view of an outcrop of the Eocene "Platy Limestones" Formation.

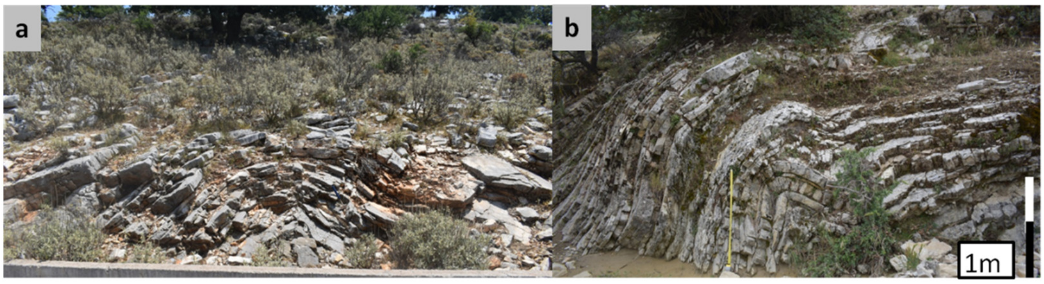

Figure 19. Internal synsedimentary deformations in a lower to upper Eocene carbonate succession, (**a**) an upright deformation, (**b**) an overturned deformation.

5.2. Interpretation of the Depositional Environments

Therefore, the identified carbonate microfacies which have been recognized in the studied succession consisting of: 1. F1 allochthonous bioclastic packstone/floatstone microbreccia corresponding to SMF 5, 2. F2 polymict clast-supported microbreccia corresponding to SMF 4 and 3. The F3 pelagic mudstone with a few scattered planktic foraminifera/pelagic wackestone with abundant planktic foraminifera correspond to SMF 3. The description and interpretation of the designated different Microfacies types is provided, underlying their depositional environments (Figure 20).

The SMF3 microfacies type represents carbonates which were deposited in a moderately inclined sea floor and basinwards in steeper slope environments. Such environments include depositional environments such as the toe-of-slope (Figures 21–23) (*deep shelf margin FZ3*), where pelagic material occurs, admixed with fine-grained detritus moved off from adjacent shallower environments. Redeposited shallow-water benthos is also observed, found together with some deep-water benthic taxa and planktic foraminifera. These settings indicate a depositional environment below the wave base and at low oxygen level (water depths perhaps 200 to 300 m) [23].

Microfacies types SMF 4 and SMF 5 occur in the FZ4 facies zone, which represents a foreslope depositional environment (Figures 21–23). This setting is characterized by a distinctly inclined seafloor (commonly 5° [23] to nearly vertical) seaward of the platform margins. Reworked platform material and pelagic admixtures with a highly variable grain size characterize a predominantly narrow facies belt. This is very fossiliferous, consisting mostly of redeposited shallow-water benthos, encrusted slope benthos, and some deep-water benthos, as well as planktic foraminifera as debris flows.

