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Research Article

Planktonic Foraminiferal Biostratigraphy, Microfacies and Mineralogy Analyses of Lower-Middle Eocene and Middle Miocene Carbonates in the Silifke-Taşucu Region (Mersin, Southern Anatolia)

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ABSTRACT

The present study focused on the planktonic foraminiferal biostratigraphy, microfacies features of lower-middle Eocene and middle Miocene sediments of the Şıhlar (lower-middle Eocene), Silifke and Mut formations (middle Miocene) in the Silifke-Taşucu region (Southern Anatolia, Turkey). This study was performed on 31 samples from these units (this information needs more details). As a result of planktonic foraminiferal biostratigraphy study, 32 species belonging to 17 planktonic foraminifera genera and four planktonic foraminiferal zones as *Turborotalia frontosa*, *Turborotalia possagnoensis* (lower-middle Eocene), *Orbulina suturalis*, and *Orbulina universa* (middle Miocene). Petrographic analysis indicates that the carbonates examined occur in four microfacies, containing packstone, wackestone, mudstone and grainstone.

Keywords: Biostratigraphy; Eocene; Microfacies; Miocene; Planktonic foraminifera

INTRODUCTION

The region conventionally known as Mut-Ermenek-Silifke Basin in the Eastern Mediterranean Province is a crucial research area due to its reefal characteristics which have an important geological and stratigraphic place in the Eastern Mediterranean Province. This region and its vicinity were preferred in many stratigraphical and micropaleontological studies about the general geology and petroleum geology such as Blumenthal et al. [1], Akarsu et al. [2], Niehoff et al [3], Özer et al. [4], Gökten et al. [5], Koçyiğit et al. [6], Gedik et al. [7], Tanar et al. [8], Tanar et al. [9], Şafak et al. [10], Nazik et al. [11], Şafak et al. [12,13], Şafak et al. [14], Özkan et al. [15,16], Atabey et al. [17], Çiçek et al. [18], Gül et al. [19], Yıldız et al. [20], Özdoğan et al. [21], Özkan-Köksoy et al. [22], Şafak et al. [23-25]. The main purpose of this research is to reveal planktonic foraminiferal biostratigraphy, microfacies features in the Eocene and Miocene sequences in Kızkalesi (Akkum) of the Silifke and Taşucu regions. The Eocene strata are located east of Mersin and Miocene sedimentary succession is in the Silifke District (Figure 1).

The Eocene sequence close to Kızkalesi (Akkum) settlement in the region is composed of limestones and clayey limestones (Şıhlar formation) and is observed in a small outcrop at Şıhlar. The Miocene sequence consists of the Silifke and Mut formations and is exposed as limestones, clayey limestones and marls. In this research, it is presented for the first time planktonic foraminiferal biostratigraphy, microfacies and XRD examination studies in the lower - middle Eocene and middle Miocene sequences in the Central Taurus Belt.

MATERIALS AND METHODS

The study was carried out on thirty-one samples of three sections in the Akkum, Silifke Castle and Silifke-Taşucu areas, which are located on the the Silifke B32-a2, P31-b2, b3 maps at a scale of 1:25.000 (Figure 1). For the planktonic foraminiferal analyses, 150 g each hard and medium hardness samples were wrapped with thick paper to be crushed using a rock hammer. Crushed samples were placed in 1 L glass beakers and treated with hot water and 15% dilute hydrogen peroxide (H_2O_2) for at least 24 hours. The disaggregated residues were washed over a mesh of 0.60, 0.120, and 0.230 mm sieves and placed in sample bags after oven drying. Planktonic foraminifera which placed in the sieved samples were extracted and separated planktonic foraminifera were placed on slides for identification of the genera and species under polarized microscope in the Çukurova University, Geological Engineering Laboratuary. In the study, 17 genera and 32 species were identified using Bolli et al. [26], Iaccarino et al. [27], Jenkins et al. [28], Rögl et al. [29], Toumarkine et al. [30], Berggren et al. [31], Olsson et al.

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[32], Pearson et al. [33], and Mikrotax URL 1-29 Photos [34-61], of the identified planktonic foraminiferal genera and species were taken with scanning electron microscope at Çukurova University (Plates I, II and Figures 2,3).

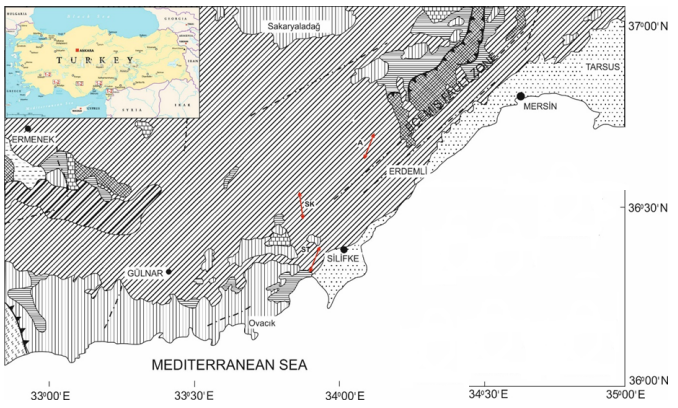


Figure 1: Geological map and location of the sections in the study area (modified after Şafak et al., 2005). Note: ( )Plio-quaternary, Oligo-miocene (mainly Miocene, ( ) mainly Oligocene), ( ) Eocene, ( ) U Cretaceous, ( ) Mesozoic (platform), ( ) Paleozoic, ( ) Ophiolite, ( ) Metamorphics, ( )Thrust, ( ) Fault, A: Akkum, ST: Silifke-Tasucu, SK: Silifke-castle.

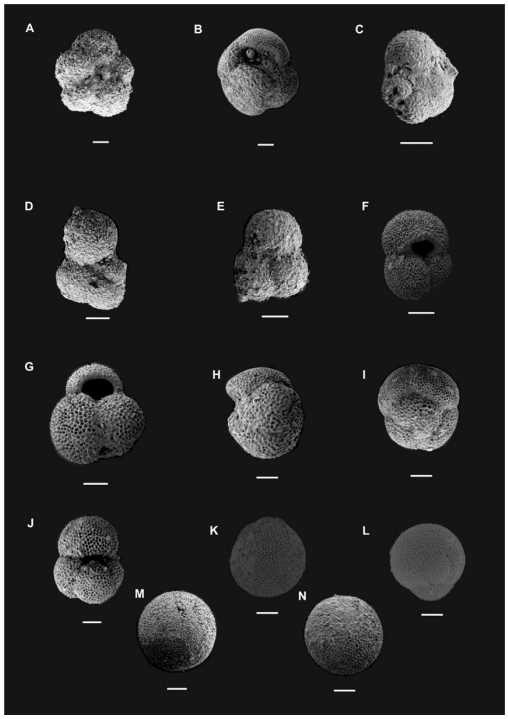


Plate I

Figure 2: Planktonic foraminifera from the investigated sections, scale bar equals 50 µm. A. *Acarinina pentacamerata* (Subbotina), umbilical view, Akkum Section, sample no. 3; B, C. Globigerinanus tokerae Nazik and Gürbüz, spiral view, side view, Silifke-Castle section, sample no. 5; D, E. Globigerinella obesa (Bolli), umbilical view, Silifke-Castle section, sample no. 7, 2; F. Globigerinoides subquadratus Brönnimann, side view, Silifke-Castle section, sample no. 8; G. Globigerinoides ruber (d'Orbigny), umbilical view, Silifke-Castle section, sample no 7; H, I. Globoquadrina dehiscens (Chapman, Parr and Collins), side view, spiral view, Silifke-Taşucu section, sample no. 6; J. Globoturborotalita euapertura (Jenkins), umbilical view, Silifke-Castle section, sample no. 6; K,L. *Orbulina suturalis* Brönnimann, side views, Silifke-Taşucu section, sample no. 3 and Silifke-Castle section, sample no. 8; M,N. *Orbulina universa* d'Orbigny, side views, Silifke-Taşucu section, sample no. 3 and Silifke-Castle section, sample no. 8.

