The calcareous nannofossil record of the uppermost Maastrichtian-lower Palaeocene in the Kırıkkale Basin, in the Central Anatolian Region (Turkey)

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Abstract

The Late Cretaceous–Early Paleogene (K–Pg) was a critical period of transition in geological time. This period encompassed short-term climatic fluctuations on a global scale, changes in ocean circulation, and sudden and large extinctions of marine and terrestrial organisms. In the study area, located in the mid to low latitudes, the Late Cretaceous and Early Paleogene were very tectonically active due to the positioning of the site close to the collision zone of two large continents. The impacts of the global K–Pg crisis can be observed in the study area. In this study, the calcareous nannofossil contents of late Maastrichtian–Danian sediments were studied, and the nannofossil biostratigraphy determined, from samples from the Samanlık and Dizilitaşlar Formations, deposited in the Kırıkkale Basin. From three stratigraphic sections, 26 nannofossil genera and 36 nannofossil species were identified from the Late Maastrichtian UC20a^{TP} and UC20b^{TP} biozones and the NP1 and NP2 biozones of the Danian. Additionally, it was determined that the K–Pg boundary was not continuous in the study area. In the Kırıkkale Basin, relatively low abundances of *Micula decussate* Vekshina, 1959 signals a diagenetic effect and stressful environment in the Late Maastrichtian, whereas the relatively low abundances of *Thoracosphaera operculata* Bramlette & Martini, 1964*, Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 and *Futyania petalosa* (Ellis & Lohmann, 1973) Varol, 1989 in the Danian assemblages indicate unstable environmental conditions and major environmental perturbations that reflect tectonic activity in the region. No nannofossils were encountered in those samples taken from turbiditic levels, which contained high proportions of sand.

INTRODUCTION

The study area is located close to the villages of Hacıbalı, Mahmutlar and Aşağısamanlık in Kırıkkale Province, in the Central Anatolian Region (Fig. 1). The depositional basins in the Central Anatolian Region formed above two continental units––the Sakarya Continent and Kırşehir Block-separated by a suture zone (GORUR et al., 1998) (Fig. 1). In the Late Cretaceous, the Sakarya Continent, Menderes–Tauride Platform and Kırşehir Block were separated by the İzmir–Ankara, Ankara–Erzincan and Inner Tauride Oceans. At the end of the Cretaceous, the Kırşehir Block and Sakarya Continent collided (TUYSUZ & DELLALOGLU, 1992; GORUR et al., 1998). The Kırşehir Block is surrounded by ophiolitic mélanges created as a result of the subduction of the İzmir–Ankara, Ankara–Erzincan and, later, the Inner Tauride Oceans (GORUR et al., 1998).

The Kırşehir Block, on which the study area is located, comprises mostly ophiolitic rock fragments and sedimentary cover rocks sitting above a metamorphic basement. The basement comprises gneiss, amphibolite, schists and marbles resulting from Cretaceous metamorphism (KETIN, 1961; ERKAN, 1975; ŞENGOR & YILMAZ, 1981; GONCUOĞLU, 1981; SEYMEN, 1982; ŞENGOR, 1985; GORUR et al., 1998). The cover rocks above this metamorphic basement extend from the Upper Cretaceous to the Holocene and mostly represent sedimentary sequences filling basins that varied in width and depth (GORUR et al., 1998).

The Kırıkkale Basin, which evolved between the Late Cretaceous and Late Palaeocene, has several features of a within-arc basin (GORUR et al., 1998), and is deep and narrow, forming a connection between the Çankırı Basin to the north and the Tuzgölü Basin to the south (NORMAN, 1972a, b; GOKCEN, 1977). The turbiditic sedimentation in the basin began before the Maastrichtian, with abundant volcanic and volcano-sedimentary contributions. GORUR et al. (1998) stated that the turbiditic sedimentation lasted until the end of the Lutetian and was coeval with shallow marine sedimentation in the east and southeast in the Late Thanetian–Ypresian.

Although several geological studies have been carried out in the region, biostratigraphic studies are limited. YILDIZ et al. (2000) investigated the biostratigraphy and palaeoecology of the Lower Maastrichtian–Paleocene sedimentary units, using trace fossils, planktonic foraminifera and calcareous nannofossils. They also determined the $\delta^{18}O$ and $\delta^{13}C$ isotope values from planktonic foraminifera tests and compared these with the abundance distributions of calcareous nannofossils purported to be sensitive to temperature, finding that the sea-surface water temperature and salinity were lower in the Early Maastrichtian than the Palaeocene, increasing from the beginning of the Danian. AKORALER (2018) and GORMUS & AKORALER (2019) investigated the benthic foraminiferal biostratigraphy and palaeoecology of the Late Cretaceous and Maastrichtian sedimentary deposits of the Kırıkkale and Kalecik regions. They posited that increased abundances of *Orbitoides* indicated tolerable temperature conditions and a shallow basin in this interval.

We investigated the nannofossil biostratigraphy in detail in the turbiditic sedimentary rocks in the Kırıkkale Basin in the İzmir–Ankara zone––one of the important tectonic belts in Turkey. In particular, we focused on determining changes in the Maastrichtian to Danian palaeoenvironment using the relative abundances of certain nannofossil species.

2. GEOLOGICAL SETTING

The study area was located in the İzmir–Ankara Zone. Rocks belonging to the İzmir–Ankara Zone were tectonically emplaced above the rocks of the Kırşehir Block, while rocks belonging to the Sakarya Zone were tectonically placed above these (DONMEZ et al., 2008). The rocks of the İzmir–Ankara Zone have tectonostratigraphic relationships with each other, the oldest unit comprising the Late Cretaceous Artova Ophiolite Complex, and the youngest being Paleocene–Early Eocene in age (Figs. 1, 2). Rocks from the İzmir–Ankara Zone typically comprise sediments from a closing basin (i.e. a basin with converging margins) that were deposited in the Late Cretaceous through to the Early Eocene. The relationships between sediments with turbiditic characteristics mainly occur in the form of underthrusts in a basin that was converging and closing (DONMEZ et al., 2008).

As explained above, the Artova Ophiolite Complex tectonically overlies rocks of the Kırşehir Block, while rocks of the Sakarya Zone have been emplaced as thrust units above this (DONMEZ et al., 2008). The Kocatepe Formation occurs above the Artova Ophiolite and comprises sequences of fragmented, clayey pelagic limestone and radiolarite-mudstone with calciturbidite intercalations (Fig. 2). The unit has been interpreted as Cenomanian–Campanian in age based on benthic and planktonic fossils (AKYUREK et al., 1997).

The Cenomanian–Campanian Karadağ Formation (AKYUREK et al., 1982, 1984) comprises volcaniclastic conglomerate, sandstone, mudstone and clayey limestone alternations, is turbiditic and has a tectonostratigraphic relationship with the Artova Ophiolite Complex (DONMEZ et al., 2008) (Fig. 2). The Lower

