Calcareous nannofossil assemblages of the Late Campanian- Early Maastrichtian form Gurpi Formation (Dezful embayment, SW Iran): Evidence of a climate cooling event

Azam Mahanipour*, Amineh Najafpour
Department of Geology, Faculty of Science, Shahid Bahonar University of Kerman, Kerman, Iran
*Corresponding author, e-mail: a_mahanipour@uk.ac.ir
(*received: 22/11/2015; accepted: 29/02/2016*)

Abstract
A succession of Late Campanian- Early Maastrichtian is analyzed from Gurpi Formation with regard to the calcareous nannofossils. Correlation Matrix was applied for the first time to the entire nannofossil assemblage to reconstruct environmental conditions. A detailed quantitative calcareous nannofossil analyses is performed on samples in order to further investigate the climate events, and interpret changes of surface water temperature. The calcareous nannofossil assemblage is divided into 3 groups as cold, cool and warm water taxa. Although cold water taxa (*Ahmuellerella octoradiata* and *Gartnerago segmentatum*) are rare (less than 1%), cool (*Eiffellithus turriseiffelii*, *Prediscosphaera cretacea*, *Micula staurophora*, *Zeugrhabdotus* spp., *Arkhangelskiella cymbiformis*, *Biscutum constans*, *Tranolithus orionatus* and *Lucianorhabdus cayeuxii*) and warm (*Watznaueria barnesae*, *Uniplanarius trifidus*, *Uniplanarius sissinghii*, *Ceratolithoides* spp. and *Broinsonia* spp.) water taxa are more frequent. The number of warm water taxa is higher than the number of cool water taxa and a reverse trend can be observed between them. Concerning the temperature index (TI), four important trends of climate variability from warmer to cooler phases (two cooling phases and two warming phases) have been documented at the studied interval. According to the recorded data, two pronounced cooling event are observed at Late Campanian and Early Maastrichtian, respectively.

Keywords: Calcareous Nannofossil, Cooling Event, Gurpi Formation, Iran, Late Campanian, Early Maastrichtian, Zagros Basin.

Introduction
A long term trend of climate cooling is started after the extreme warmth of the mid-Cretaceous greenhouse world, culminating in the Late Campanian and continued into the Early Palaeogene (Boersma and Schackleton, 1981; Jenkyns *et al*., 1994; Huber *et al*., 2002). During the Late Campanian and Maastrichtian, strong climate and temperature fluctuations are recorded by excursions in the stable isotope data (e.g., Barrera *et al*., 1997; Li and Keller, 1999; Friedrich *et al*., 2005, 2009), and global sea level falls (e.g., Li and Keller, 1999). This cooling event is also recorded by stable oxygen isotope data of bulk deposits and foraminifera (e.g., Huber *et al*., 2002; Friedrich and Meier, 2006). Temperature fluctuations are mainly associated with changes in planktonic foraminifers and calcareous nannoplankton which has been documented from different parts of the world (Pospichal and Wise, 1990; Huber and Watkins, 1992; Li and Keller, 1998; Lees, 2002; Friedrich *et al*., 2005; Thibault and Gardin, 2006, 2007, 2010). These changes in the composition of calcareous nannofossil assemblages (e.g., Watkins *et al*., 1996; Thibault & Gardin, 2006) are recorded by provinciality among calcareous nannofossils and planktonic formainiferal assemblages, identified by

Tethyan, Transitional and Austral bio-provinces that persisted to the end of the Maastrichtian (e.g., Holmes and Watkins, 1992; Huber, 1992; Campbell *et al*., 2004). Changes in the ocean circulation in the Pacific are considered as possible causes of this climate cooling event at this time interval (e.g., Jung *et al*., 2013).

Studies concentrating on the Late Campanian- Early Maastrichtian climate and paleoceanography of Zagros sedimentary basin in Iran are rare. Most of the studies of this time interval in this basin have focused predominantly on stratigraphic correlation, taxonomy and sedimentology (e.g., Hemmati-Nasab *et al*., 2008; Beiranvand & Ghasemi-Nejad, 2013). In contrast to the large number of paleontological and sedimentological data (e.g., Hemmati-Nasab *et al*., 2008; Beiranvand & Ghasemi-Nejad, 2013), few studies are concerning on the paleoecology and paleoceanography of calcareous nannofossils at the Zagros sedimentary basin in Iran. The Late Campanian- Early Maastrichtian strata have a good exposure at the Gurpi Formation in SW Iran. For observing changes in the calcareous nannofossil assemblages of Late Campanian- Early Maastrichtian, the lower part of the Gurpi Formation in SW of the Gurpi Anticline is investigated. The main goal of the present study is

to decipher the response of calcareous nannofossil assemblages to the Late Campanian- Early Maastrichtian climate events.

Review of related literature

Cretaceous sediments have good exposures in Zagros sedimentary basin in southwest of Iran. These sediments has been studied from different aspects of geology (e.g., Ziegler, 2001; Motiei, 2003; Vincent *et al*., 2010). In this basin, 17 formations are belonging to the Cretaceous deposits (Motiei, 1994). Among these formations, Gurpi Formation is one of the most important lithostratigraphic units as a source rock (Ala *et al*., 1980). The age and thickness of this formation is variable in different parts of the basin and ranging from Santonian to Maastrichtian in some parts of Khuzestan and Fars provinces and from Campanian to Plaeocene in Lurestan Province (James & Wynd, 1965; Motiei, 2003). Most important publications of of the Zagros sedimentary basin and mainly of the Gurpi Formation are written by James and Wynd (1965), Setudehnia (1972, 1978), Stoneley (1974, 1990), Motiei (2003), Ghasemi-Nejad *et al*. (2006) and Darvishzadeh *et al*. (2007). Gurpi Formation has a good extension at the Zagros sedimentary basin and is studied from different aspects of sedimentology, lithostratigraphy and biostratigraphy (e.g., calcareous nannofossils, palynomorphs and foraminifera). In this formation, foraminifers are mainly studied by Vaziri Moghadam (2002), Ghasemi-Nejad *et al*. (2006), Bahrami and Parvanehnezhad Shirazi (2010), Daneshian *et al*. (2010), and Sadeghi and Darabi (2015). Razmjooei *et al*. (2014) studied Gurpi Formation with regard to calcareous nannofossils and stable isotopes in Shahneshin section in Fars Province. They correlated Late Cretaceous stage boundaries between the Tethyan and Boreal realms at the studied interval. Ghasemi-Nejad *et al*. (2006), Beiranvand *et al*. (2013) and Zarei and Ghaseminejad (2015) studied the palynomorphs of the Gurpi Formation in Fars, Khuzestan and Lurestan provinces, respectively. The sedimentary environment of this formation is considered as an open, relatively deep marine outer ramp environment in Fars Province considering the palynofacies and lithofacies (Ghasemi-Nejad *et al*. 2006). Sea level fluctuations in this formation is also constructed by palynomorhs in Khuzestan Province (Beiranvand *et al*. 2013). This formation is also studied with regard to organic geochemistry

(Moosavi *et al*., 2013; Zarei and Ghaseminejad, 2013) and sequence stratigraphy (Zarei and Ghaseminejad, 2015). According to these studies, this formation has a good capacity as a source rock (Moosavi *et al*., 2013).