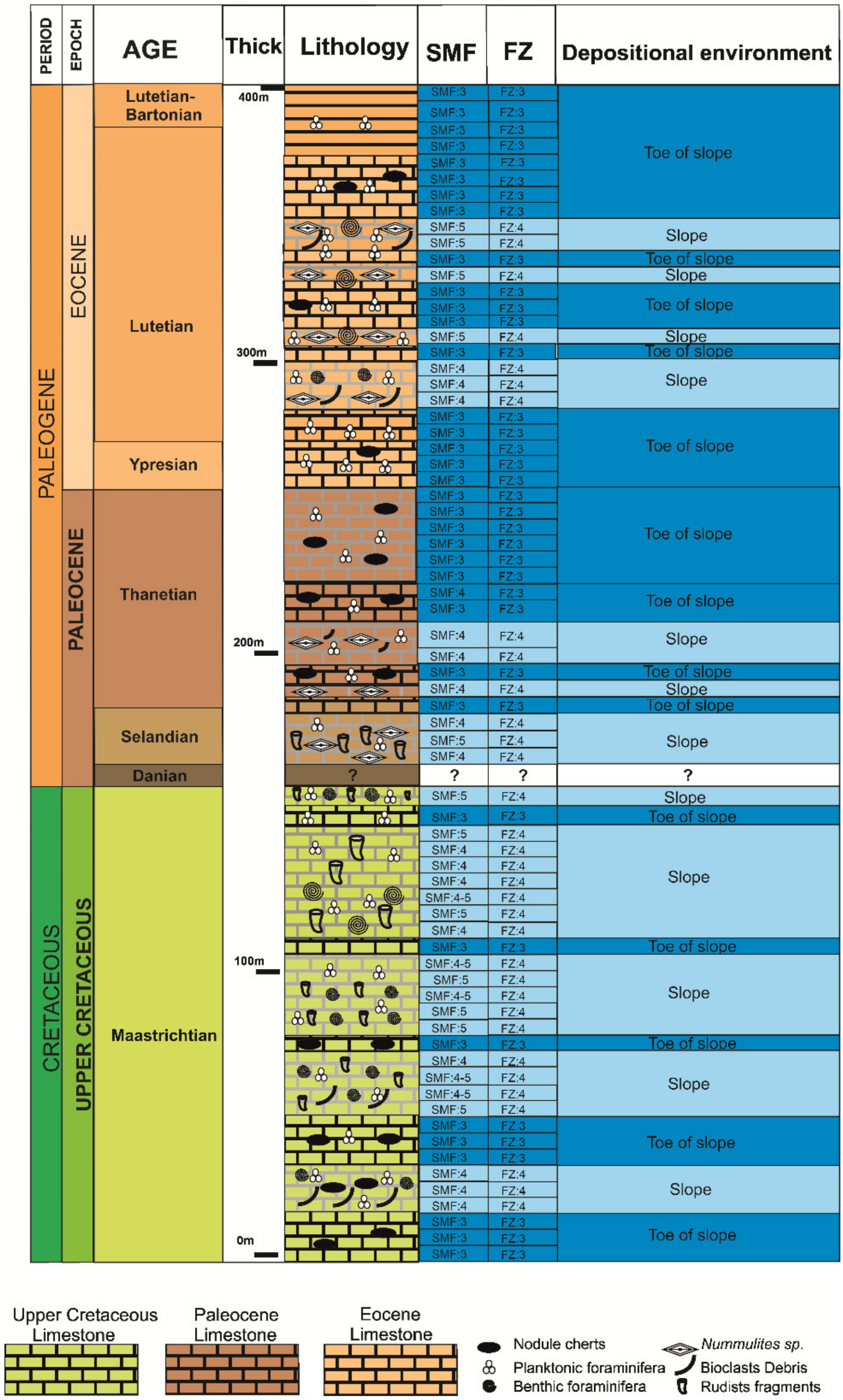

Figure 20. Synthetic lithostratigraphic column of the studied sequence, Microfacies types, and depositional environments of the studied succession at Aetoloakarnania area.