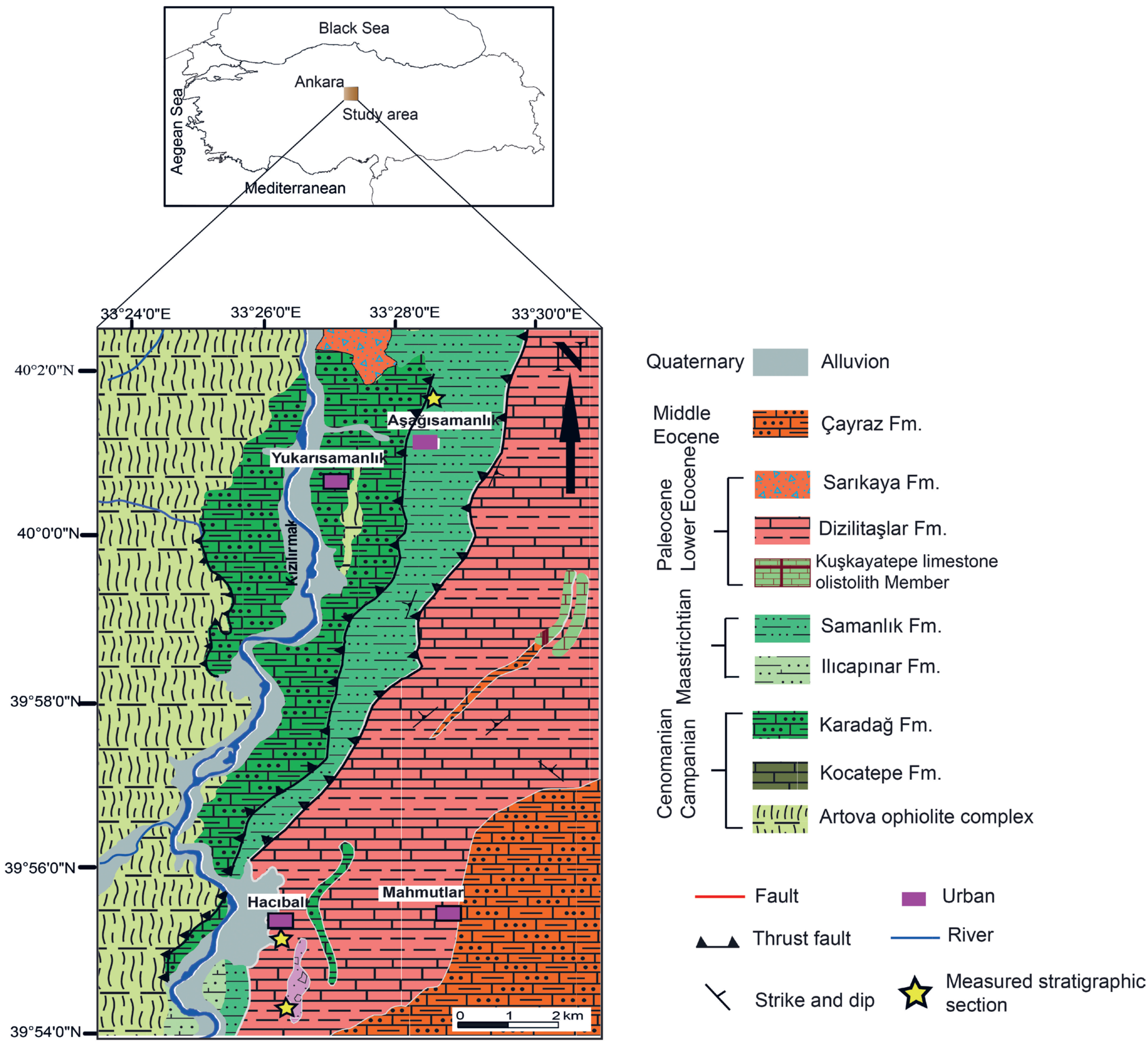

Figure 1. Map of the study area showing the geology and sampled locations (simplified after DONMEZ et al., 2008).

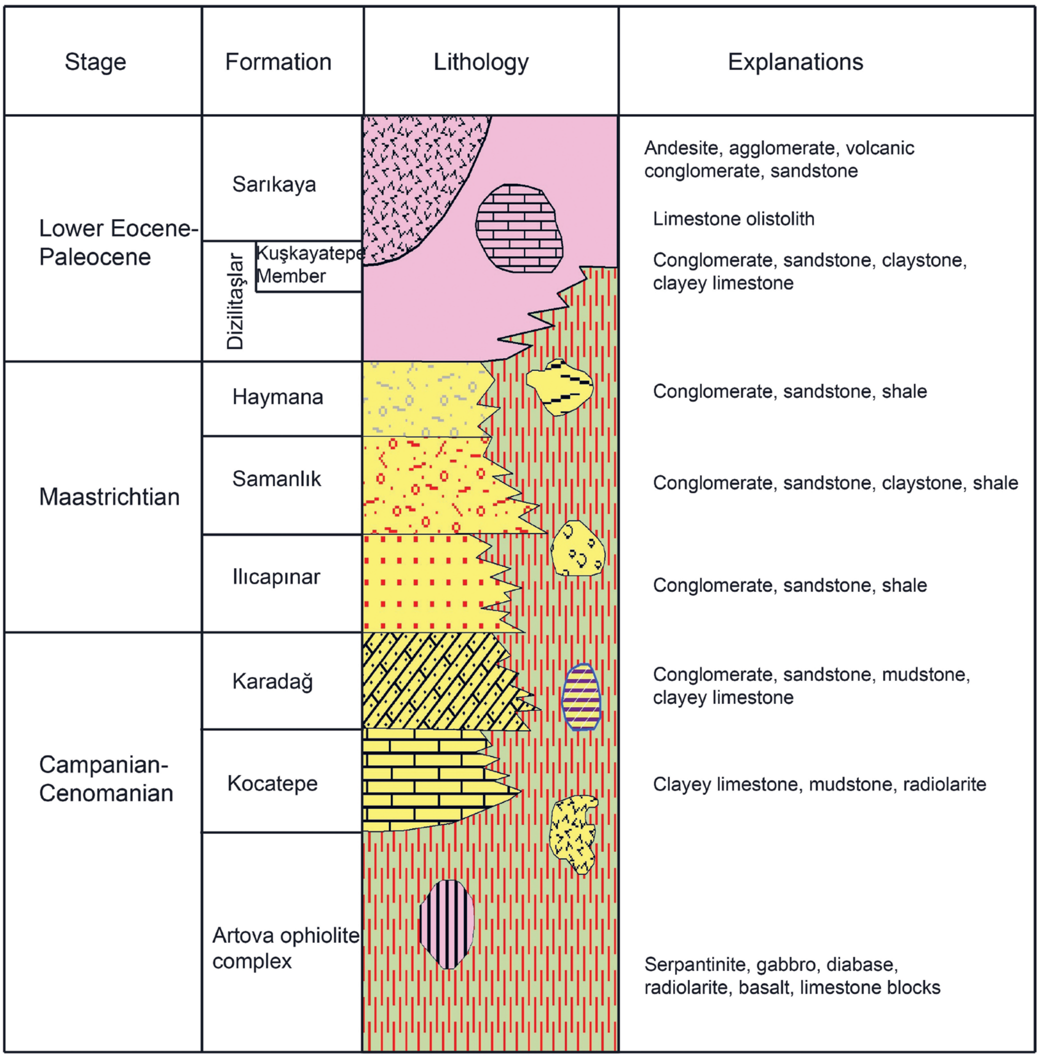

Figure 2. Generalised stratigraphic column of the Kırıkkale area (after DONMEZ et al., 2008).

Maastrichtian Ilıcapınar Formation (NORMAN, 1972a) is overlain by the Artova Ophiolitic Complex due to a thrust. The Ilıcapınar Formation is essentially turbiditic, comprising conglomerate and sandstone alternations.

The Samanlık Formation can be correlated to the Ilıcapınar Formation (AKYUREK et al., 1984), has a NE–SW orientation and is mainly turbiditic, comprising yellow, green, brown and grey conglomerate, sandstone and shale sequences (Figs. 1, 2). The unit comprises intermediate turbidites deposited in the lower part of a submarine fan at the same time as the Ilıcapınar Formation was being deposited (AKYUREK et al., 1984). The age of the Samanlık Formation is Maastrichtian based on fossils (AKYUREK et al., 1984).

The Haymana Formation (RIGO DE RIGHI & CORTESINI, 1959) overlies the Samanlık Formation and comprises intermediate turbidites with conglomerate, sandstone and shale alternations deposited in the middle of the lower part of a submarine fan (AKYUREK et al., 1997) (Fig. 2). The unit is considered to be of Maastrichtian age, based on fossil evidence, and gradually grades into the overlying Dizilitaşlar Formation (DONMEZ et al., 2008) (Figs. 1, 2).

The Dizilitaşlar Formation (NORMAN, 1972a) comprises Palaeocene–Lower Eocene turbiditic sediments deposited in a basin that developed in front of the Artova Ophiolite Complex in the Late Cretaceous. The limestone blocks occurring in this formation are known as the Kuşkayatepe Limestone Olistolith Member (DONMEZ et al., 2008) (Figs. 1, 2). The Dizilitaşlar Formation transitions into the Maastrichtian Samanlık Formation in some places, whereas it sits on top of the ophiolite, above an angular disconformity, in others (BİRGİLİ et al., 1975). The Çayraz Formation unconformably overlies the Dizilitaşlar Formation (DONMEZ et al., 2008) (Fig. 1). Above this is the Sarıkaya Formation, comprising conglomerates, sandstones and agglomerates containing volcanic material and, dominantly, andesitic lava. In this region, this formation is probably related to arc volcanism linked to a subduction event in the İzmir–Ankara Zone in the Late Cretaceous–Palaeocene (DONMEZ et al., 2008) (Figs. 1, 2).