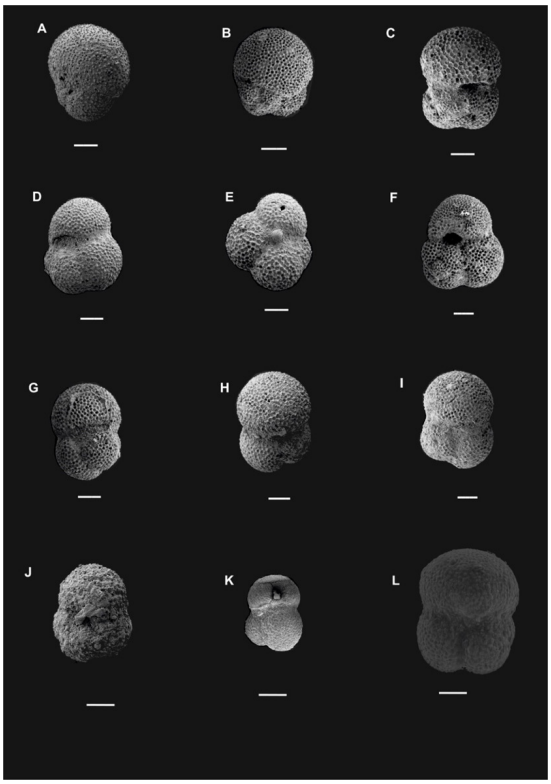


Plate II

Figure 3: Planktonic foraminifera from the investigated sections, scale bar equals 50 µm. A. *Praeorbulina glomerosa* curva (Blow), side view, Silifke-Taşucu section, sample no. 13; B. *Trilobatus bisphericus* (Todd), side view, Silifke-Castle section, sample no. 2; C. *Trilobatus immaturus* (Le Roy), side view, Silifke-castle section, sample no. 6; D-F. *Trilobatus sacculifer* (Brady), umbilical view, spiral views, Silifke-Castle section, sample no. 6; G-I. *Trilobatus trilobus* (Reuss), umbilical view, side view, and spiral view, Silifke-Castle section, sample no. 8; J. *Turborotalia possagnoensis* (Tomarkine and Bolli), umbilical view, Ihlar Section, Sample no. 5. K-L. *Turborotalia frontosa* (Subbotina), Akkum section, side view, sample no. 3.

The biostratigraphic investigations carried out in the study were based on research by Toumarkine et al. [62], zonation at the Eocene Epoch. Also, at the Miocene Epoch, based on the studies of Iaccarino et al. [27], (in Mediterranean) and Mandur et al. [63], (in Egypt/Gulf of Suez). In addition, the identified biozones were compared with the standard zones and similarities and differences of the biozones have been given with studies which was done, Turkey as the immediate surroundings of the work area (Figures 4, 5). The microfacies analysis of carbonates was carried out at Çukurova University (Department of Geological Engineering). The mineralogical and petrographic research was performed with a Leica DMEP microscope at Çukurova University. Two of the most widely used classifications are those of Folk et al. [64,65], and Dunham et al. [66]. Both classifications subdivide limestones primarily on the basis of matrix content. Most limestones are classified by Folk as allochemical rocks, if they contain over 10% allochems (transported carbonate grains). On the basis of the percentage of interstitial material, the rocks may be further subdivided into two groups: Sparry allochemical limestones (containing a sparry calcite cement of clear, coarsely crystalline mosaic calcite crystals) and microcrystalline allochemical limestone (containing microcrystalline calcite mud, i.e., micrite, which is sub-translucent, grayish or brownish particles, less than about 5 µm in size). Further subdivision is based on the allochemratios of Folk et al. [65], and are shown in Scholle et al. [67], (Figure 6).

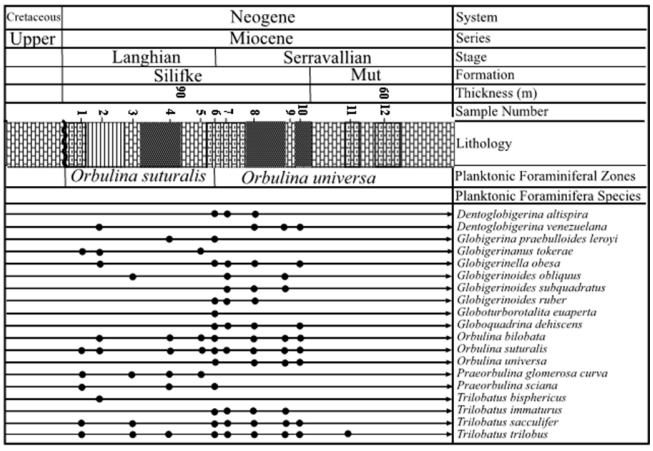


Figure 4: Distribution of planktonic foraminiferal species in the Silifke-Castle Section. Note: ( ) Limestone, ( ) Clayey limestone, ( ) Whitish Marl, ( ) Claystone.

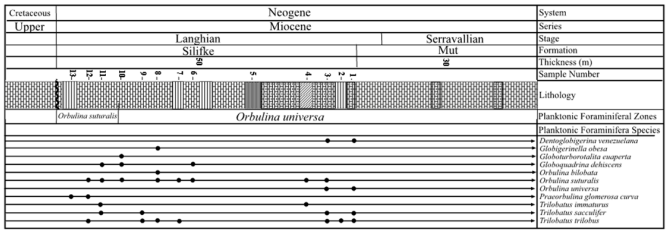


Figure 5: Distribution of planktonic foraminifera in the Silifke-Ta□ucu Section. Note: ( ) Limestone, ( ) Clayey limestone, ( ) Marl, ( ) Claystone, ( ) Clayey-silty limestone, ( ) Siltstone.

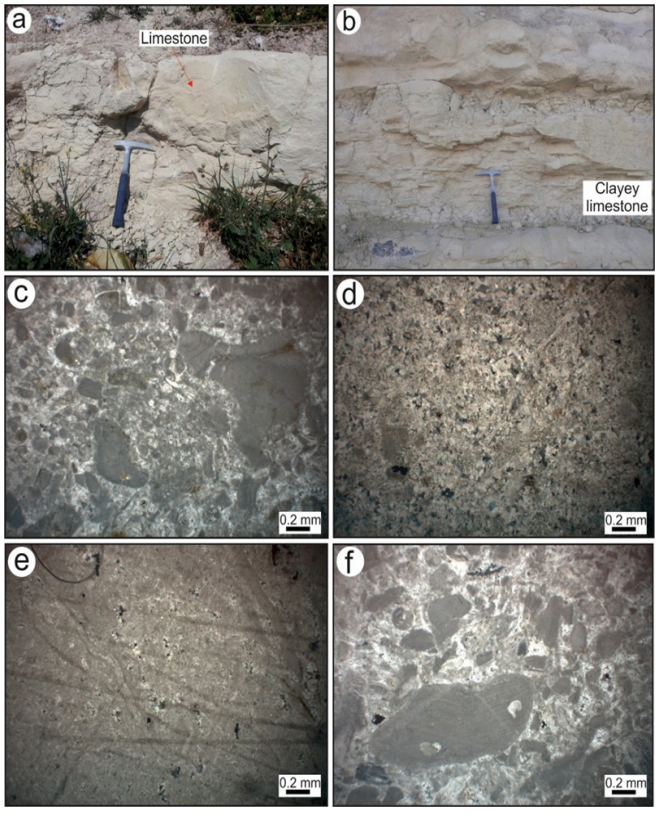


Figure 6: Field overview and microfacies photos of the studied formations in the investigated area.