In the current study, the lower part of Gurpi Formation (which encompasses the Late Campanian- Early Maastrichtian interval) is studied with regard to calcareous nannofossils and their signals as paleoclimatology.

Geological setting

The Zagros mountain belt is part of the Alpine-Himalayan system, formed as a result of the collision between the continental Arabian plate and the Iranian plate which belongs to Eurasia and the disappearance of the Neo-Tethys Ocean (Takin, 1972; Berberian and King, 1981; Agard *et al*., 2005). The Zagros Fold and Thrust Belt (ZFTB) can be laterally subdivided into three main regions of variable width, morphology and structural style that from NW to SE are: The Lurestan Arc, The Dezful Embayment and The Fars Arc (Oveisi *et al*., 2009). Our studied area is located at the Dezful Embayment at the northeast of Khuzestan province and the northeast of Lali city (Fig. 1). At the studied succession, the Gurpi Formation overlies the Ilam Formation disconformably and is overlain by the Pabdeh Formation conformably. In this study, the lower part of the Gurpi Formation with a thickness of 202 m has been investigated in Gurpi Anticline.

Material and Methods

A total of 66 samples with a sampling resolution of 1.5 m were analyzed for calcareous nannofossil assemblages from the lower part of the Gurpi Formation. Samples were processed following the gravity settling technique of Thibault and Gardin (2006). The slides were prepared in the Nannofossil Laboratory at Shahid Bahonar University of Kerman. Calcareous nannofossils were studied using an Olympus BH2 transmitting light microscope at 1000× magnification.

A detailed investigation of relative and absolute abundance of calcareous nannofossil taxa was performed on prepared samples. Quantitative analyses were performed by counting at least 300 specimens on each slide. Every specimen of the calcareous nannofossil assemblages was counted at the species level. In addition, three random transverses were studied for observing rare species. The taxonomic concepts of calcareous nannofossils

in the slides followed Perch-Nielsen (1985) and Bown (1998). The biostratigraphic zonation of Sissingh (1977) emended by Perch-Nielsen (1985) and Burnett (1998) were used. Diversity was determined as species richness and heterogeneity or species diversity index that was calculated by using Shannon Index (Shannon and Weaver, 1949). Shannon index diversity is taking into account the number of individuals as well as number of taxa. The formula for calculating the Shannon index diversity is as follow:

$$H = -\Sigma \; n_i/n \; \ln n_i/n$$

In this formula n is total number of individuals and n_i is number of individuals of taxon i.

Relative species abundances were calculated as the percentage of at least 300 specimens counted. Absolute abundance of total calcareous nannofossils was calculated as ratio between total specimens of calcareous nannofossils encountered and the total number of field of view examined for each sample. For some of the important taxa from the paleoecological point of view, relative abundance curves were plotted as percentages along the stratigraphic column. The correlation matrix

was calculated with PAST 3. The list of all of the calcareous nannofossils mentioned in the text, and figures can be found in the Appendix.

Results

Calcareous nannofossil preservation, species richness and absolute abundance

Calcareous nannofossil assemblages show well to moderate preserved specimens at the lower and middle part of the interval, while towards the upper of the section the preservation is moderate. At the Campanian- Maastrichtian interval, *W. barnesae* and *M. staurophora* are considered as two solution-resistant species that can be used for preservation evaluation (Thierstein, 1980; Thibault and Gardin, 2006). Although the relative abundance of these two taxa in this study shows an increase towards the uppermost part of the interval, the solution-susceptible taxa such as *C. ehrenbergii* and *Prediscosphaera* spp. are also present. Moreover, the number of these solution susceptible taxa does not decrease when the number of *M. staurophora* and *W. barnesae* is increasing.
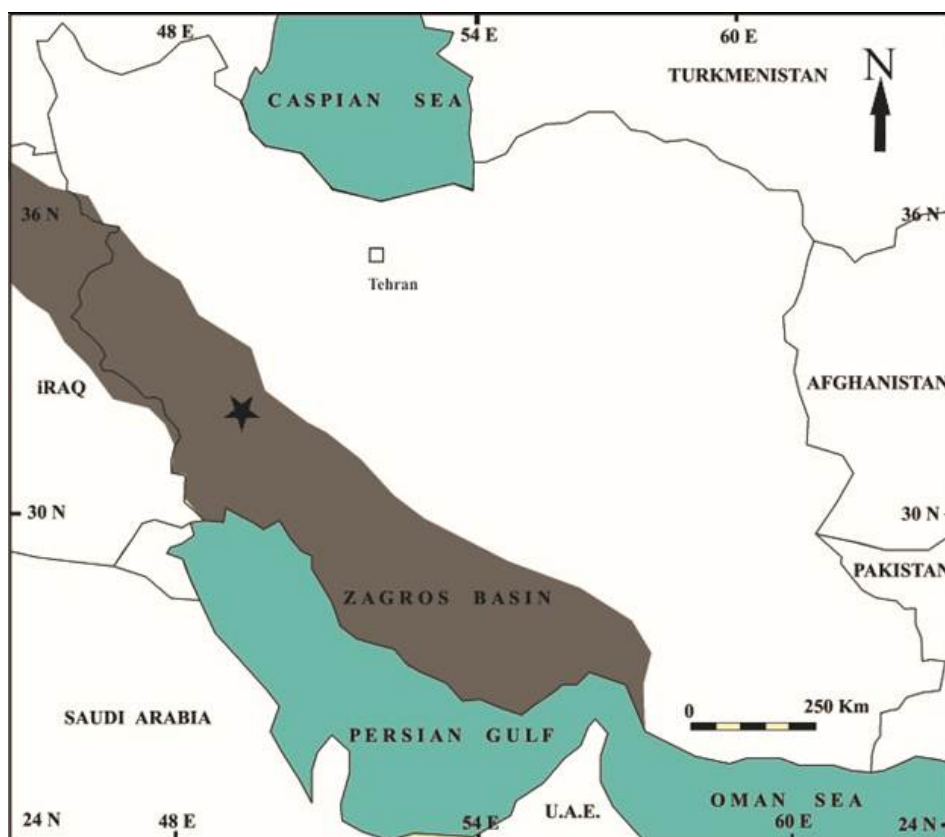

Figure 1. The location map of the studied section at the Zagros sedimentary basin in Iran

A decrease is recorded at the shannon diversity, simple diversity and the total absolute abundance curve towards the uppermost part of the interval. The vertical variation of simple diversity, Shannon diversity and absolute abundance is illustrated in Figure 2.