3. MATERIAL AND METHODS

The Samanlık and Dizilitaşlar Formations were the focus of this study, and their outcrops in the region were examined in three measured stratigraphic sections at different locations––the Kırıkkale Organised Industrial Zone, Aşağı Samanlık and the Organised Industrial Region (Fig. 1). The sample intervals varied based on the field conditions and the general structure of the geology, with samples being taken every 30 to 100 cm. A total of 99 samples were collected from the three measured sections––32 samples from the Kırıkkale Organised Industrial Zone (Samples KOS1–KOS32), 40 samples from Aşağı Samanlık (Samples AS1–

Table 1 The abundances of calcareous nannofossils with species distribution in the Kırıkkale Organized Industrial Zone Section (OSB)

Samples	*Arkhangelskiella cymbiformis*	*Calculites obscurus*	*Ceratolithoides aculeus*	*Chiastozygus amphipons*	*Cribrosphaerella ehrenbergii*	*Eiffellithus eximius*	*Eiffellithus turriseiffelii*	*Lithraphidites carniolensis*	*Lithraphidites quadratus*	*Lithraphidites praequadratus*	*Microrhabdulus decoratus*	*Micrantholihus breviradiatus*	*Micula decussata*	*Micula murus*	*Prediscosphaera cretacea*	*Retecapsa crenulata*	*Watznaueria barnesiae*	*Braarudosphaera bigelowii*	*Markalius inversus*	*Thoracosphaera operculata*	*Zeugrhabdotus sigmoides*	*Coccolithus pelagicus*	*Cruciplacolithus intermedius*	*Cruciplacolithus primus*	*Cruciplacolithus tenuis*	*Futyania petalosa*	*Neochiastozygus distentus*	Nannofossil Biozones
OSB27																		F		R	VR	VR	VR			R		NP2
OSB26																		F		R		VR			VR	R		
OSB25																		F		F		VR	VR	VR	VR	VR		
OSB24												VR	R				VR	R	VR	R		VR						
OSB23																						VR	VR		VR	VR		
OSB22	VR				VR											VR	VR	VR	VR	R	VR	VR		VR		R		
OSB21																VR	VR	R	VR	R		VR	VR	VR	VR		VR	
OSB20																	R			R	VR	VR						NP1
OSB19	barren of calcareous nannofossils																											
OSB18																												
OSB17																												
OSB16																		F		F								
OSB15																		F		F								
OSB14							VR						R					F		F								
OSB13	barren of calcareous nannofossils																											
OSB12																		F	VR	F								
OSB11													F							F								
OSB10													F							F								
OSB 9					VR				VR		R		F	VR	VR		R	R		F								UC20b^TP
OSB 8	VR	VR	VR		VR	VR	VR		VR	VR	R		F	VR	VR	VR												
OSB 7	VR	VR	VR		VR		VR		VR	VR			F	VR	VR	VR		R										
OSB 6	VR			VR	VR			VR	R	VR	R		F		VR	VR	R	R		R	VR							UC20a^TP
OSB 5	VR		VR	VR	VR			VR	VR		R		F		VR		R			R	VR							
OSB 4	VR		VR		VR	VR	VR	VR	VR		R		F		VR	VR	R	R		R								
OSB 3		VR		VR	VR			VR	VR	VR	R		R		VR	VR	R			R	VR							
OSB 2			VR	VR	VR			VR	R		R		R		VR		R			R	VR							
OSB 1	VR		VR		VR			VR	VR				R		VR		R			R								

AS40) and 27 samples from the Organised Industrial Region (Samples OSB1–OSB27)

The calcareous nannofossils were analysed in smear slides (BOWN & YOUNG, 1998). Each slide was viewed at 1600x magnification with an oil-immersion lens under polarised light using a Leica DM 2500P microscope. Some of the nannofossils were photographed using a digital camera (Leica DFC 295). The relative abundances of the nannofossils were estimated using the method described in WEI (1988). Based on this method, one or more specimens of one species in each field of view (FOV) was classed as abundant (A), one in 2–10 FOVs as common (C), one in 11–50 FOVs as few (F), and one in 51–200 FOVs as rare (R).

4. RESULTS

The Upper Cretaceous (UC) standard nannofossil biozonation scheme developed by BURNETT et al. (1998) was used to determine the samples of Late Cretaceous age, whilst the NP biozonation scheme of MARTINI (1971) was used to date the Early Palaeocene samples. The species authors can be found in the book of Calcareous Nannofossil Biostratigraphy and website (Nannotax 3; https://www.mikrotax.org/Nannotax3/index.php?dir=ntax_cenozoic).

4.1. Calcareous nannofossil implications of the deposits

Below, the distributions of the calcareous nannofossils and the biostratigraphy interpreted from them are discussed separately for each measured section.

4.1.1. Kırıkkale Organised Industrial Zone section

Lithology

This section was measured along the road through the Kırıkkale Organised Industrial Zone (Fig. 1). The Samanlık Formation crops out at the base of the section, passing upwards into the Dizilitaşlar Formation with a tectonic contact. The total thickness of the section was 37 m, with 27 samples being taken (Fig. 3). Twenty-one nannofossil genera and 27 nannofossil species were identified (Table 1).

The base of the section generally comprised brownish-grey, fine- to medium-bedded sandstones and greyish-dark green laminated shale alternations of the Samanlık Formation (Fig. 3). Fine-bedded, cream-coloured clayey limestone layers were observed between these. While the section passed upwards into the Dizilitaşlar Formation, with a faulted contact, this contact be-

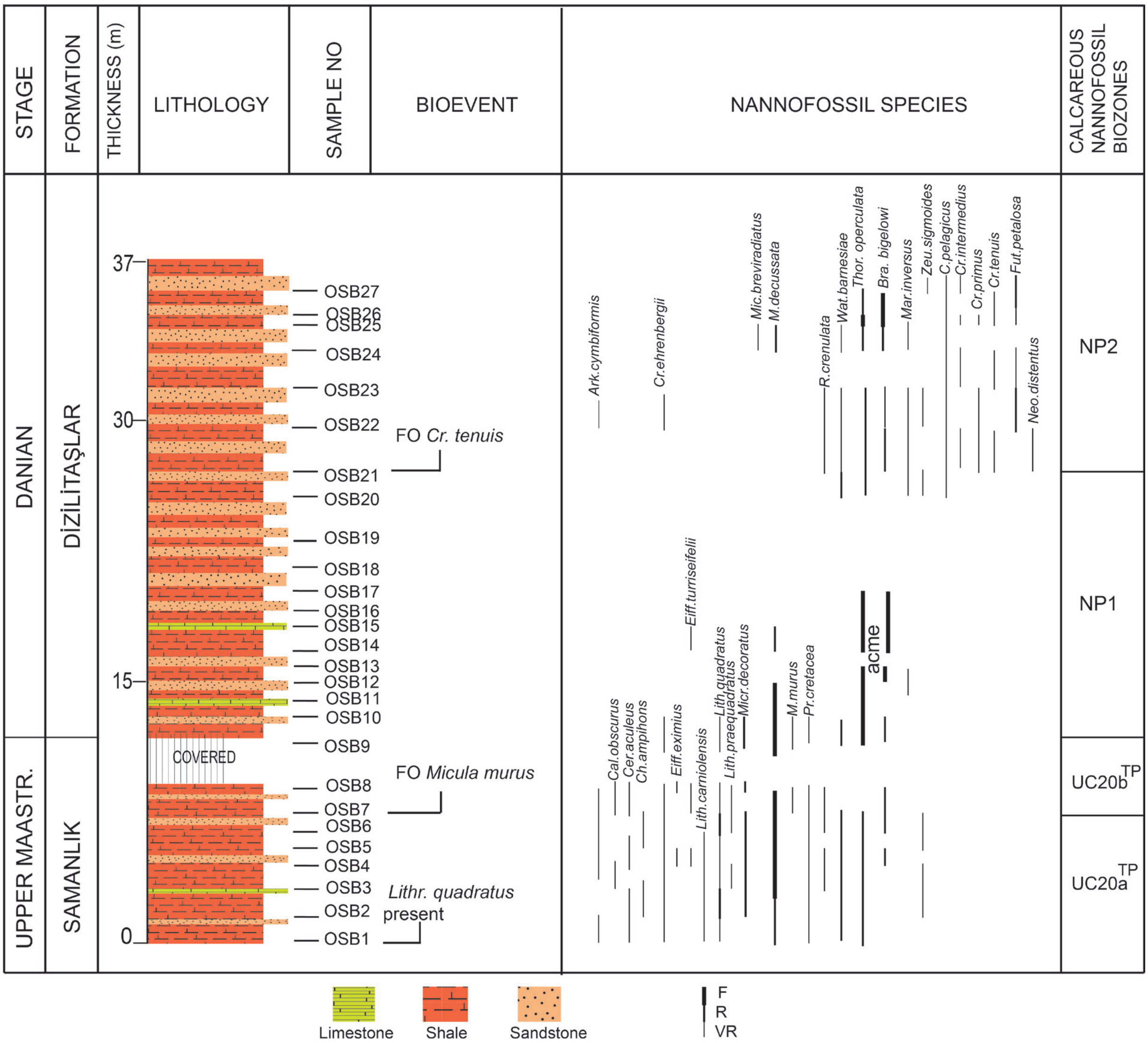

Figure 3. Lithostratigraphy, calcareous nannofossil abundances and biostratigraphy of the Organised Industrial Zone section.

tween the two formations was covered in the study area. At the base of the Dizilitaşlar Formation, the sandstones beds are fine, but they thicken (10–30 cm) towards the upper part of the formation. Fewer shales were observed in the upper part of the formation, where sandstone is more dominant. Faulting and deformation structures were frequently encountered throughout the section.

Calcareous nannofossils

The samples from the lowest 7 m of the section were determined to fall into the Nannofossil Biozone UC20a^{TP}, the assemblages containing mostly very rare *Lithraphidites quadratus* Bramlette & Martini, 1964, the base of which defines the base of UC20 (Fig. 3, Table 1). Zone UC20b^{TP} (defined from the base of *Micula murus* (Martini, 1961) Bukry, 1973) was identified in the same lithology, from 7 to 13 m (Fig. 3, Table 1). The species richness and abundance of Cretaceous nannofossil species in these samples was generally good, although the base of UC20b (Sample OSB7) exhibited low species abundance (Fig. 3, Table 1).