The X-Ray Diffraction (XRD) technique makes the mineralogical identification of rocks possible. Mineralogical determination of the samples was carried out, using a Rigaku Miniflex system (an XRD system with CuKσ radiation). The XRD pattern of ground powder samples was recorded at room temperature in the powder mode. Samples were run from 20° to 50° for diffracted angle, 2q, with a step size of 0.02° (Figure 7).

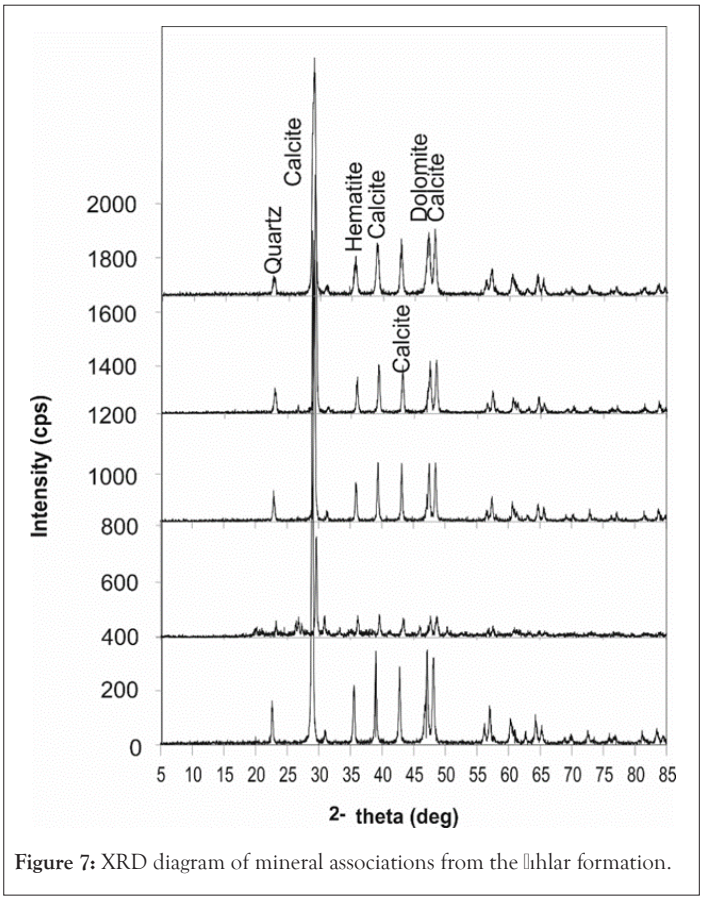


Figure 7: XRD diagram of mineral associations from the □ıhlar formation.

Geological setting and stratigraphy

The Taurus Mountains are the southern mountain ranges of Turkey and are composed of plate fragments that came together between the Eurasian and African-Arabic plates. In these mountain ranges, during the Triassic-Eocene period, ocean formation by rifting, closure by subduction and, as well as collision events had been developed. The northward subduction of the branches of Neotethys caused the emplacement of subduction zone ophiolites and ophiolitic mélange in the late Cretaceous on the Taurus Carbonate Platform [9]. Mut Basin, located in the northwest of the research area, is one of the Neogene basins opened after the Taurus orogeny. A thick succession consisting mainly of marine and terrestrial units is performed during the Mio-Pliocene period in the basin. Before the opening of this basin, there are small molasses basins. These molasses, which are the result of the first extensional tectonics that started in the Oligocene after the orogeny of the region, are lacustrine in character. These are named as Ermenek, Bucakkışla, Korucuk and Çamlıyayla basins. Among these, the Korucuk basin, located in the South of the Central Taurus Mountains and in the west of Silifke, is based on the limestones of the Aladağ Unit and the ophiolitic rocks of the Bozkır Unit and "mélange". The Çavuşlar formation, which overlying these rocks with an angular unconformity, crops out in the southeast of Gülnar. Near the Çavuşlar village, it is overlain by the late Miocene aged Tırtar formation with an angular unconformity too. The aforementioned

Oligocene sandstone, limestone, coal lithological, cross-layered Çavuşlar formation could not be traced as it progressed from Gülnar to Silifke route. Therefore, in the study area, on the Silifke-Kızkalesi road, early-middle Eocene aged, shallow marine Şıhlar limestone formation transgressively overlain by clastic Miocene units. After the emplacement of the ophiolitic "mélange", the region rose at the end of the Eocene and the sea retreated and terrestrialization began. The Eocene formations did not undergo forward folding and reached a low-grade unconformity position with the overlying Miocene limestones. As a result of terrestrialization at the end of the Eocene, the depression of the Göksu valley and two ridges to the north and south of this depression were formed. In this depression, as a result of the slow progress of the sea from south to north in the middle Miocene, marl and reefal limestones were deposited. Since the sedimentation in Miocene is related to the underlying topography, limestone was deposited on the hills and ridges, and clayey limestone and marl were deposited in the pits. Since horizontal forces were effective at the end of the middle Miocene, the layers preserved their original position [5]. The absence of Oligocene units on the Eocene formation measured in the Şıhlar-Silifke road-Kızkalesi section in this study, the Oligocene outcrop in a narrow area in the west of Silifke, and the Miocene units were observed in this way.The study area lies between the Taurus Mountains and the Mediterranean. It is located 85 km from Mersin and 70 km from Gülnar, west of Erdemli, east of Gülnar and to the south of Mut. In the study area, Devonian, middle Permian, Upper Jurassic, Upper Cretaceous, Lutetian, and Miocene ages formations are exposed. The basement rock units of the region are represented by different lithology and ages from Devonian to Lutetian. Mi ocene sediments covering transgressively these basement units are represented by conglomerate, sandstone, marl and reefal limestones (Aslanlı, Mut, Silifke formations and Sarıaydın reefal limestone) [5], (Figure 8).

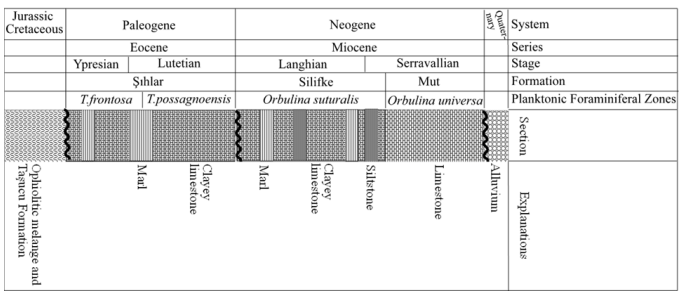


Figure 8: Synthetic unscaled column section of the study area.

In the study area, the reefal deposits consisting of discontinuous units are composed of marl-clayey limestone outcropping in the west part of Silifke-Kızkalesi (Şıhlar Limestone) Ypresian-Lutetian sequenses. The study is carried out in these reefal units (Silifke and Mut formations) consisting of clayey limestone, limestone, silty limestone and marl lithology observed in the Langhian-Serravallian deposits of Silifke-Taşucu region.