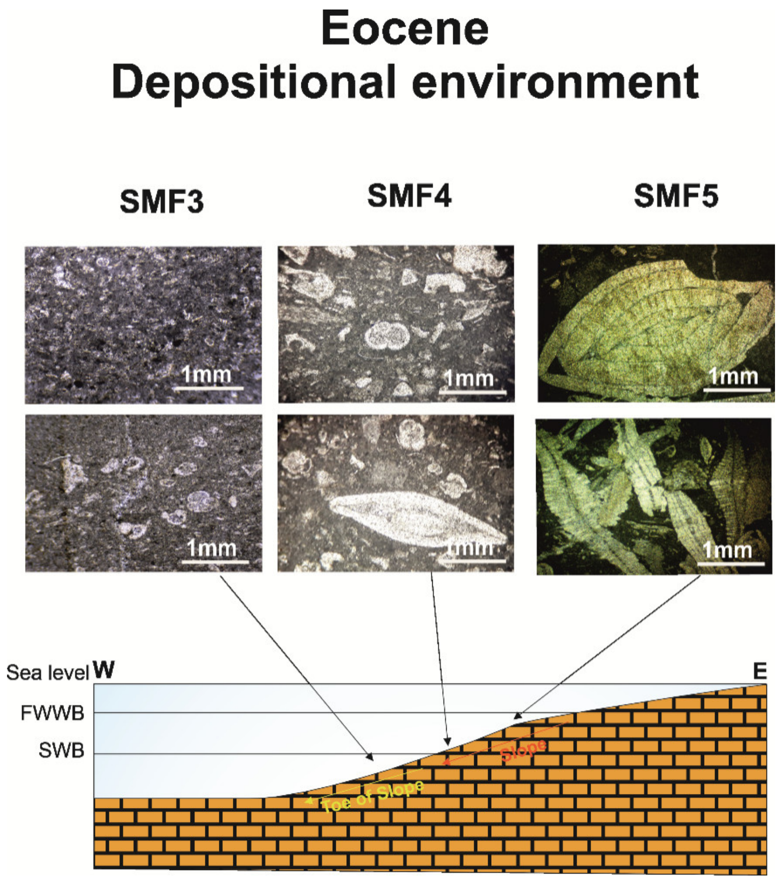

Figure 21. Microfacies types and the corresponding depositional environments/Facies Zones during the Eocene.

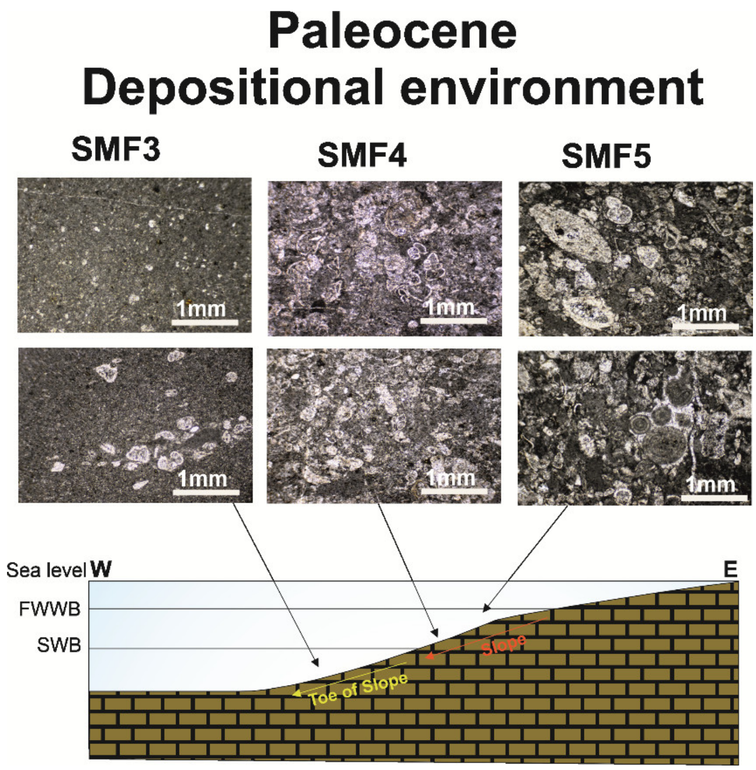

Figure 22. Microfacies types and the corresponding depositional environments/Facies Zones during the Paleocene.