Low species abundances were noted in the alternating greenish-grey shale and dark brown sandstone beds of the Dizilitaşlar Formation (Fig. 3, Table 1). The samples from 13 to 28 m fall into Nannofossil Zone NP1––the interval from the top occurrence of Cretaceous nannofossils (and containing the bases of the earliest Danian *Thoracosphaera operculata* Bramlette & Martini, 1964 and *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 acmes) to the base of *Cruciplacolithus intermedius* van Heck & Prins, 1987 (Fig. 3, Table 1). The samples from 28 to 37 m (alternating dark brown and grey, medium-bedded sandstones and dark green shales) were determined as belonging to NP2, containing *Cruciplacolithus intermedius* van Heck & Prins, 1987 (Fig. 3, Table 1).

Samples from the uppermost Dizilitaşlar Formation (above Sample OSB9) contained only scarce nannofossils (Table 1). Additionally, there were no nannofossils found in Samples OSB17–OSB19 (Table 1). Although Danian nannofossils were observed in Sample OSB20 and above, the species abundances were very

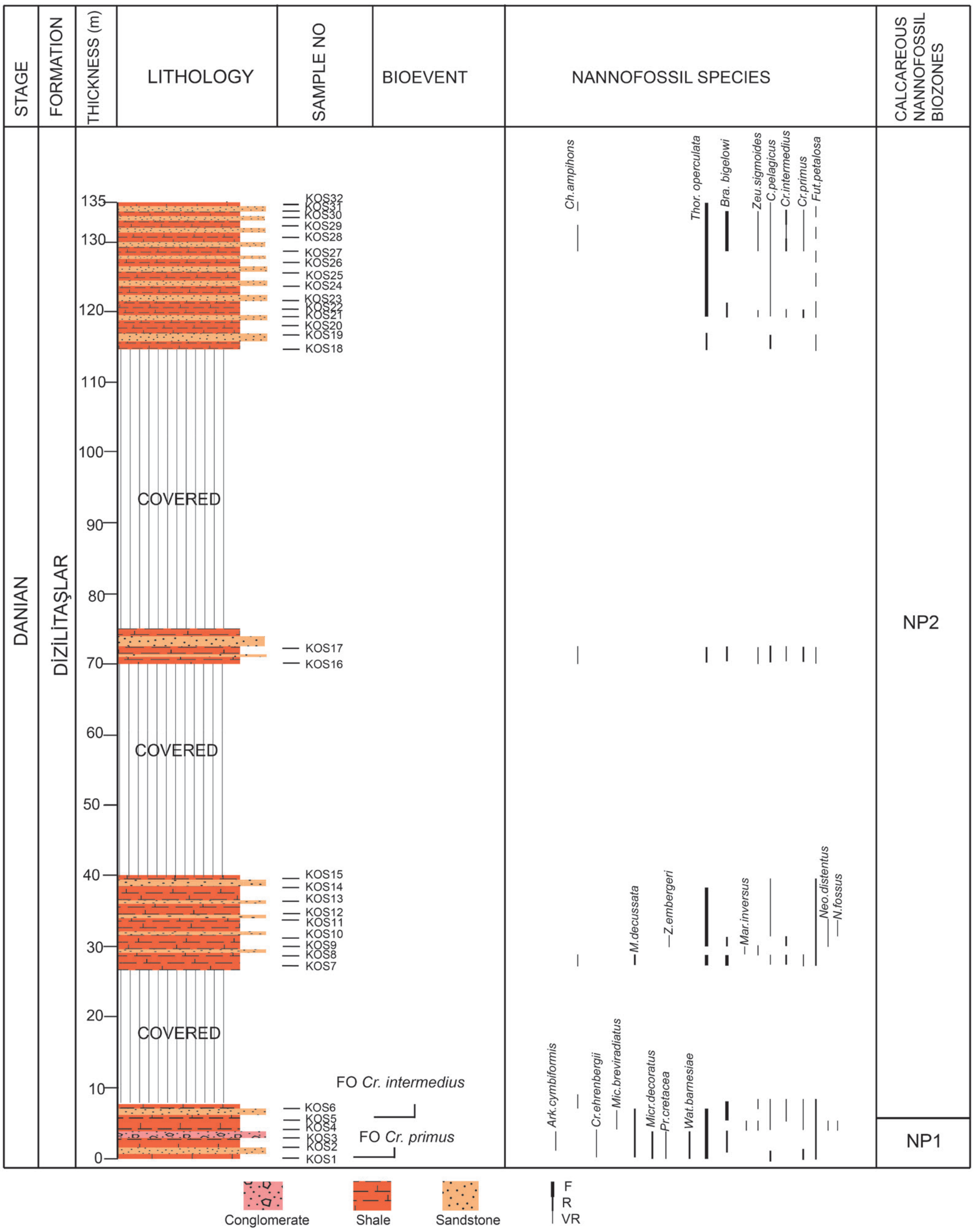

Figure 4. Lithostratigraphy, calcareous nannofossil abundances and biostratigraphy of the Aşağısamanlık section.

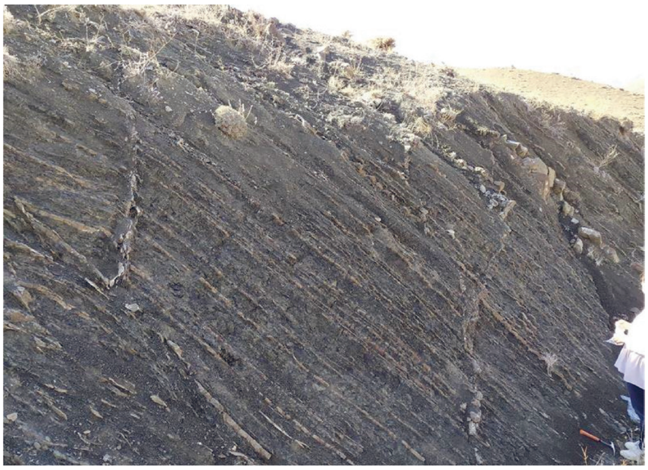

Figure 5. Field photographs of normally graded sandstones in the section outside Kırıkkale section.

low (Table 1). This data is compatible with nannofossil abundances decreasing in tandem with an increasing proportion of sand towards the top of the section.

4.1.2. Section outside Kırıkkale

Lithology

This section was sampled at the entrance to the Organized Industrial Zone immediately outside Kırıkkale, on the road, almost 1 km south of Hacıbalı village (Fig. 1). The Dizilitaşlar Formation in this section is almost 135 m thick (Fig. 4) and comprises yellow and brown, medium-bedded sandstones (Fig. 5), greyish-brown, poorly-sorted conglomerate and greyish-brown, fine-bedded, occasionally laminated shale alternations. The same lithology continued from the base to the top, and a total of 32 samples were collected (Fig. 4).

The sandstones are generally medium to coarse grained, with normal grading. In some places in the middle part of the section, there are coarse-grained, unconsolidated sandstone layers reaching up to 1 m in thickness. The thickness of the turbiditic sandstones in the section reach almost 1 m. The shales beds are 30–40 cm thick. Small-scale faulting and sliding are observed, causing disruption to the stratigraphy in a large part of the section.

Calcareous nannofossils

Generally, the samples contain low nannofossil species abundances, with 17 nannofossil genera and 19 species being identi-