Şıhlar limestone

Name of the unit: The name was taken from the north of the Şıhlar area, which is 7.5 km from the centre of the Silifke district. This name was used for the first time by Gökten et al. [5], at the Bükdeğirmeni Dam and at the Şıhlar location.

Type locality: The Eocene sequence of the region is located at the Şıhlar location, which is 1.5 km from Bükdeğirmeni village and 6 km from the centre of the Silifke district.

Type section: The type section is at Şıhlar, located on the north side of the Şıhlar stream.

Auxiliary section: It is the Akkum Section, located to the west of Kızkalesi between UTMS coordinates of X1: 601193.06, Y1: 4035235.50 and X2: 601290.00, Y2: 4035356.00 on the 1: 25.000 scale Silifke B32-a2 map and is 55 m in measured thickness (Figures 1, 5).

Upper and lower boundaries: The upper and the lower boundaries are Jurassic limestone, unconformable with the middle to upper parts of the Silifke formation.

Lithology: It consists of clayey limestone and well-bedded limestones.

Thickness: According to Gökten et al. [5], 50 m, in this study measured as 55 m.

Fossil content and age: Gökten et al. [5], recognized benthic foraminiferal species, (e.g., Chapmanina species), ostracods, and radiolarians in this unit. More diversified fossils are discovered in this formation (see below).

Silifke formation

Name of the unit: The name of the unit was used for the first time by Gökten et al. [5], and was taken from the Silifke District.

Type locality: The examined unit occurs in the Silifke area.

Type section: The type section of the unit is located in Silifke District and it was measured in Silifke region by Gökten et al. [5], who divided the formation into four members. These members are Bozlağan, Medetsiz, Çamdüzü and İmamlı members from old to young.

Auxiliary section: In this research, two auxiliary sections measured in the unit. One of them is Silifke Castle Section, which is located between UTMS coordinates of X1: 582183.58, Y1: 4025737.54 and X2: 582209.03, Y2: 4025942.23 coordinates (on the 1: 25.000 scale Silifke P31-b2 map). The other is Silifke-Taşucu section, which is located between UTMS coordinates of X1: 584060.13, Y1: 4025440.50 and X2: 583407.06, Y2: 4024821.75 coordinates (on the 1: 25.000 scale Silifke P31-b3 map) (Figures 1, 8).

Upper and lower boundaries: The Cretaceous Ophiolitic Melange and the Upper Jurassic Taşucu formation at the lower boundary of the unit show an angular unconformity, while they are in conformity with the Mut formation at the upper boundary and transition laterally in some regions. In areas, where the Mut formation is missing, the Sarıaydın formation is conformable with a reef limestone.

Lithology: The carbonate consists of predominantly marl levels and clayey limestones, overlain by reef limestones and clayey limestones.

Thickness: 900 m, according to Gökten et al. [5]; however, it was measured at about 200 m during present study due to the fact that the section is partly covered.

Fossil content and age: Gökten et al. [5], defined ostracods, planktonic and benthic foraminiferal species in the Bozlağan member (late Burdigalian), containing *Henryhowella asperrima*, and *Globigerinoides ruber, Globigerinoides subquadratus, Globigerinella obesa, Globoquadrina dehiscens, Orbulina bilobata, Orbulina suturalis,*

Sphaeroidina bulloides, *Trilobatus bisphericus*, *Trilobatus trilobus*, *Ammonia beccarii*, *Gyroidina soldanii*, *Marginulina murex*, *Robulus cultratus*, *Robulus orbicularis* and *Uvigerina schwageri*. Similar planktonic and benthic foraminiferal species assemblage, with *Orbulina universa*, had been described in the Medetsiz member (late Burdigalian-early Helvetian) by the same author. A number of planktonic and benthic foraminiferal species, including *Globigerina praebulloides*, *Globigerinella obesa*, *Trilobatus bisphericus*, *Trilobatus immaturus*, *Trilobatus trilobus*, *Globorotalia praemenardii*, *Orbulina universa*, *Sphaeroidina bulloides*, *Gyroidina soldanii*, *Uvigerina longistriata*, *Siphonina tubulosa*, *Robuluscultratus*, *Marginulina hirsute*, *Cibicides dutemplei* and *Elphidium crispum* had been recognized in the Helvetian (Serravallian) stage deposits within the Çamdüzü member. A number of planktonic and benthic foraminiferal taxa, such as *Orbulina species*, and *Amphistegina species*, were determined in the İmamlı member in the Langhian-Serravallian (middle Miocene).

Mut formation

Name of the unit: The unit was named the Mut Limestone by Sezer et al. [68].

Type locality: The Eğre Mountains and Avlamadağ located on the northern side of the Mut district.

Type section: The section was measured beginning at Türbebeleni Hill at Derinçay village (UTMS coordinates X: 76250, Y: 31900, Z: 1789 (Silifke O30-b4)) and finishing at Kartalkaya Hill of Avlama Mountain (UTMS coordinates X: 64460, Y: 29660, Z: 162 (Silifke O30-c1)).

Auxiliary section: A complementary section is found in the Silifke Castle section at Silifke P31-b2 map (UTMS coordinates: X1: 582209.03, Y1:4025942.23 and X2: 582183.58, Y2: 4025737.54). The Silifke-Taşucu section at Silifke P31-b3 map (UTMS coordinates: X1: 584060.13, Y1: 4025440.50 and X2: 583407.06, Y2: 4024821.75) (Figures 1,4,5).

Upper and lower boundaries: The lower boundary was observed as transitional and is conformable with the Silifke formation. The upper boundary is not seen in the study area and the upper boundary is compatible with the lithologies from the late Miocene on the Erdemli-Aslanlı road.

Lithology: The Mut formation consists of thin-bedded, whitish- to cream-colored reef limestones with clayey-marly limestones beds at intermediate levels.

Thickness: 125 m, according to Gökten et al. [5]. In this study, the unit's thickness was found as 150 m in the Silifke Castle section and it was measured as 80 m in the Silifke-Taşucu section.

Fossil content and age: Ostracode species, such as *Bairdia subdeltoidea*, *Cnestocythere truncate*, *Cytherella vulgate*, *Incongruellinarotundata*, *Miocyprideis* cf. *Sarmatica*, *Pokornyella deformisminor*, and *Xestoleberis glabrescens* occur throughout with planktonic foraminiferal species, e.g., *Orbulina suturalis* and *Paragloborotalia mayeri* assigned by Tanar et al. [8], to Langhian-Serravallian (middle Miocene).

RESULTS

Investigated sections

In the study area, three stratigraphic sections such Akkum, Silifke Castle and Silifke-Taşucu sections were measured from the locations where the Şıhlar limestone, Silifke and Mut formations are best represented (Figure 1).

Akkum section

This section measured in the Şıhlar limestone. It lies between the UTMS X1: 601193.06, Y1: 4035235.50 and X2: 601290.00, Y2: 4035356.00 coordinates (on the 1: 25.000 scale Silifke B32-a2 map) and is 55 m thick. The Cenozoic deposits overly those of Mesozoic *via* an obvious unconformity. Therefore, Şıhlar formation unconformably overlies the Upper Jurassic limestones. This formation is composed of light marl and clayey limestone. The unit is light pink, well layered, sandy biopelmicrite limestones in microfacies, clayey limestones and intercalated, including breccias towards the base. The breccias contain angular micritic limestone, quartzite and meta sandstone Gökten et al. [5]. Six samples were taken throughout the section. The samples selected for this study were taken from clayey limestone levels that may contain fossils, whitish colored, well layered, medium hardness, intercalated with marl sequence. From the samples of the section 13 species of the 7 planktonic foraminifera genera belonging to the lower-middle Eocene have been identified and the studied section documents the *Turborotalia frontosa* Zone (between 9 and 26 meters of the section) and the *Turborotalia possagnoensis* Zone (between 26-33 meters of the section) (Figures 1,6,9).