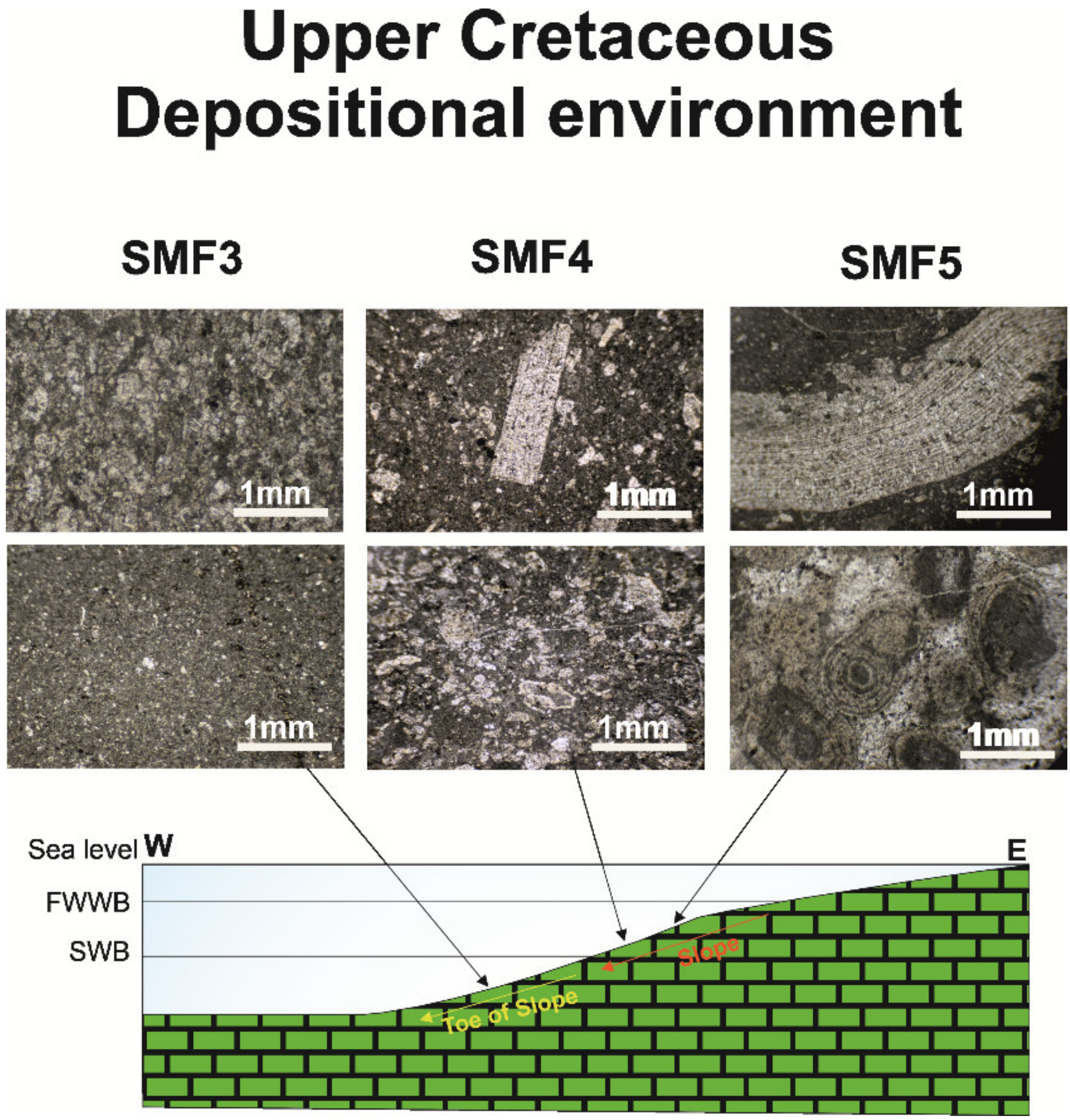

Figure 23. Microfacies types and the corresponding depositional environments/Facies Zones during the Maastrichtian**.**

6. Discussion

The identified carbonate formations of the study area display three different standard Microfacies types (SMF), representing different depositional conditions, with different lithologies, sedimentary features, energy conditions, and biota (supplementary material Table S1, Figure 20).

According to field observations, Microfacies analysis, and biostratigraphy, it is considered that the Maastrichtian (Senonian limestones Formation) limestones were deposited in a slope to toe-of-slope environment. Specifically, the thick-bedded microbrecciated limestones, where nodules and thin layers of chert are observed, locally indicate limestone deposits that were transported and redeposited to a deeper setting. This is evidenced by the presence of allochthonous bioclastic material, consisting of rudist fragments, which are typical reef materials, as well as benthic foraminifera, such as *Orbitoides* and Miliolidae, and oolitic grainstones reflecting shallow water conditions. All these were transported from a neighboring shallow environment, a platform or a reef and then were redeposited to a deeper environment together with planktic foraminifera (Globotruncanids) (SMF 4-5), designating a deeper environment with relatively high energy, as the slope (FZ: 4). Such a shallow environment indicating a platform or a reef that provided these components in our study area could be the Gavrovo platform to the east. In addition, a certain part of the Senonian limestones is classified as well as mudstone/wackestone with planktic foraminifera, radiolaria, and some scattered benthic foraminifera corresponding to a toe-of-slope environment (FZ: 3), which is a relatively low energy environment.