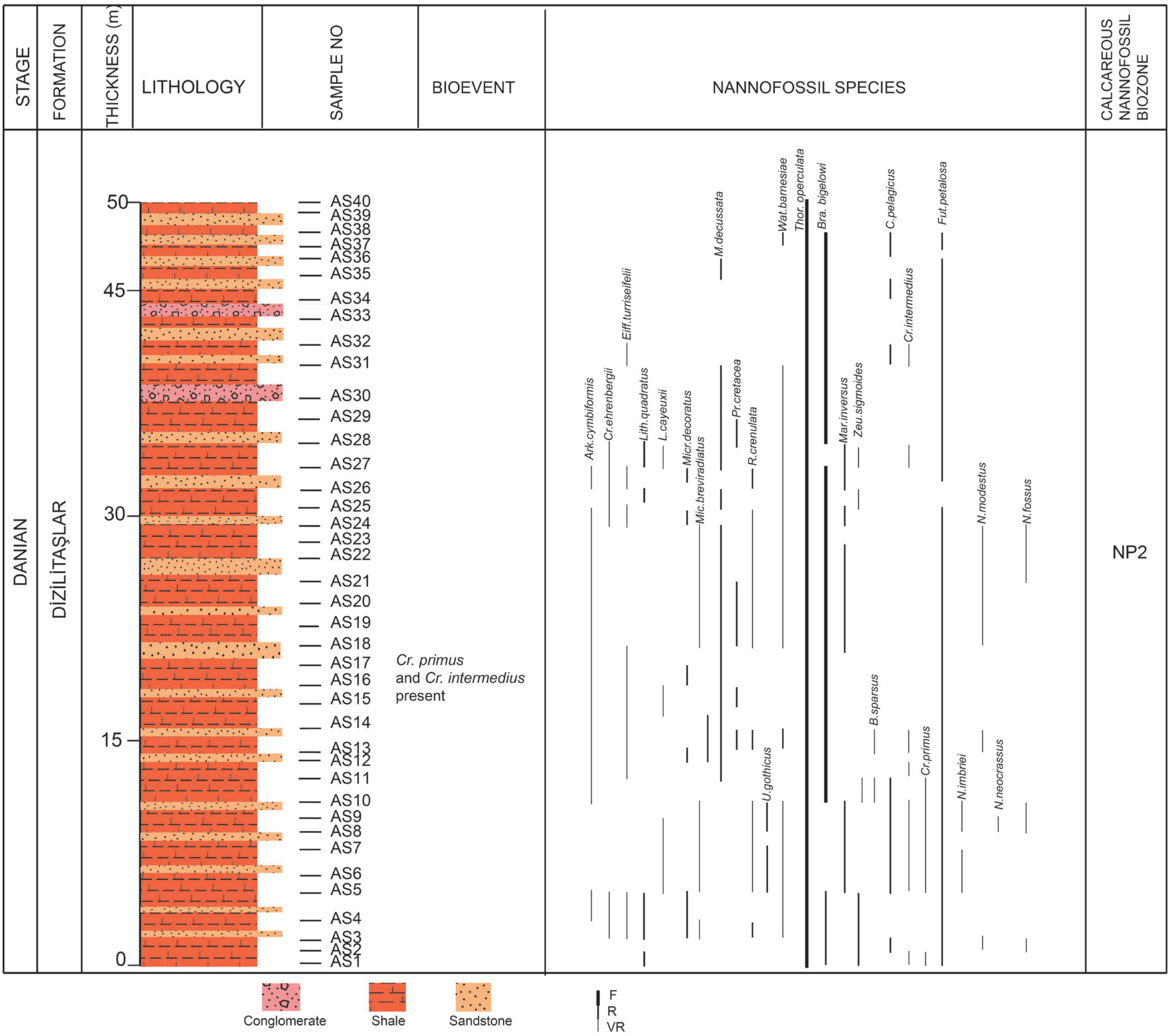

Figure 6. Lithostratigraphy, calcareous nannofossil abundances and biostratigraphy of the section outside Kırıkkale.

Table 2 The abundances of calcareous nannofossils with species distribution in the Outside Kırıkkale (KOS) section

Samples	Nannofossil species																			Nannofossil Biozones
	Arkhangelskiella cymbiformis	Chiastozygus ampihons	Cribrosphaerella ehrenbergii	Micrantholihus breviradiatus	Micula decussata	Microrhabdulus decoratus	Prediscosphaera cretacea	Zeugrhabdotus embergeri	Watznaueria barnesiae	Braarudosphaera bigelowii	Markalius inversus	Thoracosphaera operculata	Zeugrhabdotus sigmoides	Coccolithus pelagicus	Cruciplacolithus primus	Cruciplacolithus intermedius	Futyania petalosa	Neochiastozygus distentus	Neocrepidolithus fossus	
KOS32												F		VR						
KOS31												F		VR			VR			
KOS30		VR								F		F	VR	VR	VR	R	VR			
KOS29										F		F	VR	VR	VR	R				
KOS28		VR								F		F	VR	VR	VR	VR	VR			
KOS27		VR								F		F	VR	VR	VR	R				
KOS26												F		VR			VR			
KOS25												F		VR						
KOS24												F		VR			VR			
KOS23												F		VR						
KOS22												F		VR			VR			
KOS21										R		F	VR	VR	R	VR	VR			
KOS20										barren of calcareous nannofossils										NP2
KOS19																				
KOS18												R		R			VR			
KOS17										barren of calcareous nannofossils										
KOS16		VR								R		R	VR	R	R	VR	VR			
KOS15										barren of calcareous nannofossils										
KOS14												F		VR			R			
KOS13												F		VR			R			
KOS12												F		VR			R			
KOS11												F		VR			R			
KOS10												F		VR			R	VR	VR	
KOS9								VR		R		F				R	R	VR		
KOS8											R		VR	VR			R			
KOS7		VR			R					F		F	VR	VR	VR	R	R			
KOS6		VR			R					F		F	VR	VR	VR	VR	R			
KOS5					R					F		F		VR	VR	VR	R			
KOS4				VR	R						R	F	VR	VR	VR		R	VR	VR	
KOS3	VR		VR		R	R	VR		R	R		F					R			NP1
KOS2	VR		VR		R	R	VR		R	R		F			R		R			
KOS1			VR		R	R	VR		R			F		R			R			

Figure 7. Field view of the Dizilitaşlar Formation taken from the Aşağısamanlık section showing shale–sandstone alternations.

fied (Table 2). Two biozones were identified (Fig. 4). The lowest 6 m of the section contained both Cretaceous and Danian nannofossils (Fig. 4). The alternating brown sandstone and greyish-dark green shales were determined as representing Zone NP1, from the last Cretaceous nannofossils to the base of *Cruciplacolithus primus* Perch-Nielsen, 1977 (Fig. 4, Table 2). The relative abundance of Cretaceous nannofossil species decreased up-section. Above Sample KOS9, the taxa present were mostly Danian (Table 2), although their species abundances were generally very low.

The first occurrence of *Cruciplacolithus intermedius* van Heck & Prins, 1987 was found in the same lithology, at 5 m, and was used to indicate the base of the NP2 zone (Fig. 4, Table 2). This marker species has been found to be more appropriate for dating marginal sea sediments (THIBAULT et al., 2018) where the definitive marker, Cruciplacolithus tenuis (Stradner, 1961) Hay & Mohler 1967, is absent, as was the case here, possibly due to the unstable environmental conditions in the region. Some samples were barren, while other samples only contained very low numbers of species. Although few in number, *Thoracosphaera operculata* Bramlette & Martini, 1964 and *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 dominated in this section (Table 2) as in the previous section (Table 1).

4.1.3. Aşağı Samanlık section

Lithology

The Aşağı Samanlık section was sampled on the road to Aşağı Samanlık village (at the junction with the Kırıkkale–Çankırı road) (Fig. 1). The section is 50 m thick and comprises dark green and grey shales and dark brown sandstone alternations belonging to the Dizilitaşlar Formation throughout (Fig. 6). Forty samples were taken, which yielded 22 nannofossil genera and 25 nannofossil species (Table 3).

The Aşağı Samanlık section exhibits typical turbiditic features, with laminated shales and fine- to medium-bedded sandstones (Fig. 7). Small faults and slides were observed in the section. The shale beds at the base of the section are generally 70–80 cm thick, while the sandstone beds vary from 2 to 5 cm thick. Towards the top of the section, the sandstone beds occasionally reach 10 cm thick. The number of occasional sandstone beds increases towards the top of the section, where they reach 10–15 cm thick, while the shale beds are relatively decreased in number.

Rarely, trace fossils were observed in the sandstone layers. Within the sequence, there are unconsolidated, loose-textured conglomerate levels, 70–80 cm thick.

Calcareous nannofossils

The samples from the lower part of the section contained Danian and Cretaceous nannofossils. There were relatively higher species abundances in the shale samples (Table 3). *Cruciplacolithus intermedius* van Heck & Prins, 1987 has been found in the region in the upper part of NP1, close to the base of NP2, according to THIBAULT et al. (2018) (Figs. 6, 8, Table 3). Zone NP2 was interpreted up to a height of 50 m in the section (Fig. 6, Table 3). THIBAULT et al. (2018) identified the bases of NP1 and NP2 using a *Cruciplacolithus* lineage involving different sizes of *Cruciplacolithus primus* Perch-Nielsen, 1977. However, in our samples, small and large (>7 µm) *Cruciplacolithus primus* Perch-Nielsen, 1977 specimens could not be discriminated between. Scattered occurrences of *Cruciplacolithus primus* Perch-Nielsen, 1977 and *Cruciplacolithus intermedius* van Heck & Prins, 1987 were found in the lower part of the section, encountered together with *Cruciplacolithus primus* Perch-Nielsen, 1977, which was not found above Sample AS10, whereas *Cruciplacolithus intermedius* van Heck & Prins, 1987 was present in a few samples above this