In short, we note that the Şıhlar limestone in Akkum section cotains more diversified fauna than described by Gökten et al. [5]. Especially planktonic foraminiferal species, e.g., *Acarinina bullbrooki*, *Acarinina pentacamerata*, *Acarinina soldadoensis*, *Globigerina officinalis*, *Parasubbotina inaequispira*, *Pseudoglobigerinella bolivariana*, *Subbotina eocaena*, *Subbotina senni*, *Turborotalia frontosa*, and *Turborotalia pomeroli* were found; ostracods genera and species, such as *Loxocorniculum* species, *Nucleolina multicostata*, *Paracytheridea* species, *Trachyleberidea stricta*, *Xestoleberis subglobosa* and also were recognized. In our study, according to this fossils content, the Ypresian-Lutetian (early-middle Eocene) age for the Şıhlar limestones (Plates I, II and Figure 7) is indeed confirmed.

Silifke-castle section

This section lies between the UTMS X1: 582183.58, Y1: 4025737.54 and X2: 582209.03, Y2: 4025942.23 coordinates (on the 1: 25.000 scale Silifke P3-b2 map) and is 150 m thick. The Cenozoic deposits over the Upper Cretaseous limestones *via* an important unconformity. This section was measured from the Silifke and Mut formations. The first ninety meters of the section belong to Silifke formation and the other 60 meters to the Mut formation. Silifke formation's lithology in the section consists of alternate of marl, clayey limestones, siltstone and clayey-silty limestone. Mut formation consists of predominantly limestone and clayey limestone. Eleven samples were taken throughout the section. The samples selected for this study were taken from clayey and clayey limestone levels that may contain fossils. From the samples of the section 19 species of the 10 planktonic foraminifera genera belonging to the Langhian-Serravallian stage (middle Miocene) have been identified and the studied section documents the *Orbulina suturalis* subzone (between 1 and 64 meters of the section) and the *Orbulina universa* Subzone (between 64-150 meters of the section) (Figures 1,4,6).

Silifke-taşucu section

This section is located between the UTMS X1: 584060.13, Y1: 4025440.50 and X2: 583407.06, Y2: 4024821.75 coordinates (on the 1: 25,000 scale Silifke P31-b3 map), with a thickness of

80 m. The basement is formed by Upper Cretaseous limestones. This section was measured in the Silifke and Mut formations. The first fifty meters of the section belong to Silifke formation and the other 30 meters to the Mut formation. Silifke formation's lithology in the section consists of alternate of marl, clayey limestones, siltstone and clayey-silty limestone. Mut formation consists of predominantly limestone and clayey limestone. Thirtheen samples were taken throughout the section. The samples selected for this study were taken from clayey and clayey limestone levels that may contain fossils. From the samples of the section 11 species of the 7 planktonic foraminifera genera belonging to the Langhian-Serravallian stage (middle Miocene) have been identified and the studied section documents the *Orbulina suturalis* subzone (between 1 and 17 meters of the section) and the *Orbulina universa* subzone (between 17-50 meters of the section) (Figures 1,5,6).

In the present work we demonstrate that in the study area the Silifke formation and especially its Bozlağan member (late Burdigalian) contains ostracods species, including *Bairdia (Bairdoppilata) supradentata, Carinocythereis antiquate, Cytherelloidea postdenticulata, Cytherelloidea vandenboldi, Cytherelloidea glypta*, and *Neomonoceratina helvetica.* More over among planktonic species *Dentoglobigerina altispira, Dentoglobigerina venezuelana, Globigerina praebulloides leroyi, Globigerinanus tokerae, Globigerinoides obliquus, Globigerinoides subquadratus, Globigerinoides ruber, Globoturborotalita euapertura, Globoquadrina dehiscens, Orbulina bilobata, Orbulina suturalis, Praeorbulina glomerosa curva, Paludinella sicana, Trilobatus immaturus, Trilobatus sacculifer* (Plates I, II and Figures 4,5) to those listed by Gökten et al. [5], confirming the Langhian-Serravallian (middle Miocene) age of this member.

About Mut formation in the Silifke Castle section, ostracods include additional species such as *Hermanites haidingeri, Krithe papillosa, Neonesidea corpulenta and Pokornyella deformis minor* assocated to planktonic foraminifera taxa, such as *Globigerinella obesa, Trilobatus bisphericus, Trilobatus trilobus* confirming the Serravallian (middle Miocene) age of the Mut formation (Plates I, II and Figures 4,5) like as suggested by Tanar et al. [8].

Biostratigraphy

Distribution of the recognized planktonic foraminiferal species including index biozonal biomarkers in the study deposits from Şıhlar, Silifke and Mut formations allows to perform detailed biostratigraphy. Adopting the Toumarkine et al. [63], biozonotion for the Eocene epoch, and Iaccarino et al. [27], four planktonic foraminiferal biozones were delinated in this study arranged from older to younger as follows: *Turborotalia frontosa*, *Turborotalia possagnoensis* (lower-middle Eocene), *Orbulina suturalis* and *Orbulina universa* (Langhian-Serravallian). The identified biozones in Italy were compared with the standard zones of Bolli et al. [69,70], (in Trinidad) Premoli et al. [71], (in Caribbean Sea), Blow et al. [72], and Berggren et al. [73], and Berggren et al. [74], (in tropical and subtropiacal regions) and Wade et al. [75], (tropical regions). Also, similarities and differences of identified biozones have been given with studies which were done in Turkey as the immediate surroundings of the work area. For the Miocene Epoch; based on the studies of Iaccarino et al. [76], (in Mediterranean) and Mandur et al. [63], (in Egypt/Gulf of Suez), the identified biozones were compared with the standard zones of Blow et al. [72], and Berggren et al. [77], and Wade et al. [75], (tropic regions). Also, similarities and differences of identified biozones have been given with studies which were done in Turkey and Northern Cyprus as the immediate surroundings of the work area (Figures 5,10).

Turborotalia frontosa zone

Category: Concurrent range zone.

Age: Early to middle Eocene.

Authors: Toumarkine et al. [62].

Definition: This zone occurs from the first appearance of *Turborotalia frontosa* to the first appearance of *Turborotalia possagnoensis*.

Association: *Acarinina bullbrooki, Acarinin soldadoensis, Acarinin pentacamerata, Parasubbotina inaequispira, Planorotalites capdevilensis, Pseudoglobigerinella bolivariana, Subbotina eocaena, Subbotina senni, Turborotalia frontosa* (Plates I, II and Figure 6).

Occurence: This zone is observed in the Akkum section, in samples no. 2 and 3, between 9-26 meters (Figures 5, 11).

Remarks and correlation: At the lower Eocene, the *Acarinina pentacamerata* zone identified by Bolli et al. [69,70], (in Trinidad), Premoli et al. [71], (in Caribbean Sea) and Yıldız et al. [78], (in Turkey/Isparta). It is equivalent of *Acarinina densa* zone identified by Blow et al. [72], and Berggren et al. [73], (P9) and of *Acarinina cuneicamerata* zone identified by Berggren et al. [74], (in tropical and subtropiacal regions).