Biostratigraphy
The studied interval is spanning from the middle part of CC22 to the middle part of CC24 zones of Sissingh (1977) emended by Perch-Nielsen which corresponds UC15e^{TP} subzone to the middle part of

UC18 zones of Burnett (1998). Nine bioevents are delineated at the interval. The last occurrence (LO) of *Reinhardtites anthophorus* is documented at 70 m marks the base of CC23. The LO of *Eiffellithus eximius* is recorded 6.5 m after the LO of *R. anthophorus* defines the top of UC15e^{TP}. The last occurrence of curved spines (87.5 m), *U. trifidus* with long rays (95.5 m) and *Broinsonia parca parca* (98.5 m) are documented within CC23a/UC16 after the LO of *E. eximius* (76.5 m), respectively.
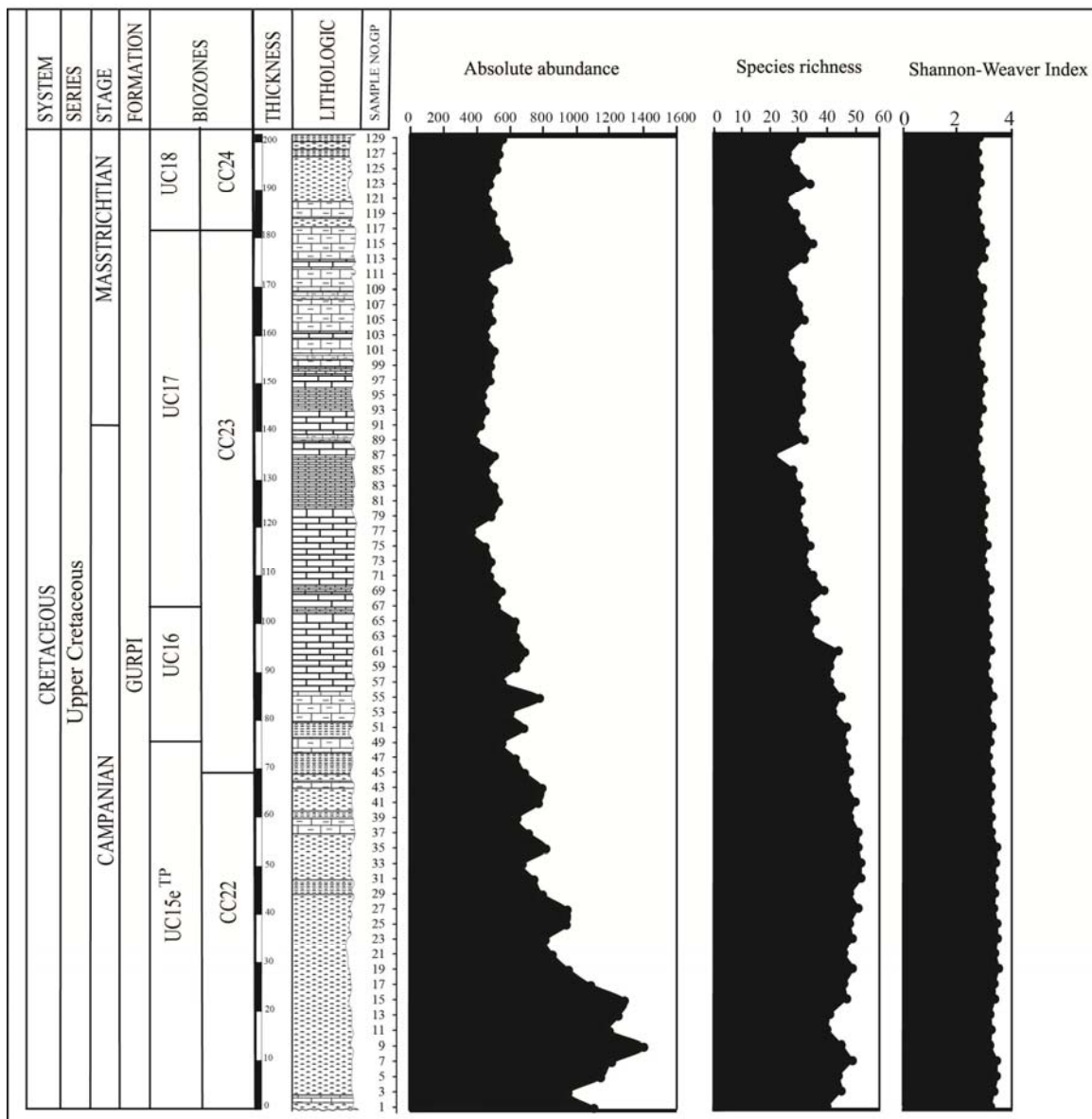

Figure 2. Absolute abundance, species richness and Shannon-Weaver Index of calcareous nannofossils at the Late Campanian- Early Maastrichtian of the studied interval

The last occurrence of *Broinsonia parca constricta* observed at 105 m, marks the base of CC23b/UC17. The LOs of *U. trifidus* with short rays and *Uniplanarius gothicus* are located within CC23b/UC17 (142 and 148 m, respectively) and below the LO of *Tranolithus orionatus* (182.5 m) which defines the base of CC24/UC18. At the studied interval, the LO of *U. trifidus* with short rays is considered as the closest marker for defining the CMB (Najafpour *et al*., 2015), similar to other parts of the world (Ogg *et al*., 2012; Gardin *et al*., 2012; Thibault *et al*., 2012). Calcareous nannofossil bioevents and biozonations of the studied interval along with standard biozonations of Sissingh (1977), Perch-Nielsen (1979, 1985) and Burnett (1998) are illustrated in Figure 3.

Calcareous nannofossil assemblages
Calcareous nannofossil examination indicates that the assemblage of this site is dominated by

Watznaueria spp. (mean relative abundance 19%), *Micula* spp. (mean: 12%), *Retecapsa* spp. (mean: 10%), *Prediscosphaera* spp. (mean: 8%), *Cribrosphaerella ehrenbergii* (mean: 6%), *Microrhabdulus* spp. (mean: 6%), *Eiffellithus* spp. (mean: 5%). The taxa with an average relative abundance of less than 5% are as follows: *A. cymbiformis* (mean: 4%), *Placozygus fibuliformis* (mean: 3%), *Uniplanarius* spp. (mean: 3%), *Reinhardtites* spp. (mean: 2%), *Ceratolithoides* spp. (mean: 2%), *Zeugrhabdotus* spp. (mean: 2%), *Broinsonia* spp. (mean: 1%), *T. orionatus* (mean: 1%). This assemblage is similar to other low to middle latitude sites.