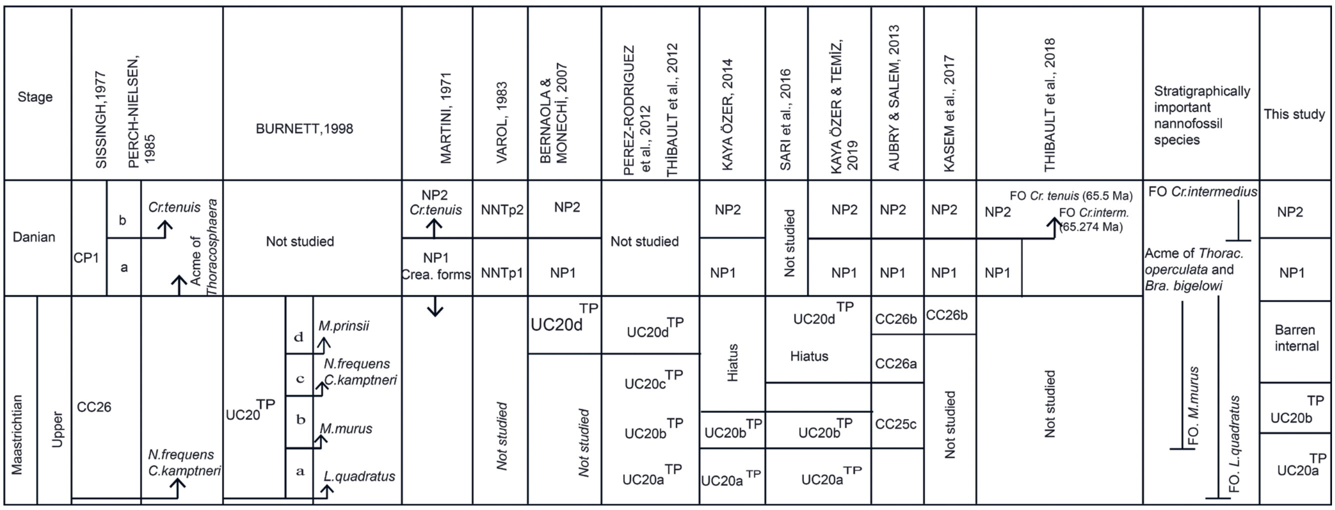

Figure 8. Summary of the calcareous nannofossil biozonation schemes applied to the Maastrichtian–Danian sediments, along with age estimates for the study area, correlated with those of other studies from different middle- and low-latitude localities.

Table 3 The abundances of calcareous nannofossils with species distribution in the Aşağı Samanlık (AS) stratigraphic section

Samples	Nannofossil species																									
	Arkhangelskiella cymbiformis	*Cribrosphaerella ehrenbergii*	*Eiffellithus turriseiffelii*	*Lithraphidites quadratus*	*Lucianorhabdus cayeuxii*	*Microrhabdulus decoratus*	*Micrantholihus breviradiatus*	*Micula decussata*	*Prediscosphaera cretacea*	*Retecapsa crenulata*	*Uniplanarius gothicus*	*Watznaueria barnesiae*	*Braarudosphaera bigelowii*	*Markalius inversus*	*Thoracosphaera operculata*	*Zeugrhabdotus sigmoides*	*Biantholithus sparsus*	*Futyania petalosa*	*Coccolithus pelagicus*	*Cruciplacolithus intermedius*	*Cruciplacolithus primus*	*Neochiastozygus imbriei*	*Neochiastozygus modestus*	*Neocrepidolithus neocrassus*	*Neocrepidolithus fossus*	Nannofossil Biozone
AS40															F											
AS39															F											
AS38													F		F											
AS37												R	F		F			R	R							
AS36													F		F				R							
AS35								R					F		F			R								
AS34													F		F			R	R							
AS33													F		F			R								
AS32													F		F			R								
AS31			VR					R				VR	F		F			R	R	VR						
AS30								R				VR	F		F			R								
AS29								R				VR	F		F			R								
AS28								R	R			VR	F		F			R								
AS27		VR	VR	R	VR	R		R				VR		R	F	VR		R		VR						
AS26	VR	VR	VR							R		VR	F	R	F			R								
AS25		VR		R		R		R				VR	F		F	VR										
AS24	VR	VR	VR							VR		VR	F	R	F			R								
AS23	VR						VR	R		VR		VR	F		F			R					VR		VR	
AS22	VR						VR	R		VR		VR	F	R	F			R					VR		VR	
AS21	VR						VR	R		VR		VR	F	R	F			R					VR		VR	NP2
AS20	VR						VR	R	R	VR		VR	F	R	F			R					VR			
AS19	VR						VR	R	R	VR		VR	F	R	F			R					VR			
AS18	VR						VR	R	R	VR		VR	F	R	F			R					VR			
AS17	VR	VR	VR					R					F		F			R								
AS16	VR		VR			R		R					F		F			R								
AS15	VR		VR		VR			R	R				F		F			R								
AS14	VR		VR					R					F		F			R								
AS13	VR		VR					R	R	R		R	F		F		VR	R		VR			VR			
AS12	VR		VR			R		R					F		F			R								
AS11	VR		VR					R					F		F			R		VR						
AS10	VR									VR		VR	F	R	F	VR	VR	R	R		VR					
AS9					VR		VR			VR	R	VR		R	F			R	R	VR	VR	VR			VR	
AS8					VR		VR			VR	R	VR		R	F			R	R	VR	VR	VR		VR	VR	
AS7					VR		VR			VR		VR		R	F			R	R	VR	VR					
AS6					VR		VR			VR	R	VR		R	F			R	R	VR	VR	VR				
AS5					VR		VR			VR	R	VR		R	F			R	R	VR	VR	VR				
AS4	VR	VR	VR	R		R		R				VR	R		F	R		R								
AS3		VR	VR	R		R	VR	R		R		VR	R		F	R		R								
AS2													R		F	R		R	R				VR		VR	
AS1				R					VR	VR			R		F	R		R		VR	VR					

level. The *Cruciplacolithus* lineage was not observed in NP2 here possibly because of the unstable regional conditions.

Nannofossil species abundances decreased towards the top of the section, particularly from Sample AS30, with only a few reworked Cretaceous specimens among a small but greater proportion of Danian species being identified in the uppermost beds (Table 3). Samples with a high proportions of sand appeared to have reduced species richness.

5. DISCUSSION

5.1. Biostratigraphy

The Samanlık and Dizilitaşlar Formations contain turbidites with high sand contents. Upper Maastrichtian nannofossil species were only identified in the Kırıkkale Organized Industrial Zone section (Fig. 3). In this section, Upper Maastrichtian species abundances were generally very low, apart from *Micula decussate* Vekshina, 1959, *Microrhabdulus decorates* Deflandre, 1959 and *Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968 (Table 1), with the species richness and relative abundances of the nannofossils showing a significant decrease at the K–Pg boundary (Table 1). In the study area, the K–Pg boundary was not continuous, but was identified based on the increased abundances (albeit still only a few specimens) of *Thoracosphaera operculata* Bramlette & Martini, 1964 and *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 (Fig. 3, Table 1) in the Danian in the Organised Industrial Zone section. Nannofossils were still rare and generally poorly preserved in the Danian samples, while samples that contained high proportions of sand tended to be barren of nannofossils (Tables 1, 3).

The base of NP2 is defined by the base of *Cruciplacolithus tenuis* (Stradner, 1961) Hay & Mohler 1967, which has been dated at 65.538 Ma in the North Pacific (WESTERHOLD et al., 2008) and at 65.094 Ma in the South Atlantic (THIBAULT et al., 2018). However, according to the SHIPBOARD SCIENTIFIC PARTY (2004), the base of *Cruciplacolithus tenuis* (Stradner, 1961) Hay & Mohler 1967 is at 65.5828 Ma in the South Atlantic, which agrees with the age in the Pacific Ocean and the base of NP2. The base of NP2 in the studied region can be approximated by large (>7 μm) specimens of *Cruciplacolithus primus* Perch-Nielsen, 1977, which have been included in *Cruciplacolithus intermedius* van Heck & Prins, 1987 (= *Cruciplacolithus tenuis s.l.* of PERCH-NIELSEN, 1985) by THIBAULT et al. (2018). THIBAULT et al. (2018) used the base of *Cruciplacolithus* cf. *C. intermedius*, dated at 65.709 Ma in the South Atlantic, to approximate the base of NP2, while the base of *C. intermedius s.s.* has been astronomically calibrated to 65.274 Ma (WESTERHOLD et al., 2008). WESTERHOLD et al. (2008) also explained that the base of NP2, as determined by the base of *Cruciplacolithus intermedius* van Heck & Prins, 1987, correlates with, or lies above, the top of the first recovery phase of the $\delta^{14}C$ isotope curve for the region. GILLEAUDEAU et al. (2018) also identified the base of NP2 using the base of *Cruciplacolithus intermedius* van Heck & Prins, 1987. The Kırıkkale Basin was a deep-sea basin that prevailed during unstable environmental conditions due to tectonic activity in the Maastrichtian through the Early Danian. In the study area, *Cruciplacolithus tenuis* (Stradner, 1961) Hay & Mohler 1967, the actual marker for the base of NP2, was not found in this unstable environment except for in one section, and so the base of NP2 had to be correlated using the base of *Cruciplacolithus intermedius* van Heck & Prins, 1987 (Fig. 8).

In Fig. 8, the nannofossil zones identified in this study are compared with the stratigraphic distributions of selected nannofossils from other Tethyan localities with similar assemblages and similar ages, including the Kırıkkale Basin.