Beyond, at the lower part of the middle Eocene, it is the *Hantkenina nuttalli* zone identified by Bolli et al. [70,71], (in Trinidad), Premoli et al. [71], (in Caribbean Sea) and Berggren et al. [74], (in tropical and subtropical regions). It is coeval with *Hantkenina aragonensis* zone (P10) identified by Blow et al. [72], and Berggren et al. [73], and with *Hantkenina nuttalli* zone (P10) identified by Berggren et al. [77], and *Guembelitroides nuttalli* zone (E8) identified by Wade et al. [75], (in Tropic regions).

The *Turborotalia frontosa* zone delinetad the interval between lower and middle Eocene epoch by Toumarkine and Bolli et al. [70], in Italy. In the study area, this zone was identified at the same stratigraphic level by İbilioğlu et al. [79], (in Turkey/Elazığ) and Şafak et al. [80], (in Turkey/Adıyaman). At this stratigraphic level, Pleurostomella (Astrorotalia) palmerae-*Hantkenina nuttalli* zone (P9) identified by Berggren et al. [77], and *Turborotalia frontosa* zone (E7b) and base of the *Guembelitroides nuttalli* zone (E8) identified by Wade et al. [75], (in Tropic area). In the present work, *Turborotalia frontosa* zone is recognized in the Şıhlar formation and indicates the lower-middle Eocene. However, the index species is not observed at the base of the formation. (Figure 10).

Turborotalia possagnoensis zone

Category: Concurrent range Zone.

Age: Middle Eocene.

Author: Toumarkine et al. [62].

Definition: This zone occurs between the first appearance of *Turborotalia possagnoensis* and the last appearance of *Turborotalia frontosa*.

Association: *Acarinina soldadoensis, Globigerina officinalis, Parasubbotina inaequispira, Pseudoglobigerinella bolivariana, Subbotina eocaena, Subbotina senni, Turborotalia frontosa, Turborotalia pomeroli, Turborotalia possagnoensis* (Figure 9).

Occurence: This zone is observed in the Akkum Section, in samples no. 4-6, between 26-33 meters (Figures 9,10).

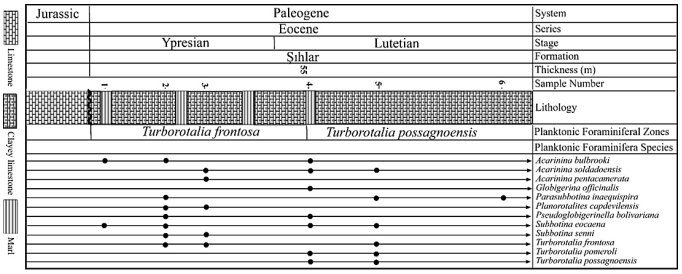


Figure 9: Distribution of planktonic foraminiferal species in the Akkum section. **Note:** (▭) Limestone, (▭) Clayey limestone, (▭) Marl.

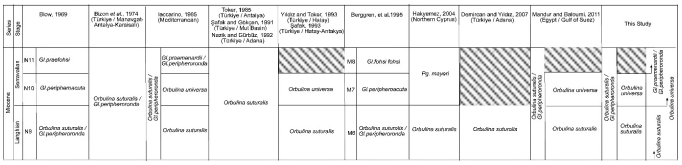


Figure 10: Correlation of middle Miocene planktonic foraminiferal zones proposed by several authors.

Remarks and correlation: The *Turborotalia possagnoensis* zone was described at the basal level of middle Eocene epoch by Toumarkine et al. [62], (in Italy). This zone was recognized at the same stratigraphic level by İbilioğlu et al. [79], (in Turkey/Elazığ) and Şafak et al. [80], (in Turkey/Adıyaman). It covers the upper part of *Hantkenina nuttalli* zone and *Globigerinatheka subconglobata* and *Morozovella lehneri* zones by Bolli et al. [69,70], (in Trinidad) and Premoli et al. [71], (in Caribbean Sea). It also covers the upper part of *Hantkenina aragonensis* zone and the Globigerinatheka kugleri and Morozovella lehneri zones by Blow et al. [72], and Berggren et al. [73]. It is equivalent of the upper part of *Hantkenina aragonensis/ Acarinina topilensis-Globigerinatheka (Prg.) kugleri* and *Morozovella lehneri* zones (P10-12) by Berggren et al. [77], (P10-12) as well as by Berggren et al. [74], (in tropical and subtropiacal regions) and Wade et al. [75], (in tropic regions) two named this interval (E8-E11). Also, Yıldız et al. [78], (in Turkey/Isparta) defined the *Hantkenina aragonensis* zone at the lower part of the *Turborotalia possagnoensis* zone. In this study, *Turborotalia possagnoensis* zone was recognized in samples from Şıhlar formation and indicates the middle Eocene. At the Akkum section the index species is recognized in samples 4 and 5 collected in the upper part of the section (Figures 7,10).

Orbulina suturalis/Globorotalia peripheroronda zone

Category: Concurrent range zone

Age: Middle Miocene (Langhian-Serravallian)

Author: Bizon et al. [81].

Definition: The interval from the first occurrence of *Orbulina suturalis* from the last occurrence of Globorotalia peripheroronda.

Association: *Dentoglobigerina altispira, Dentoglobigerina venezuelana, Globigerina praebulloides leroyi, Globigerinanus tokerae, Globigerinella obesa, Globigerinoides ruber, Globigerinoides subquadratus, Globoquadrina dehiscens, Globoturborotalita euapertura, Orbulina bilobata, Orbulina suturalis, Orbulina universa, Praeorbulina glomerosa curva, Paludinella sicana, Trilobatus bisphericus, Trilobatus immaturus, Trilobatus sacculifer, Trilobatus trilobus* (Figures 8,9).

Occurence: This zone was determined in the Silifke and Mut formation's samples from the Silifke Castle section in samples no. 1-12, between 1 and 150 m and in the Silifke-Taşucu section in samples no. 13-1, between 1 and 50 m. The upper boundary of this zone could not be determined in this study so such Globorotalia praemenardii and Globorotalia peripheroronda are not found in the samples (Figures 10, 11).

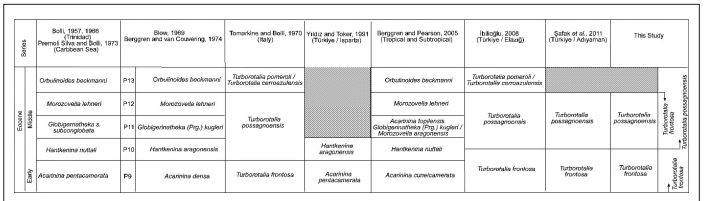


Figure 11: Correlation of lower-middle Eocene planktonic foraminiferal zones proposed by several authors.

Remarks and correlation: The *Orbulina suturalis/Globorotalia peripheroronda* zone was described at the interval between upper level of Langhian and lower level of Serravallian stages by Iaccarino et al. [27], (in Mediterranean). This zone is divided into 3 subzones by the same author (idem.) which are *Orbulina suturalis*, *Orbulina universa* and *Globorotalia praemenardii/Globorotalia peripheroronda* subzones. This zone was identified at the same stratigraphic level by Bizon et al. [82], (in Turkey/Manavgat-Antalya-Karaisalı) and Mandur et al. [63], (in Egypt/Gulf of Suez). At the same level, the *Orbulina suturalis/Globorotalia peripheroronda*, *Globorotalia peripheroacuta*, and *Globorotalia praefohsi-Globorotalia fohsi fohsi* zones (N9-N11) identified by Blow et al. [72], and Berggren et al. [74], (M6-M8) and *Orbulina suturalis*, *Fohsella peripheroacuta*, and *Fohsella praefohsi* zones (M6-M8) identified by Wade et al. [75], (in tropic regions).