The most common genus at the studied interval is *Watznaueria* spp., which is represented by *Watznaueria barnesae* (8-23%), *Watznaueria biporta* (0-7%), and *Watznaueria fossacincta* (0-3%).
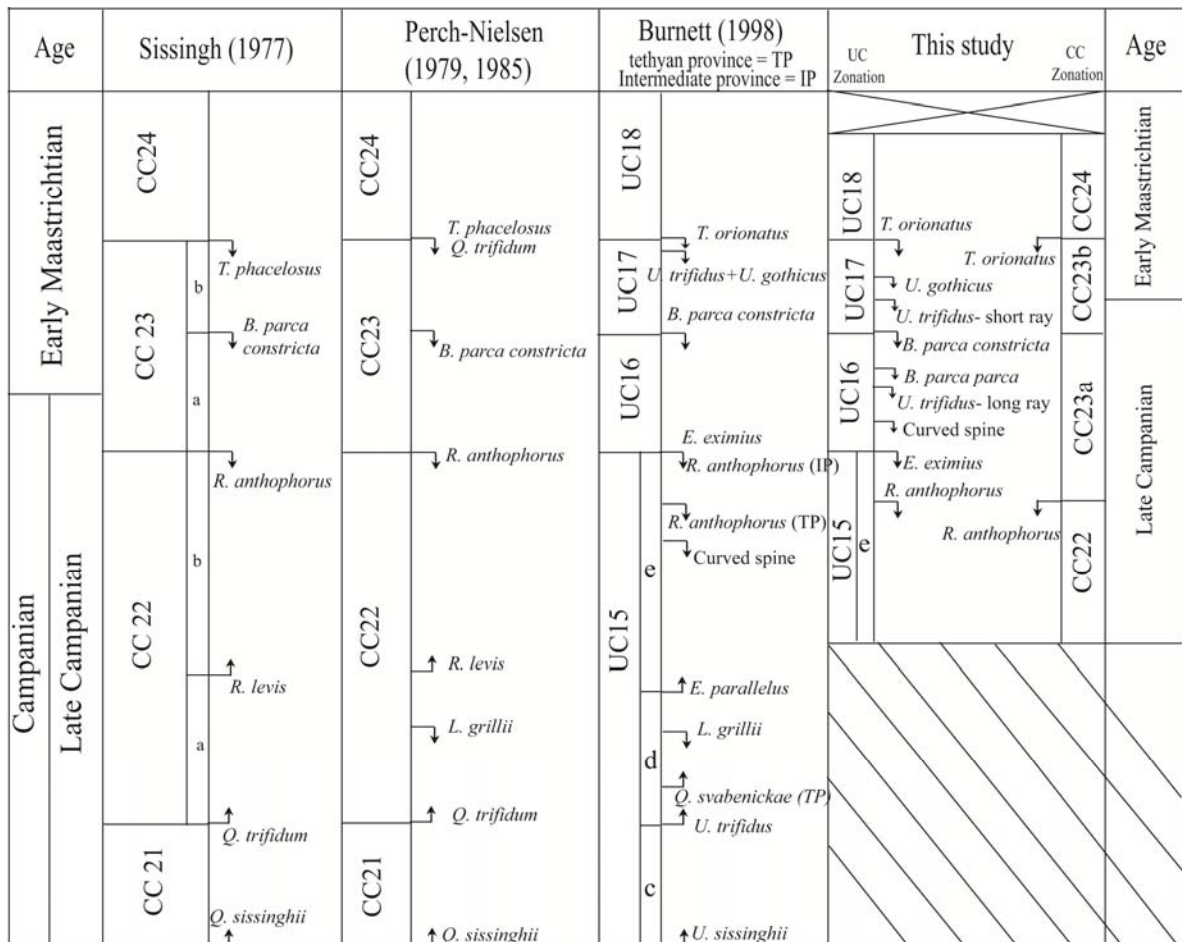

Figure 3. Calcareous nannofossil bioevents and biozonations of the studied interval and correlation with Sissingh (1977), Perch-Nielsen (1979, 1985) and Burnett (1998) at the Late Campanian- Early Maastrichtian

The relative abundance of *Watznaueria* spp. is ranging from 12 to 28% with the highest value at the upper part of the section. The most abundant species of this genus is *Watznaueria barnesae* with a mean relative value of 15%. The maximum value of this species is also recorded at the lower and the upper part of the section, respectively in the Late Campanian and the first part of the Maastrichtian, along with a minimum value in the middle part and the uppermost part of the section (near the Campanian - Maastrichtian boundary (CMB) and the uppermost part the interval).

The second common genus, *Micula* spp., is ranging between 2 to 29% and mainly represented by *Micula staurophora* (0-15%), *Micula swastica* (0-11%), *Micula concava* (1-6%) and *Micula praemurus* (0-3%). The relative abundance of *Micula staurophora* with a mean relative abundance of 5% is low at the lower part of the section (in UC15e^{TP} and UC16), and an increase in its relative abundance from the uppermost part of the Campanian towards the top of the succession can be observed. The other species of this genus, *M. swastica*, with a close morphology to *M. staurophora* has a mean value of 4%. A prominent peak in abundance of this species is recorded at the middle and upper part of the succession.

The relative abundance of *Retecapsa* spp. is varying from 3 to 14% which includes of *Retecapsa angustiforata* (1-7%), *Retecapsa ficula* (0-3%), *Retecapsa crenulata* (0-5%), *Retecapsa surirella* (0-1%) and *Retecapsa* sp. (0-10%). The relative abundance of this species shows some minor fluctuations at the interval.

Prediscosphaera spp. is fluctuating between 4 and 14%. This genus shows two peaks in abundance at the lower and middle part of the section. *Prediscosphaera cretacea* reaches 4% in the relative abundance. Other species are mostly broken and considered as *Prediscosphaera* sp., with the relative abundance varying from 4 to 11%. In broken specimens, two or three specimens are counted as one species. The highest abundance of *P. cretacea* is recorded at the lower part (the first part of UC15e^{TP}) and its relative abundance deceases towards the top.

Cribrosphaerella is only recorded by *Cribrosphaerella ehrenbergii* with its relative abundance ranging between 2 to 10% and shows only minor fluctuation.

Eiffellithus spp. is varying from 1 to 9% and includes of *Eiffellithus eximius* (0-5%), *Eiffellithus gorkae* (0-3%), *Eiffellithus parallelus* (0-3%) and *Eiffellithus turriseiffelii* (0-6%). Highest abundance of this genus is recorded at the lower part of the section (at the Late Campanian), while towards the upper part of the section (the uppermost Campanian- Early Maastrichtian), the abundance is lower with some fluctuations.

Microrhabdulus spp. is fluctuating between 1 to 10% and consists of *Microrhabdulus attenuatus* (0-6%), *Microrhabdulus belgicus* (0-1%) and *Microrhabdulus decoratus* (0-8). Its abundance shows two peaks at the middle (Late Campanian) and the upper part of the succession (Early Maastrichtian), where its abundance increases up to 10%.

A prominent peak in the abundance of *Arkhangelskiella* spp. is observed at the middle part of the interval (8%) and represented by two species of *Arkhangelskiella cymbiformis* (0-8%) and *Arkhangelskiella confusa* (0-1%). The relative abundance of *A. cymbiformis* varies between 0 to 8%. Its relative abundance is nearly constant with the highest value is recorded at the uppermost part of Campanian and near the CMB.