The Paleocene limestones, designated as the "limestones with microbreccia" Formation, have been classified as the same lithofacies as the Upper Cretaceous (Maastrichtian) limestones [17–19]. These rocks, with notable microbreccia, have derived from the erosion of Cretaceous carbonates from both the Gavrovo (to the east) and the Apulian platforms (to the west). At some horizons, bedded or nodular cherts are additionally found. During the Paleocene Epoch, the environmental conditions have failed to change significantly since the Late Cretaceous. Consequently, the Paleocene Epoch is also characterized by slope (FZ: 4) to toe-of-slope (FZ: 3) environmental settings. Packstones with planktic foraminifera, scattered benthic foraminifera such as Miliolidae, and debris of bivalves (SMF 4) are found, indicating a high energy environment such as a slope. In addition, as in the Maastrichtian similar pelagic lime mudstones/wackestones with planktic foraminifera (SMF 3) have been identified, representing a toe-of-slope depositional environment, respectively.

During the Eocene Epoch the "platy limestones" [16–18] that were deposited are characterized by nodular cherts and are represented by wackestone-packstone biomicrites (SMF3). This microfacies type is attributable to a deep-sea up to a toe-of-slope environment [19].

Regarding the Eocene succession, three different stages of evolution were recognized in the study area:

1. early Eocene (Ypresian-Lutetian), the integration of Microfacies and the biostratigraphic analyses suggest that the "platy limestones" Formation, which are defined by wackestone/packstone limestones with Globigerinidae and nodular cherts (SMF 3), correspond to a toe-of-slope depositional environment (FZ: 3), and without any doubt they characterize a deep-sea environment.

2. During the upper part of the lower Eocene (Lutetian) in the study area, toe-of-slope (FZ: 3) is not the only depositional setting that has been recognized. The presence of SMF 4 and SMF 5 microfacies types has been also noticed, which are attributable to shallower environments such as a slope (FZ: 4) and are in accordance with field observations (Figure 24), where thick bedded microbreccia limestones were deposited. Specifically, microfacies SMF 5 is composed of packstones/rudstones with planktic foraminifera in combination with transported components deriving from a relatively shallow environment such as a shallow carbonate platform. These components consist of scattered benthic foraminifera such as *Nummulites* sp., *Discocyclina* sp., *Quiqueloculina* sp., *Alveolina* sp., as well as algae and bivalve debris, indicating a relatively high energy environment. Additionally, SMF 4 is represented by polymict clast supported microbreccia consisting of carbonate litho- and bioclasts with scattered planktic and benthic foraminifera, indicating a slope depositional environment (FZ: 4). This microbreccia derived from the erosion of the Cretaceous carbonates from the Gavrovo platform to the east.

Figure 24. Part of the Eocene (Lutecian) carbonate succession.

3. Upper Eocene (Lutetian-Bartonian), when the transitional deposits were deposited, just before the appearance of the terrigenous clastic submarine fans. Within the carbonates pelagic mudstones/wackestones have been repeatedly observed, containing planktic foraminifera and radiolaria that correspond to SMF 3. Despite the fact that the presence of SMF 3 corresponds to a toe-of-slope environment, the occurrence of a mud-dominated SMF 3 during this period (Lutetian-Bartonian), associated with scarce, thin limestone beds that contain planktic foraminifera indicates a deeper environment, the deeper part of the toe-of-slope (FZ: 3).

Therefore, the above mentioned three stages of evolution of the basin for the Eocene introduce continuous stable conditions from the Maastrichtian to the lower Eocene (Ypresian), despite the fact that a deepening of the respective basin during the Eocene (Figure 20) was expected. A gradual shallowing during the upper part of the Eocene (Ypresian to Lutetian) is suggested, whereas between Lutetian to Bartonian the basin was gradually deepening.