Later, Hakyemez et al. [83], (in Northern Cyprus) defined *Paragloborotalia mayeri* zone as equivalent of *Orbulina universa* and *Globorotalia praemenardii/Globorotalia peripheroronda* subzones.

In this study, two subzones of the *Orbulina suturalis/Globorotalia peripheroronda* zone was determined which are *Orbulina suturalis* and *Orbulina universa* subzones. *Globorotalia praemenardii/Globorotalia peripheroronda* subzone could not be determined in this study until *Globorotalia praemenardii* and *Globorotalia peripheroronda* were not found in the samples of the Silifke and Mut formations (Figures 4,5,11).

Orbulina suturalis subzone

Category: Lineage subzone

Age: Middle Miocene (Langhian)

Author: Cita et al. [84], in Cita, 1976.

Definition: The interval with the zonal marker from the first appearance of *Orbulina suturalis* to the first occurrence of *Orbulina universa*.

Association: *Dentoglobigerina altispira, Dentoglobigerina venezuelana, Globigerina praebulloides leroyi, Globigerinanus tokerae, Globigerinella obesa, Globigerinoides obliquus, Globigerinoides ruber, Globoquadrina dehiscens, Orbulina bilobata, Orbulina suturalis, Orbulina universa, Praeorbulina glomerosa curva, Paludinella sicana, Trilobatus bisphericus, Trilobatus immaturus, Trilobatus sacculifer, Trilobatus trilobus* (Figures 4,5).

Occurence: This zone was determined in the Silifke formation's samples from the Silifke Castle section in samples no. 1-5, between 1 and 64 m and in the Silifke-Taşucu section in samples no. 13-9, between 1 and 17 m (Figures 4,5).

Remarks and correlation: The *Orbulina suturalis* subzone was described as upper level of Langhian by Iaccarino et al. [27], Mandur et al. [63], (in Egypt/Gulf of Suez) as subzone of *Orbulina suturalis/Globorotalia peripheroronda* zone in Mediterranean. In this study, *Orbulina suturalis* subzone is recognized at the upper level of the Langhian stage in samples from Silifke formation (Figures 4,5).

This subzone has been identified at the same stratigraphic level described as zone by Yıldız et al. [85], (in Turkey/Hatay), Şafak et al. [23], (in Turkey/Hatay-Antakya), Hakyemez et al. [83], (in Northern Cyprus), Demircan et al. [86], (in Turkey/Adana), Wade et al. [75], (in tropic region) (M6).

The *Orbulina suturalis* subzone, is equivalent of the *Orbulina suturalis/Globorotalia peripheroronda* zone (N9) defined by Blow et al. [72], and Berggren et al. [74], (M6). The *Orbulina suturalis* zone has been also recognized by Toker et al. [87], (in Antalya), Şafak et al. [10], (Mut Basin), Nazik et al. [88], (in Adana) and indicates the interval between upper Langhian and lower Serravallian stages in Turkey. It is equivalent of the *Orbulina suturalis/Globorotalia peripheroronda* zone determined by Bizon et al. [82], (in Manavgat-Antalya-Karaisalı) in Turkey (Figures 4,5,11)

Orbulina universa subzone

Category: Concurrent range subzone

Age: Middle Miocene (Serravallian)

Author: Iaccarino et al. [76].

Description: The interval with the zonal marker from the first appearance of *Orbulina universa* to the first appearance of Globorotalia praemenardii.

Association: *Dentoglobigerina altispira, Dentoglobigerina venezuelana, Globigerinella obesa, Globigerinoides obliquus, Globigerinoides subquadratus, Globigerinoides ruber, Globoquadrina dehiscens, Globoturborotalita euapertura, Orbulina bilobata, Orbulina suturalis, Orbulina universa, Trilobatus immaturus, Trilobatus sacculifer, Trilobatus trilobus* (Figures 10,11).

Occurence: The upper boundary of this zone could not be determined in this study as Globorotalia fohsi peripheroronda was not found in the samples. This zone was documented in the samples of Silifke formation's upper level and Mut formation from the Silifke Castle section in samples no. 6-12, between 64 m and 150 m and in the Silifke-Taşucu section in samples no. 10-1, between 17 m and 50 m.

Remarks and correlation: The *Orbulina universa* subzone indicates lower part of Serravallian according to Iaccarino et al. [27]. It is equivalent of subzone of *Orbulina suturalis/Globorotalia peripheroronda* zone defined in Mediterranean. This subzone has been identified at the same stratigraphic level by Mandur et al. [63], (in Egypt/Gulf of Suez). In the present study, *Orbulina universa* subzone is recognized in samples from Silifke and Mut formations and indicates the lower part of the Serravallian stage.

This subzone has been identified at the same stratigraphic level described as zone by Yıldız et al. [85], (in Turkey/Hatay), Şafak et al. [12], (in Turkey/Hatay-Antakya). Coming in contrast to the *Orbulina universa* subzone, the Globorotalia peripheroacuta zone (N10) is defined by Blow et al. [72], and Berggren et al. [77], (M7). Later *Orbulina suturalis* zone has been recognized by Toker et al. [87], (in Antalya), Şafak et al. [10], (Mut Basin), Nazik et al. [88], (in Adana) at the interval between upper level of Langhian and lower level of Serravallian stages in Turkey. Also, at the lower level of the Serravallian stage, *Paragloborotalia mayeri* zone was identified by Hakyemez et al. [83], (in Northern Cyprus). In this stratigraphic level, Fohsella peripheroacuta and Fohsella praefohsi zones (M7-M8) have been determined by Wade et al. [75], (in tropical region) (Figures 10,11).

Petrography and mineralogy

XRD analysis: Typical X-ray diffractograms of powdered sedimentary rocks are shown in Figure 7. The patterns indicate that all samples have rock, clay, and formation minerals. The XRD results show that the clayey limestones are dominated by calcite, dolomite, quartz, and hematite. In the Şıhlar formation, the mineral suite contains the following: Calcite 72%, dolomite 12%, hematite 5%, quartz 5%, and kaolinite 5% (Figure 7). Eocene limestones are described for the first time in this study. For this purpose, XRD analyses were carried out, and the mineral associations of these rocks were revealed. Boero et al. [89], identified the critical role of limestone in defining the particular pedoclimate, under which the hematite of terra rossa forms. Kaolinite occurs by chemical weathering in humid and warm climatic conditions [25,90-94].

These results indicate that the studied samples are also affected by weak diagenesis. Moreover, the quartz content in carbonate indicate detrital influence that is not negligible [95].

Microfacies analysis

Carbonates of the Eocene and Miocene limestones of the Silifke/Mersin region, which include packstone, wackestone, grainstone, and mudstone (Figure 6) are found in thick and medium beds. Significant fragments noted were non-skeletal, skeletal and intraclast grains, abundant sparitic cement, relatively minor micritic cement, and some quartz crystals. These carbonates are rich in planktonic foraminifera and ostracods.

Packstone: In Eocene limestone, packstone layers alternate with clayey limestone and wackestone at a scale from centimetres to metres. The packstone includes minor quartz grains and rare hematite. The intraclasts and minor quartz are cemented by sparry calcite. The packstone contains sparry calcite cement and minor micritic matrix, as well as bivalve shell fragments, ostracods and planktonic foraminifera.