P. fibuliformis does not exceed 8% of the assemblage and shows no particular trend at the lower part of the interval. A remarkable peak up to 8% is recorded at the upper part of the interval near the CMB, which decreases towards the uppermost part of the section.

Uniplanarius spp. is represented by *Uniplanarius gothicus* (0-3%), *Uniplanarius sissinghii* (0-2%), *Uniplanarius trifidus* with short and long rays (0-5%). It shows the highest abundance at the lower-middle part of the interval at the Late Campanian (9%). The lowest abundance of this species is recorded at the uppermost part of the Campanian and before its last occurrence (sample 91, 142 m).

Maximum abundance of *Reinhardtites* spp. (8%) is recorded at the lower part of the succession. At the upper part of the section, it is only sporadically present and fluctuating between 0 to 1%. Two species of this genus, *Reinhardtites anthophorus* (0-2%) and *Reinhardtites levis* (0-7%), are presented at the studied interval.

The relative abundance of *Ceratolithoides* spp. is ranging from 0 to 7% and shows higher percentages at the upper part of the succession in Maastrichtian. It is mainly consists of *Ceratolithoides aculeus* (0-4%), *Ceratolithoides amplector* (0-3%), *Ceratolithoides indiensis* (0-4%) and *Ceratolithoides* sp. (0-3%).

Zeugrhabdotus spp. is abundant at the lower part of the section (6%) in the Late Campanian then it decreases towards the uppermost part of the section (fluctuating between 0 to 1%). The common species of this genus are *Zeugrhabdotus bicrescenticus* (0-5%), *Zeugrhabdotus diplogrammus* (0-4%), *Zeugrhabdotus embergeri* (0-3%), and *Zeugrhabdotus sigmoides* (0-1%).

The highest abundance of *Broinsonia* spp. is recorded at the lower part of the section (5%). It decreases towards its last occurrence at 105 m (sample 67) in the Late Campanian. *B. parca parca* (0-3%) and *B. parca constricta* (0-3%) are the two common species.

Maximum abundance of *T. orionatus* is identified at the lower and middle part of the section at the Late Campanian, and followed by a decrease down to 1% towards its last occurrence.

Discussions

Some of the calcareous nannofossil taxa are reliable indicators of surface water temperatures which strongly related to the thermal structure of surface water. The Campanian- Maastrichtian global cooling event is high and comparable to the Oligocene event (Miller et al., 2005). During the Late Campanian- Maastrichtian cooling event, high provincialism in the calcareous nannofossil assemblages is recognized (e.g., Burnett, 1998). Several sites record the Late Campanian- Early Maastrichtian cooling event (Lees, 2002; Friedrich *et al*., 2009, 2012; Jung *et al*., 2013), suggesting a global phenomenon.

In this work, we examine an extended Late Campanian- Early Maastrichtian interval at the lower part of the Gurpi Formation. We considered the paleoecological preferences of the recorded species according to the literature (Table 1). In the following discussion, you can find the most indicative taxa from the paleoecological point of view for reconstructing the paleo-climate at the Late Campanian- Early Maastrichtian in the lower part of Gurpi Formation.

The abundance curve of temperature indicative taxa is shown in figures 4 and 5. In this study, samples are characterized by relatively high abundances of *W. barnesae*. This is the most common oceanic species, and it has been considered as a warm water indicator (Watkins et al., 1996). Although in some of the previous studies (e.g., Mutterlose, 1996), *W. barnesae* is considered as a cosmopolitan species, it was rare or absent at the high latitude sites during

some intervals in the Maastrichtian (Bukry, 1973; Watkins et al., 1996; Bergen and Sikora, 1999) and towards the equator and low latitude sites, a significant increase is recorded (Thierstein, 1981; Pospichal, 1996). It also shows an affinity towards low fertility condition (Herrle *et al*., 2003; Kessels *et al*., 2003). This genus is the most solution resistant species, and assemblages that contain more than 40% of this species along with low abundance of dissolution prone species (such as *Biscutum constans* and *Discorhabdus ignotus*), are considered to be heavily altered (Roth & Krumbach, 1986; Williams & Bralower, 1995). The abundance curve of this genus is in consistency with the temperature index (TI) curve and no increase in its abundance along with the decrease in solution susceptible taxa is recorded in this study. At the correlation matrix (Table 2), a positive affinity can be observed between *W. barnesae* and *Ceratolithoides* spp., while a negative trend can be observed with *A. cymbiformis*, *T. orionatus*, *P. cretacea*, *L. cayeuxii* and *Zeugrhabdotus* spp., which is in consistency with their temperature affinity. It also shows a positive trend with species richness, Shannon Index and absolute abundance. At the DSDP Hole 390A (Black Nose) also a positive trend is recorded between this species and *Ceratolithoides* spp. (Linnert & Mutterlose, 2009). *Ceratolithoides* is considered as an oceanic, tropical-temperate species (Perch-Nielsen, 1985; Lees, 2002). At the studied interval, the relative abundance of *Ceratolithoides* spp. is increasing from the CMB towards the top of the section (Early Maastrichtian). In the Late Campanian, it is less abundant compared to the Early Maastrichtian. At the correlation Matrix, it shows a positive affinity with *Micula staurophora, E. turriseiffelii*, and *W. barnesae* and a negative component loading is recorded with *U. trifidus + U. sissinghii*, *Broinsonia* spp., *T. orionatus*, *B. constans*, *A. cymbiformis*, *Zeugrhabdotus* spp., *L. cayeuxii* and *P. cretacea*. From the *Uniplanarius* spp. group, *U. trifidus* and *U. sissinghii* are believed to be typical of tropical environment (Roth, 1978; Shafik, 1990) indicating warm water condition (Roth, 1978). Lees (2002) believed that *U. Sissinghii* and *U. trifidus* with a long to medium rays are common in the tropical oceanic settings, although their presence is also recorded up to the Austral province that can be the result of oceanic currents. In its abundance curve, the highest value is recorded at the lower and middle part of the section (Late Campanian) before the start of cooling phase (uppermost part of the Campanian).