Even though the palaeoenvironmental evolution of the Ionian zone, according to the proposed scenario [16,17] in which the Jurassic to lower Eocene period is characterized as a syn-rift stage, suggesting that the study area was affected by normal syn-sedimentary fault activity, field observations in the present study do not record such an intensive tectonic deformation during the Eocene.

Nevertheless the fact that the Eocene slowly changed and that the upper part of the Eocene deposits (Lutetian to Bartonian) occurred with deeper conditions (toe-of-slope), and the presence of a few internal synsedimentary deformations (Figure 19), could be related to the Pindos thrust activity (Figure 25). Avramidis and Zelilidis [40,41] as well as Bourli et al. [16], suggested that the Pindos thrust was activated during the upper Eocene, but according to the present work Pindos Thrust seems that it could have started its activation earlier, probably during the lower Eocene and thus, the studied area, as it was situated far from the Pindos thrust, it could be related with the forebulge area of the newly formed Pindos foreland (Figure 25B,C). Therefore, the Eocene in the studied area could be characterized as part of the new Pindos foreland, improving in this way the proposed model by Bourli et al. [16]. To conclude, possible sea-level effects cannot be ruled out and will even be associated with the eustatic sea-level drop that occurred between the Upper Cretaceous and the Paleocene [46,47] as we can clearly observe an intense cyclicity along the stratigraphic column.