Wackestone: In the carbonates studied, there was a yellow- to cream-coloured Eocene wackestone with fossils and shells, composed of sparite and lacking internal texture. The wackestone contains 5-7% intraclasts, 2-3% entire shells and minor amounts of quartz crystals.

Grainstone: The upper part of the Şıhlar limestone is represented by ooidal and peloidal grainstone microfacies, abundant in planktonic foraminifera and rare benthic foraminifera. The limestone examined is described as a grain-supported rock that includes less than 1% mud material.

Mudstone: The matrix has locally presented with blocky (drusy) cement and is crossed by calcite veins. The mudstone is defined by fine-grained carbonate in a mixture of silt and clay grains.

These different facies invoke that the hydrodynamic conditions

in the area are far from to stable during the studied formations deposition. For example, mudstone facies indicates quiet paleoenvironment in contrast grainstone indicates turbulent paleoenvironnement. The change in facies are undoubtedly related to reefal facies sequences organisation.

DISCUSSION

At the Akkum section (Figure 9) the Eoce deposits which are 24 thick include two planktonic foraminifera biozones; the *Turborotalia frontosa* zone (17 m), characterizes the intermediate zone of early-middle Eocene. Through this biozone interval the planktonic foraminiferal association is diversified, including the index species and eight other species, i.e., *Acarinina bullbrooki, Acarinina soldadoensis, Acarinina pentacamerata, Subbotina eocaena, Subbotina senni, Parasubbotina inaequispira, Pseudoglobigerinella bolivariana* and *Turborotalia pomeroli.* The *Turborotalia possagnoensis* zone assigned to the lutetian is less thick (7 m). Through the interval deposits of this biozone, the planktonic foraminifera association includes the index zonal biomarker and eight other Eocene species ; most of them are inherited from the previous interval (e.i., *Acarinina soldadoensis, Parasubbotina inaequispira, Pseudoglobigerinella bolivariana, Subbotina eocaena, Subbotina senni, Turborotalia frontosa*) and only three species are added, i.e. *Turborotalia possagnoensis* (zonal index species), *Globigerina officinalis,* and *Turborotalia pomeroli*). In the studied material the absence of species belonging to *Hantkenina* and *Globigerinatheka* and *Morozovella* genera is a remarkable fact, whereas Bolli et al. [69,70] used *Globigerinatheka subconglobata* and *Morozovella lehneri* zones in Trinidad. Such biozones was recognized in the middle Eocene of Elazig and Adıyaman regions in Turkey [79,80]. In Isparta, the *Hantkenina aragonensis* zone was defined in response to the upper levels of this zone [78]. In the Caribbean, in response to this zone, Hantkenina nuttali, *Globigerinatheka subconglobata* and *Morozovella lehneri* zones have been reported [71], and *Hantkenina aragonensis, Globigerinatheka (Prg.) kugleri* and *Morozovella lehneri* zones (P10-12) [72,73], *Hantkenina nuttali, Acarinina topilensis-Globigerinatheka (Prg.) kugleri/Morozovella aragonensis Morozovella lehneri* zones [74], have been defined. The absence of spinose and keeled species may be related to colder marine water distribution in the study area.

About the Miocene, the *Orbulina suturalis/Globorotalia peripheroronda* zone indicates the Langian-Serravalian. It is subdivided into two subzones, *Orbulina suturalis* subzonre indicating the Langhian and Orbolina universa subzone assigned to the Serravalian. The *Orbulina suturalis* subzonre interval deposition is 86 m in the Silifke-TaŞucu section. In this interval the planktonic foraminiferal association is diversified. Eleven species are recognized including the index species *Dentoglobigerina venezuelana, Globigerinella obesa, Globoquadrina dehiscens, Globoturborotalita euapertura, Orbulina bilobata, Orbulina suturalis, Orbulina universa, Praeorbulina glomerosa curva, Trilobatus immaturus, Trilobatus sacculifer, Trilobatus trilobus.* In the Silifke-Castle section, the the *Orbulina suturalis* subzone interval is 33 m thick. In its foraminiferal association *Dentoglobigerina altispira, Globigerinanus tokerae, Paludinella sicana, Trilobatus bisphericus, Globigerina praebulloides leroyi* are supplemented.

The *Orbulina universa* subzone indicates the Serravalian. Its deposition interval is well developed in the two studied sections, although its upper boundary could not be detected as Globorotalia praemenardi was not found. Through this interval, the planktonic foraminifera association is composed of the index species and other species that most are inherited from the previous subzone (Figures 4,5)

In the studied sections a major unconformity underlying the base of the Cenozoic sequences. The magmatic rocks corresponding to the Mersin Ophiolite are represented by gabbro, diorite, quartz diorite and serpentinite; they constitute the basement of the Eocene and Miocene carbonate units. These sedimentary units, composed of limestones and clayey limestones are rich in calcite; however dolomite, quartz, hematite and kaolinite are less represented. Except calcite the other minerals are provided from tardive alteration of the different signaled magmatic rocks.

CONCLUSION

• As a result of the biostratigraphic study, based on planktonic foraminiferal assemblages, four biozones are recognized; *Turborotalia frontosa* and *Turborotalia possagnoensis* biozones date respectively the Ypresian and the Lutetian and *Orbulina suturalis* and *Orbulina universa* characterize respectively the Langhian and the Serravallian.

• In fact, the weakly extended limestones outcropping in the Silifke region detailed for the first time reveal divers planktonic foraminiferal species including the zonal biomarkers assigned to the early-middle Eocene.

• In Silifke region and its surroundings, the Miocene deposits represente *Orbulina suturalis* zone and assigned to the Burdigalian. In the study sections we demonstrate that the Miocene deposits cover *Orbulina suturalis* and *Orbulina universa* biozones indicating rather the Langhian and Serravalian.

• The *Orbulina universa* zone, subdivided into Globorotalia mayeri/ Globigerinoides bisphericus and Globorotalia mayeri subzones indicates the middle Miocene, and especially the Serravallian in Silifke section and its vicinity.

• Based on planktonic foraminifera it is established that Şıhlar formation is Ypresian-Lutetian in age and Silifke and Mut formations belong to Langhian-Serravallian stratigraphic interval.

• Petrographic and XRD analysis invoke that the examined carbonates of Şıhlar formation are represented by four microfacies, including mudstone, packstone, wackestone and grainstone. Moreover, the limestones and clayey limestones examined contain quartz, calcite, hematite, dolomite, and rare kaolinite. In addition, the petrography of the underlying units on which the sedimentary units unconformably lie was also studied, and the magmatic rocks in the study area constitute the basement units. The magmatic rocks of the Mersin ophiolite are represented by gabbro, diorite, quartz diorite and serpentinite.

• The hematite occurrence in the Eocene limestones is consistent with the previous study suggestion. These limestones identified as the critical role, defining the particular pedoclimate, under which the hematite of terra rossa had been formed. Forthermore, kaolinite occurrence suggests chemical weathering in humid and warm climatic conditions like as considered by several authors.

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AUTHOR CONTRIBUTION

Ümit Şafak: conceptualization, data collection, investigation, validation, writing review, and editing. Ayşegül Güney: conceptualization, data collection, writing original draft, formal analysis, and methodology. Nusret Nurlu: conceptualization, data collection, writing original draft, formal analysis, and methodology. Hande Sonsun: conceptualization, data collection, writing original draft, formal analysis, and methodology.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to infuence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues data sets with DOIs.

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