Table 1. Published paleoecological preferences of selected nannofossil species

Species	Thibault and Gardin (2006)	Pospichal and Wise (1990)	Thierstein (1981)	Linnert and Mutterlose (2013)	Shafik (1990)	Roth (1978)	Lees (2002)	Mutterlose (1996)	Watkins et al. (1996)	Thierstein (1976)	Mutterlose (1992)	Watkins and Self-Trail (2005)	Tantawy (2002)	Street and Bown (2000)	Watkins (1992)
W.barnesae			Warm	Warm				Cosmopolitan	Warm			Warm			
Ceratolithoides spp.		Warm					Tropical-temperate					Warm			Warm
U. trifidus + U. sissinghii					Tropical	Tropical	Tropical								
B. parca parca					Extra-tropical										
B. matalosa + B. enormis							Cool		Cool						
B. signata				Warm											
A. octoradiata	Cold	Cold	Cold				Cold		Cold	Cold		Cold			Cold
G. segmentatum	Cold	Cold	Cold				Cold			Cold					
K. magnificus	Cold	Cold	Cold				Cold			Cold					
N. frequens	Cold	Cold	Cold				Cold								
Lucianorhabdus spp.										Cold					
T. orionatus							Cool		Cool		Cool				
A. cymbiformis		Cool	Cool				Intermediate					Cool			Cool
M. staurophora	Stressful condition	Cool										Cool	Stressful condition		Cool
B. constans							Cool							Cool	
Zeugrhabdotus spp.							Cool							Cool	
E. turriseiffelii		Cool	Cool									Cool			Cool
P. Cretacea		Cool	Cool									Cool			Cool

Table 2. Correlation matrix of important taxa

|	Watznaueria barnesae	E. turriseiffellii	E. eximius	P. cretacea	Micula staurophora	M. swastica	Zeugrhabdotus spp.	Retecapsa spp.	Arkhangelskiella cymbiformis	Broinsonia spp.	Biscutum constans	Ceratolithoides spp.	U. trifidus+U. sissinghii	T. orionatus	L. cayeuxii	G. segmentatum	D. ignotus	Absolute abundance	Species richness	Shannon Index
Watznaueria barnesae	1.00																			
E. turriseiffellii	-0.01	1.00																		
E. eximius	-0.25	-0.20	1.00																	
P. cretacea	-0.31	-0.08	0.55	1.00																
Micula staurophora	0.14	0.36	-0.67	-0.49	1.00															
M. swastica	0.04	0.37	-0.61	-0.54	0.72	1.00														
Zeugrhabdotus spp.	-0.45	-0.33	0.77	0.47	-0.74	-0.64	1.00													
Retecapsa spp.	0.02	0.02	-0.61	-0.31	0.42	0.28	-0.48	1.00												
Arkhangelskiella cymbiformis	-0.44	-0.17	-0.29	-0.29	0.00	0.16	0.06	0.20	1.00											
Broinsonia spp.	-0.22	-0.14	0.81	0.70	-0.65	-0.53	0.67	-0.54	-0.30	1.00										
Biscutum constans	0.09	-0.36	0.28	0.16	-0.31	-0.43	0.19	-0.15	-0.12	0.14	1.00									
Ceratolithoides spp.	0.35	0.41	-0.46	-0.36	0.71	0.56	-0.61	0.13	-0.29	-0.42	-0.24	1.00								
U. trifidus+U. sissinghii	-0.11	-0.43	0.62	0.53	-0.75	-0.81	0.65	-0.29	-0.20	0.58	0.49	-0.64	1.00							
T. orionatus	-0.37	-0.22	0.69	0.58	-0.65	-0.48	0.71	-0.48	-0.05	0.72	0.18	-0.49	0.57	1.00						
L. cayeuxii	-0.14	-0.30	0.52	0.11	-0.43	-0.45	0.54	-0.31	-0.02	0.27	0.15	-0.38	0.42	0.22	1.00					
G. segmentatum	0.19	0.06	-0.14	-0.16	0.03	-0.02	-0.07	-0.01	-0.06	-0.11	0.12	0.06	0.14	0.01	0.04	1.00				
D. ignotus	0.02	0.11	-0.25	-0.01	0.25	-0.03	-0.34	0.21	0.00	-0.20	0.28	0.17	-0.07	-0.13	-0.23	0.01	1.00			
Absolute abundance	0.23	-0.35	-0.11	-0.06	-0.14	-0.09	-0.07	0.05	-0.01	0.02	-0.02	0.04	0.21	0.09	-0.36	0.15	0.05	1.00		
Species richness	0.34	-0.23	-0.14	-0.24	-0.11	-0.06	-0.17	0.13	0.01	-0.06	0.05	0.05	0.21	0.00	-0.40	0.09	0.05	0.93	1.00	
Shannon Index	0.37	-0.32	-0.11	-0.10	-0.14	-0.11	-0.20	0.17	-0.10	-0.01	0.04	-0.03	0.25	0.04	-0.37	0.10	0.15	0.95	0.98	1.00
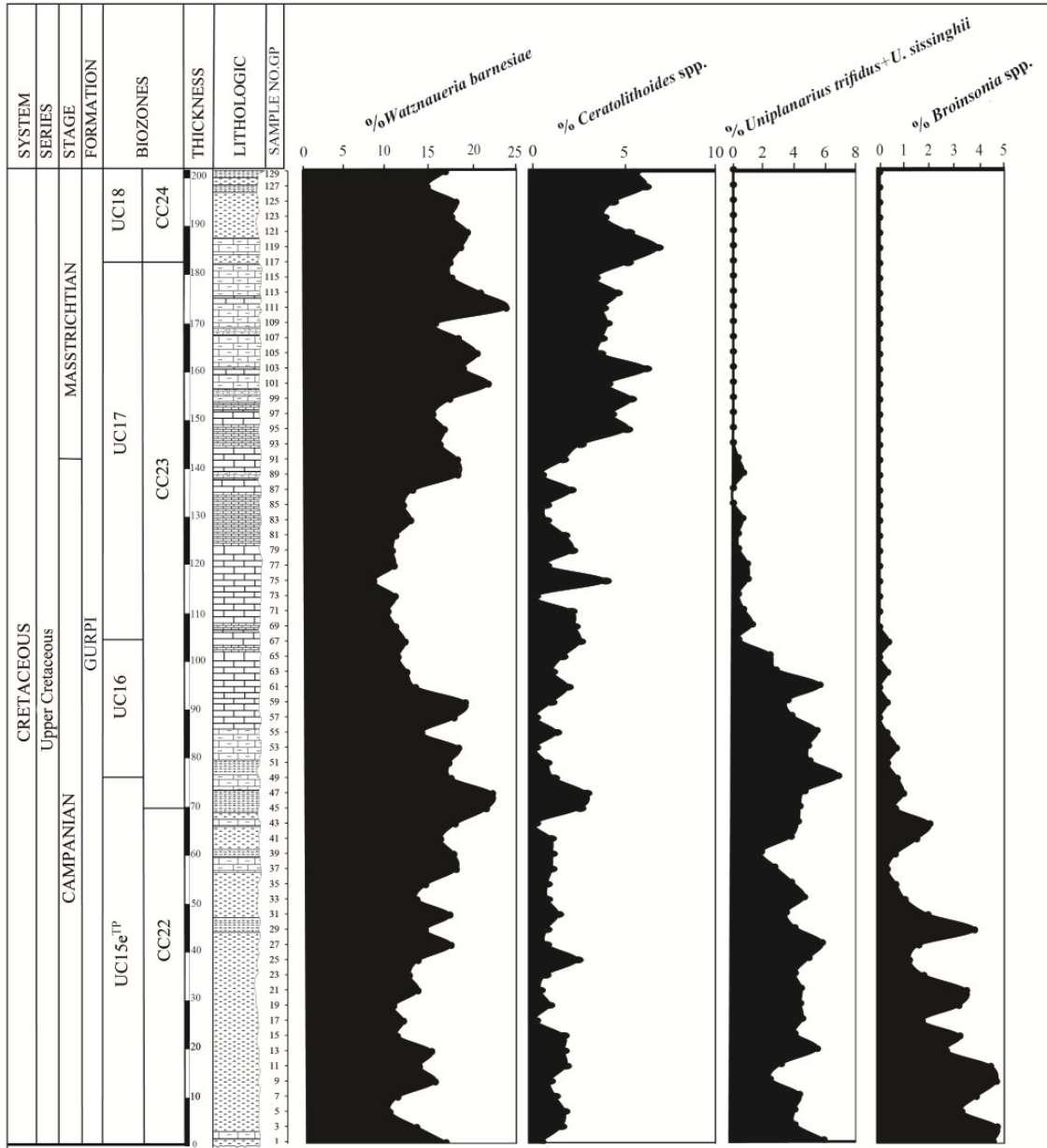
Figure 4. Relative abundance of warm water taxa at the lower part of the Gurpi Formation at the studied interval