5.2. Palaeoecological interpretation

The asteroid impact at the K–Pg boundary caused dramatic biotic and biogeochemical changes in the oceans, and planktonic foraminifera and calcareous nannofossils were severely affected by the ensuing environmental crisis in the marine pelagic ecosystem (SMIT, 1982; POSPICHAL & WISE, 1990; BERGGREN & NORRIS, 1997; MOLINA et al., 1998; HUBER et al., 2002; BOWN, 2005; FUQUA et al., 2008; SCHULTE et al., 2010; GUERRA et al., 2021). Some nannofossil species survived the impact event, adapting to the changed environmental conditions (BOWN, 2005). Here, the K–Pg boundary was determined based on a significant decrease in the abundance of nannofossil species, an increase in survivor Cretaceous species, such as *Thoracosphaera operculata* Bramlette & Martini, 1964, and observations of the new Palaeocene taxa (LAMOLDA et al., 2005; BERNAOLA & MONECHI, 2007).

Few to rare abundances of *Micula decussate* Vekshina, 1959 and *Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968 occurred in the Upper Maastrichtian samples in the study area (Table 1). *Micula decussate* Vekshina, 1959 has been interpreted, in some studies, as a species that thrives in low-productivity, relatively cool and stressed environments (WATKINS & SELF-TRAIL, 2005; KELLER et al., 2007; THIBAULT & GARDIN, 2007; MAHANIPOUR et al., 2022). *Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968 is considered to be a warm water, cosmopolitan, eutrophic and opportunistic species in low-latitude regions by MUTTERLOSE (1996), POSPICHAL (1996) and LEES (2002), and as being more efficiently able to adapt to different environmental and stress conditions by, for example, AGUADO et al. (2016). LEES et al. (2005) explained that *Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968 is likely to have been ecologically r-selected for rapid reproduction in heightened nutrient. Both *Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968 and *Micula decussate* Vekshina, 1959 are considered to be highly resistant to dissolution and have been used to test the preservation of nannofossil assemblages (HILL, 1975; THIERSTEIN, 1980). In the Kırıkkale Basin, however, rare occurrences of *Micula decussate* Vekshina, 1959 and *Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968, in tandem with low abundances of other taxa, are interpreted as being possibly due to the unstable and stressful environment of the Late Maastrichtian, which is in agreement with previous foraminifera data determining a shallower basin and less saline environment with decreased temperature.

Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947 and *Thoracosphaera operculata* Bramlette & Martini, 1964 were found to be rare in the Maastrichtian, increasing to the 'few' abundance category, except in some samples, in the Danian (Tables 1, 3). *Braarudosphaera* spp. became important components of the nannofossil assemblages in the Danian after the K–Pg extinction event. *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 evolved in the Cretaceous and is common and/or persistent in the Cretaceous of some Tethyan regions (BERNAOLA & MONECHI, 2007). JONES et al. (2019) stated that this species survived after the K–Pg event because it was able to adapt to the ensuing unstable environment, as also explained by POSPICHAL & BRALOWER (1992), peaking in

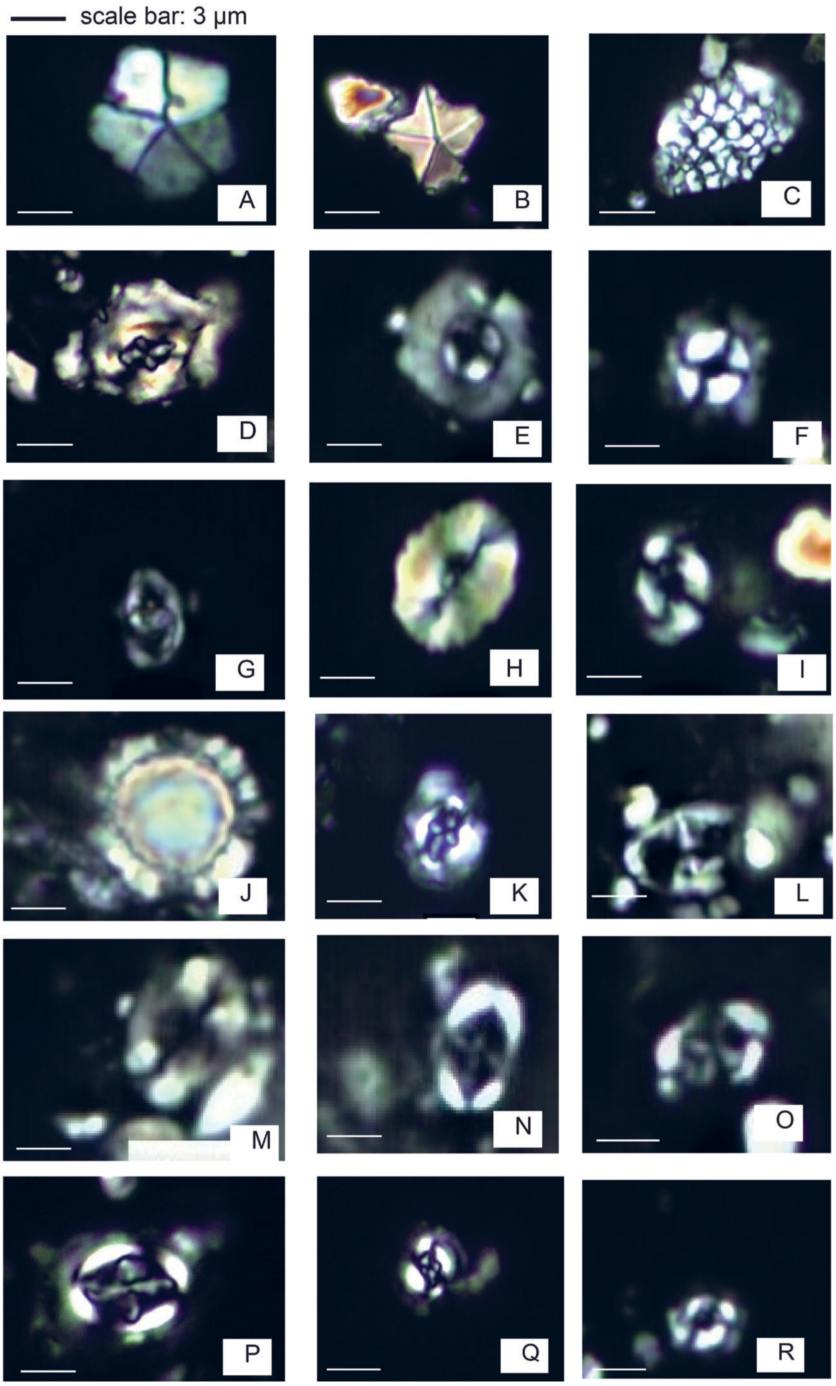

Figure 9. Selected calcareous nannofossil images identified in the sections. All photomicrographs were taken using polarised light. A–*Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947, Sample AS1; B–*Micrantholithus breviradiatus* Bown 2005, Sample AS21; C–*Thoracosphaera operculata* Bramlette & Martini, 1964, Sample AS1; D–*Cruciplacolithus tenuis* (Stradner, 1961) Hay & Mohler 1967, Sample OSB21; E–*Markalius inversus* (Deflandre, 1954) Bramlette & Martini 1964, Sample AS22; F–*Coccolithus pelagicus* (Wallich 1877) Schiller 1930, Sample AS37; G–*Zeugrhabdotus embergeri* (Noël 1959) Perch-Nielsen 1984, Sample KOS9; H–*Neocrepidolithus fossus* Romein, 1977) Romein 1979, Sample AS2; I–*Cruciplacolithus intermedius* van Heck & Prins, 1987, Sample AS1; J–*Futyania petalosa* (Ellis & Lohmann, 1973) Varol 1989, Sample OSB27; K–*Cruciplacolithus intermedius* van Heck & Prins, 1987, Sample KOS5; L–*Zeugrhabdotus sigmoides* (Bramlette & Sullivan, 1961) Bown & Young 1997, Sample AS10; M–*Neocrepidolithus neocrassus* (Perch-Nielsen, 1968) Romein 1979, Sample AS8; N–*Neochiastozygus modestus* Perch-Nielsen 1971, Sample AS13; O–*Neochiastozygus distentus* (Bramlette & Sullivan, 1961) Perch-Nielsen 1971, Sample OSB21; P–*Cruciplacolithus intermedius* van Heck & Prins, 1987, Sample AS8; Q–*Cruciplacolithus primus* Perch-Nielsen, 1977 (large), Sample OSB21; R–*Cruciplacolithus primus* Perch-Nielsen, 1977 (small), Sample OSB22.

abundance just above the K–Pg boundary. *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 is also very resistant to diagenetic alteration (JONES et al., 2019). High abundances of *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 have mostly been associated with low-salinity coastal waters (PELEO-ALAMPAY et al., 1999; BARTOL et al., 2008), the influx of terrestrial material into oceanic waters (ŠVÁBENICKÁ, 1999) and eutrophication (CUNHA & SHIMABUKURO, 1997). It is believed to have evolved in unusual palaeoceanographic conditions and has been viewed as an opportunist that responds to reduced competition (THIERSTEIN et al., 2004). Several researchers have reported episodes of *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 enrichment in open-ocean sediments (SIESSER et al., 1992;