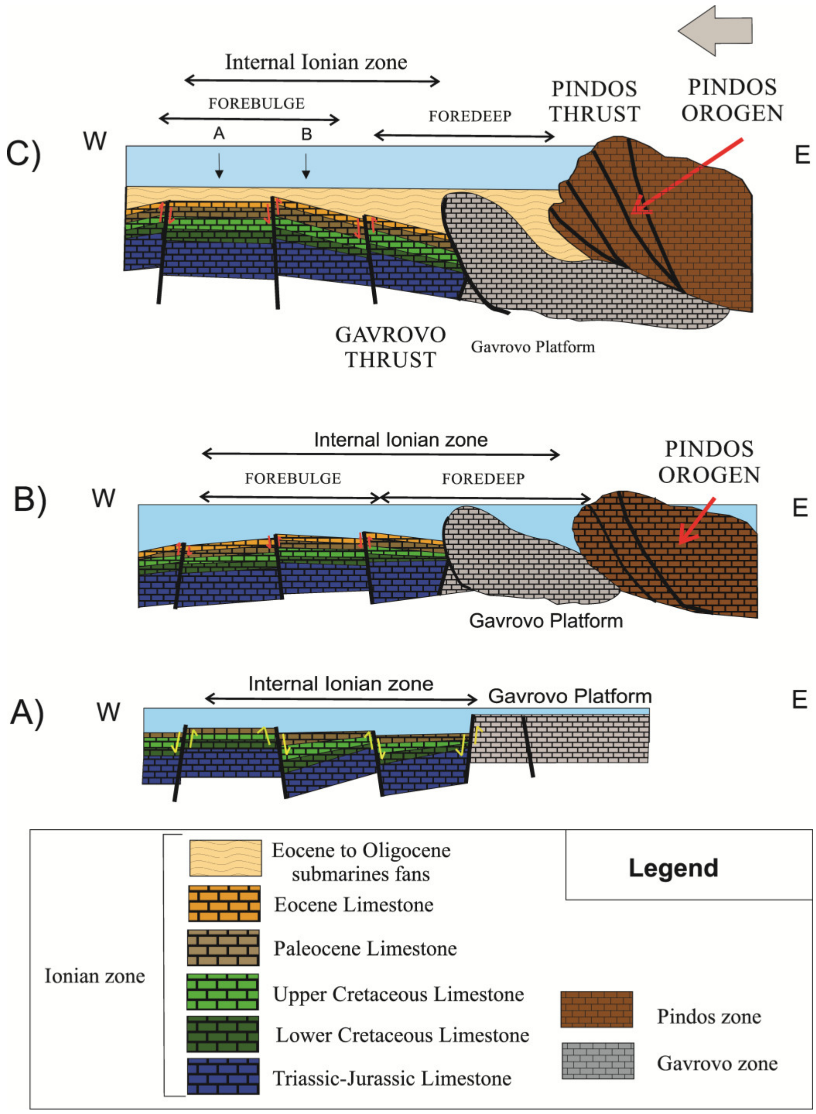

Figure 25. Evolutionary model of the studied part of the Ionian basin, illustrating the Maastrichtian-lower Eocene depositional conditions in the eastern part of the Ionian basin represented by three cross-sectional evolutionary stages. Stage **A** shows the depositional conditions during the rifting period (Jurassic-Paleocene). Stages **B** and **C** show the gradual formation and evolution of Pindos foreland basin during the compressional regime (Lower Eocene). Notice the gradual development of the forebulge area.

Additionally, it is important to mention that in the synthetic lithostratigraphic column, cycles and sequences that were recognized within the sedimentary succession, were characterized by "systematic" changes in their depositional conditions (Figure 21). Carrying out a more detailed sample collection in the study area and applying statistical treatment of the frequency data, it could be possible to recognize, apart from environmental controls, the sedimentary rhythms as well, which are reflected by couplets of strata or groups of couplets, influenced by sea-level changes or by climatic and seasonal fluctuations, depending on the scale of cyclicity.

7. Conclusions

The aim of this investigation was the recognition and interpretation of the different depositional environments and conditions of the carbonate sequence of the Ionian zone in Aetoloakarnania, from the Maastrichtian to the Eocene. Field observations, Microfacies analysis and biostratigraphy results indicate that the Maastrichtian carbonate sequence is represented by the three different Microfacies types SMF 3, SMF 4 and SMF 5, corresponding to two different depositional environments/Facies Zones. Specifically, SMF 3 is represented by mudstones/wackestones with planktic foraminifera and radiolaria indicating a toe-of-slope environment (FZ: 3), SMF 4 is represented by polymict clast-supported microbreccia, and SMF 5 includes allochthonous bioclastic breccias, indicating a slope (FZ:4) environment, respectively.

The Paleocene limestones of the study area have been classified as similar to the Maastrichtian limestones, represented by the three different Microfacies types SMF 3, SMF 4 and SMF 5 as well, and corresponding to two different depositional environments/Facies Zones: toe-of-slope (FZ: 3) and slope (FZ: 4), respectively.

Finally, Eocene limestones are defined by the presence of SMF 3 microfacies, which is characterized by mudstone limestones with very few and very small, planktic foraminifera, corresponding to a deep environment. More specifically, the Lutetian to Bartonian deposits represent the deeper part of the toe-of-slope (FZ: 3). Although results showed that during the Eocene deep water conditions occurred, it is important to mention that in the study area apart from SMF 3, microfacies from relatively shallower environments such as SMF 4 and SMF 5 have been recognized as well, indicating the depositional environment of a slope (FZ: 4). Particularly during the Maastrichtian -Paleocene-lower Eocene, similar depositional conditions (SMF 3, SMF 4 and SMF 5) have been recognized, indicating similar depositional environments (FZ: 3 and FZ: 4) (Figures 21–23).

Supplementary Materials: The following are available online at www.mdpi.com/2076-3263/12/3/106/s1, Table S1: Description of Microfacies analyses of the samples from Aetoloakarnania area and their age determination.

Author Contributions: Conceptualization, A.G.M. and A.Z.; methodology, E.Z., A.G.M. and A.Z.; validation, All authors; formal analysis, E.Z., A.G.M., G.I. and A.Z.; investigation, All authors; data curation, E.Z. and C.B.; writing—original draft preparation, E.Z. and A.Z.; writing—review and editing, All authors; visualization, E.Z. and A.Z.; supervision, A.G.M. and A.Z.; project administration, A.G.M. and C.B.; funding acquisition, A.G.M. and A.Z. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: There is no conflict of interest.

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