With the start of the cooling phase, its abundance is decreasing to 1% and fluctuating between 0 to 1% before its LO which can be the result of cooling phase. *B. parca parca* is considered as an important component of extra-tropical province (Shafik, 1990), while other species of *Broinsonia* are considered as high latitude taxa like *Broinsonia matalosa* and *Broinsonia enormis* (Lees, 2002; Mutterlose, 1992; Watkins *et al*., 1996). Linnert and Mutterlose (2013) recorded a decrease in the relative abundance of *Broinsonia* especially *Broinsonia signata* at the late Cenomanian and

regard it as a signal of cool water condition. They have checked that a decrease in the relative abundance of this genus is recorded both in low and high nutrient environments.

In this study, *B. parca parca* and *B. parca constricta* show similar trends and are considered with each other as *Broinsonia* spp. The abundance curve of this group shows the highest value at the lower part of the section (Late Campanian), and a decrease in its abundance towards its LO is also recorded.
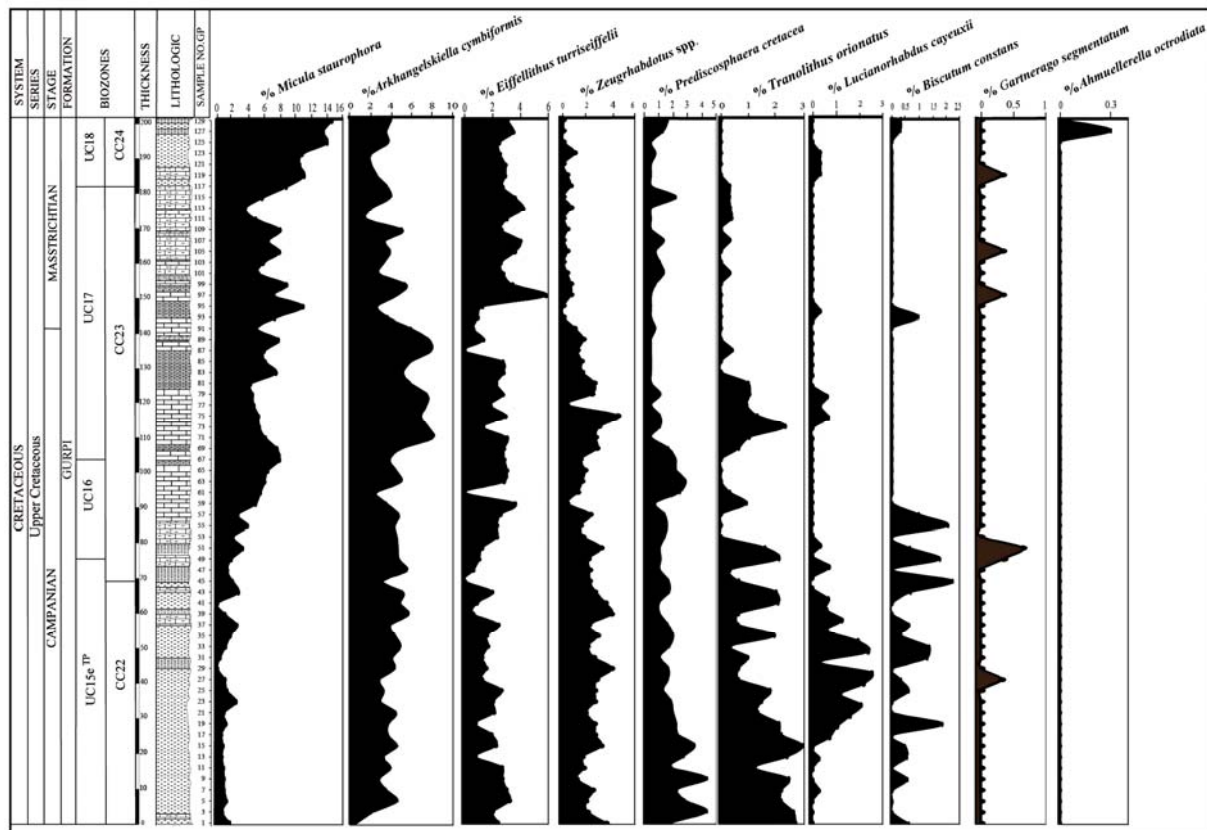
Figure 5. Relative abundance of cool water taxa at the lower part of the Gurpi Formation at the studied interval

Ahmuellerella octoradiata, *Gartnerago segmentatum*, *Kamptnerius magnificus* and *Nephrolithus frequens* are interpreted to prefer cold water that are mainly abundant at the high latitude sites, and are so rare at low latitudes (Thierstein, 1981; Pospichal and Wise, 1990; Lees, 2002; Thiabault and Gardin, 2006). In this study, the relative abundance of *A. octoradiata* and *G. segmentatum* are less than 1% and *N. frequens* and *K. magnificus* are not present. *Lucianorhabdus* is also considered as a high latitude species (Thierstein, 1976; Wind, 1979). Its highest relative abundance (3%) is recorded in a few samples at the lower part of the section at the Late Campanian. *Tranolithus orionatus* is also included as a high latitude and cool water species which is common to abundant in the Austral province of both shelf and open ocean environments (Mutterlose, 1992; Watkins *et al*., 1996; Lees, 2002). At the lower part of the studied interval (during the Late Campanian), it is much more abundant (3%) before its LO in the Early Maastrichtian. In the result of correlation matrix, a positive trend with *U. trifidus + U. sissinghii*, *Broinsonia* spp., *Zeugrhabdotus* spp., *B.*

constans, *E. eximius*, *L. cayeuxii*, and *P. cretacea* and a negative correlation with *Ceratolithoides* spp., *W. barnesae*, *Retecapsa* spp. and *M. staurophora* can be observed.