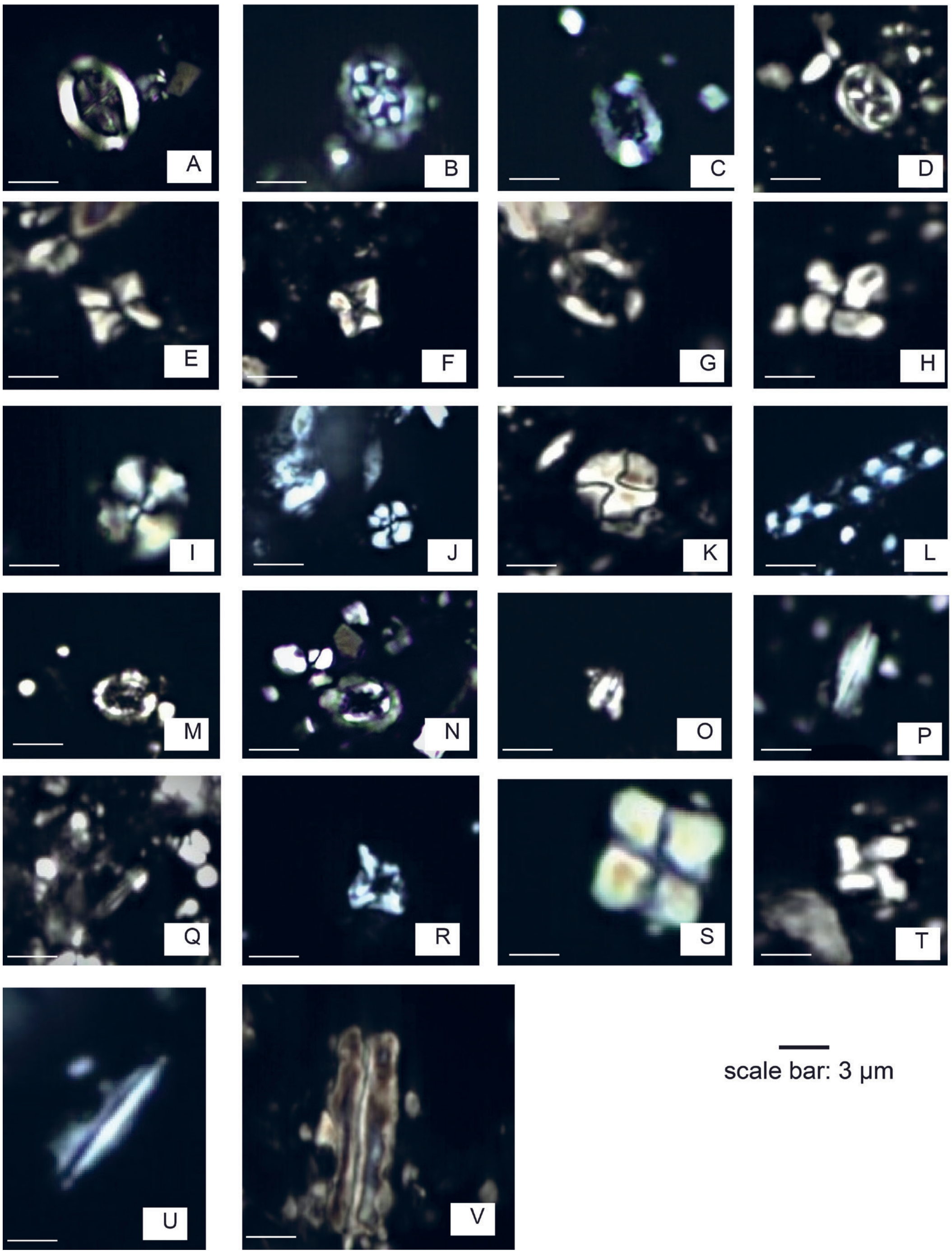

Figure 10. Selected calcareous nannofossil images identified in the sections. All photomicrographs were taken using polarised light. A–*Arkhangelskiella cymbiformis* Vekshina 1959, Sample OSB5; B–*Prediscosphaera cretacea (*Arkhangelsky, 1912) Gartner 1968, Sample AS1; C–*Retecapsa crenulata* (Bramlette & Martini, 1964) Grün & Allemann 1975, Sample AS1; D–*Chiastozygus amphipons* (Bramlette & Martini, 1964) Gartner 1968, Sample OSB2; E–*Micula decussate* Vekshina, 1959, Sample OSB4; F–*Micula decussate* Vekshina, 1959, Sample OSB8; G–*Eiffellithus turriseiffelii* (Deflandre, 1954) Reinhardt 1965, Sample OSB4; H–*Micula murus* (Martini, 1961) Bukry, 1973, Sample OSB8; I–*Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968, Sample AS26; J–*Watznaueria barnesiae* (Black, 1959) Perch-Nielsen, 1968, Sample OSB1; K–*Calculites obscurus* (Deflandre, 1959) Prins & Sissingh in Sissingh 1977, Sample OSB7; L–*Microrhabdulus decorates* Deflandre, 1959, Sample OSB2; M–*Cribrosphaerella ehrenbergii* (Arkhangelsky, 1912) Deflandre in Piveteau 1952, Sample AS17; N–*Cribrosphaerella ehrenbergii* (Arkhangelsky, 1912) Deflandre in Piveteau 1952, Sample AS17; O–*Ceratolithoides aculeus* Stradner, 1961) Prins & Sissingh in Sissingh 1977, Sample OSB7; P–*Lithraphidites quadratus* Bramlette & Martini, 1964, Sample OBS8; Q–*Lithraphidites carniolensis* Deflandre 1963, Sample OSB4; R–*Micula decussate* Vekshina, 1959, Sample OSB1; S–*Uniplanarius gothicus* (Deflandre, 1959) Hattner & Wise 1983, Sample AS5; T–*Micula murus* (Martini, 1961) Bukry, 1973, Sample OSB7; U–*Lithraphidites praequadratus* Roth 1978, Sample OSB8; V–*Lucianorhabdus cayeuxii* Deflandre 1959, Sample AS15.

PELEO-ALAMPAY et al., 1999; KELLY et al., 2003; EISENACH & KELLY, 2004; GAMBOA & SHIMABUKURO, 2006). The cause of unstable environmental conditions coincides with the tectonic and volcanic activity in the region that induced dramatic change in nannoplankton assemblage linked to the subduction event in the İzmir–Ankara Zone.

Thoracosphaera operculata Bramlette & Martini, 1964 is another species that evolved in the Cretaceous and survived into the Danian, being observed at the K–Pg boundary in most studies on mid- and low-latitude regions (TANTAWY, 2003; MOLINA et al., 2006; KAYA-OZER, 2014; KAYA-OZER & TEMIZ, 2019; MAHANIPOUR et al., 2021). The increasing abundance of this species across the K–Pg suggests it is an opportunistic species, and it has been interpreted as indicating a high-stress environment (TANTAWY, 2003; AGUADO et al., 2005; KAYA-OZER, 2014). Acmes of *Thoracosphaera operculata* Bramlette & Martini, 1964 may correlate with episodes of increased environmental stress, higher atmospheric CO_2 contents, fluctuations in marine salinity and pH, and/or significant warming over a short period of time, such as the conditions that followed the K–Pg boundary event (LAMOLDA et al., 2005).

In the Danian, the few relative abundances of *Thoracosphaera operculata* Bramlette & Martini, 1964 and *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 in assemblages also containing rare *Futyania* are interpreted as indicating stressful conditions and significant environmental perturbations in the Kırıkkale Basin that resulted from the tectonic activity that occurred in the Danian in the study area. The lack of species in some samples, especially those from sandstone-dominated intervals, was notable.

Some of the species found in this study are illustrated in Figs. 9 and 10.

6. CONCLUSIONS

A detailed nannofossil biostratigraphic analysis was performed on the Samanlık and Dizilitaşlar Formations, deposited in the Kırıkkale Basin. Four nannofossil biozones–UC20a^{TP} and UC20b^{TP} and NP1 and NP2–were identified, indicating the Late Maastrichtian to Danian periods, in three stratigraphic sections.

The nannofossil species abundances were generally low in both the Upper Maastrichtian and the Danian. The low abundances of *Micula decussate* Vekshina, 1959 and the lack of species richness in the Upper Maastrichtian suggest stressful environmental conditions with lower temperature and salinity. The K–Pg boundary was not continuous but was identified by the relatively increased abundances of *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 and *Thoracosphaera operculata* Bramlette & Martini, 1964.

In the Danian, the low species richness and the presence of opportunistic species, such as *Braarudosphaera bigelowii* (Gran & Braarud, 1935) Deflandre, 1947 and *Thoracosphaera operculata* Bramlette & Martini, 1964, were interpreted as indicating stressed environmental conditions in the study area. The finding of reworked fossils and the low species abundances accord with the tectonically active environment of the Maastrichtian through the Palaeocene here.

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