Although *A. cymbiformis* is recorded in both high and low latitude sites (Lees, 2002), some authors (Wind, 1979; Thierstein, 1981; Watkins and Self-Trail, 2005) consider this species as a high latitude taxa. Lees (2002) also recorded common occurrence of this species at the junction between the Austral and Temperate Provinces. The abundance curve of *A. cymbiformis* shows an increase at the uppermost Campanian and near the CMB which exactly corresponds to an interval of decreased warm water taxa that is in consistency with its cool water affinity. At the correlation matrix, a negative correlation with *U. trifidus + U. sissinghii*, *Ceratolithoides* spp., *Broinsonia* spp., *W. barnesae*, *B. constans*, *P. cretacea* and *E. turriseiffelii* can be observed. A positive correlation between this species and *Zeugrhabdotus* spp. and *Retecapsa* spp. is recorded.

Micula staurophora, common oceanic taxa is considered to be more abundant in high latitude

than low latitude sites in the Maastrichtian (Pospichal and Wise, 1990; Watkins, 1992; Watkins Watkins and Self-Trail, 2005). *M. staurophora* is also considered as a solution-resistant species that can be used for preservation evaluation (Thierstein, 1980; Thibault and Gardin, 2006). In some of the previous studies, high abundance of this species is recorded at the warmer conditions with well-preserved specimens at the uppermost part of the Maastrichtian, where cool water taxa are rare (Thibault and Gardin, 2006). As a result, an increase in abundance of this species in well preserved samples is considered to be the result of an unfavorable, stressful environmental conditions (Tantawy, 2002; Thiabult and Gardin, 2006). From the uppermost Campanian to CMB and the Early Maastrichtian, an increase in abundance of this species is recorded along with the presence of solution susceptible taxa that can be the result of a stressful condition, not preservation. A positive correlation with *Ceratolithoides* spp., *M. swastica, E. turriseiffelii, Retecapsa* spp., *W. barnesae* and *D. ignotus* and a negative correlation with *U. trifidus + U. sissinghii, Broinsonia* spp., *L. cayeuxii, T. orionatus, B. constans, A. cymbiformis, Zeugrhabdotus* spp., *E. eximius* and *P. cretacea* are recorded.

B. constans and *Zeugrhabdotus* spp. are also suggested as cool water species (Street and Bown, 2000; Lees, 2002). The relative abundance of *B. constans* is less than 2% at the studied interval and only recorded in some samples. Highest abundance of *Zeugrhabdotus* spp. is recorded at the lower and middle part of the section. As this group is also affected by nutrient content, its higher abundance where warm water taxa are recorded can be the result of higher nutrient content.

Eiffellithus spp. include of *E. turriseiffelii, E. eximius, E. gorkae* and *E. parallelus*. In previous studies, high relative abundance of *Eiffellithus turriseiffelii* is recorded at high latitude than low latitude sites in the Maastrichtian (Pospichal and Wise, 1990; Watkins, 1992; Lees, 2002; Watkins and Self-Trail, 2005). At the studied interval, *E. eximius* is only recorded at the lower part of the section before its LO in the Late Campanian with some minor fluctuations. At the correlation matrix, a positive trend can be observed between this species and *Ceratolithoides* spp., *M. staurophora* and *M. swastica*, while a negative trend can be observed with *B. constans, T. orionatus, L. cayeuxii, Zeugrhabdotus* spp. and *U. trifidus + U.*

sissinghii. These trends in correlation matrix can be the result of nutrient index or other factors. Here we consider it as a cool water species according to the previous studies.

A correlation matrix which is displaying taxa with similar and opposing affinities is illustrated in Table 2. The most important positive pairing are those of *P. cretacea/Zeugrhabdotus* spp. (0.47), *P. cretacea/T. orionatus* (0.57), *P. cretacea/Broinsonia* spp. (0.69), *P. cretacea/U. trifidus + U. sissinghii* (0.53), *M. staurophora/Ceratolithoides* spp. (0.71), *Zeugrhabdotus* spp./*T. orionatus* (0.71), *Zeugrhabdotus* spp./*L. cayeuxii* (0.54), *Zeugrhabdotus* spp./*Broinsonia* spp. (0.67), *Zeugrhabdotus* spp./*U. trifidus + U. sissinghii* (0.65), *T. orionatus/ Broinsonia* spp. (0.72), *T. orionatus/U. trifidus + U. sissinghii* (0.57), *Broinsonia* spp./ *U. trifidus + U. sissinghii* (0.58). The most pronounced negative pairings are those of *Zeugrhabdotus* spp./*M. staurophora* (-0.73); *T. orionatus/M. staurophora* (-0.65), *W. barnesae/ A. cymbiformis* (-0.43), *Broinsonia* spp./*M. staurophora* (-0.64), *Zeugrhabdotus* spp./*Ceratolithoides* spp. (-0.60), *Micula staurophora/U. trifidus + U. sissinghii* (-0.74), *U. trifidus + U. sissinghii/ Ceratolithoides* spp. (-0.63). Considering the results of the correlation matrix, some differences can be observed between species with similar temperature affinities and vice versa that can be interpreted as the effect of other factors like nutrients, oceanic currents, thermocline and so on. For example, *Micula staurophora, T. orionatus* and *Zeugrhabdotus* spp. are considered as cool water species in previous studies, but a negative trend can be observed between them at the studied interval. At the Goban spur also a negative trend has been observed between *Micula staurophora* and *T. orionatus* (Linnert et al., 2011). This may be the result of *M. staurophora* affinity to stressful condition as previously suggested (Thiabult & Gardin, 2006; Tantawy, 2002) or its affinity to the amount of nutrient.

The paleolatitudinal preferences of the above mentioned taxa are as follow: Warm water taxa mainly includes of *W. barnesae, U. trifidus, U. sissinghii, Ceratolithoides* spp. and *Broinsonia* spp., spp., while cool water taxa are *E. turriseiffelii, P. cretacea, M. staurophora, A. octoradiata, Zeugrhabdotus* spp., *A. cymbiformis, B. constans, T. orionatus, L. cayeuxii* and *G. segmentatum*. In order to estimate paleoceanographic variability through this time interval, taxa with similar affinity to temperature have been grouped. The curves of warm and cool water taxa along with each other

have been illustrated in Figure 6. The temperature index (TI) is also calculated as follows, and its diagram is shown in Figure 7.

TI= (Relative abundance of warm water taxa/ (Relative abundance of warm water taxa + Relative abundance of cool water taxa)) × 100.

Although the number of cold water taxa is less than 1%, calcareous nannofossil analyses of the studied interval indicate the presence of warm and cool water species along with each other and an opposite trend can be observed between them. Regarding the calcareous nannofossil data, four major trends of changing surface water temperature from warmer to cooler phases are recorded within the studied interval (Fig. 6). Images of some nannofossil species considered in this study are presented on Plate 1.
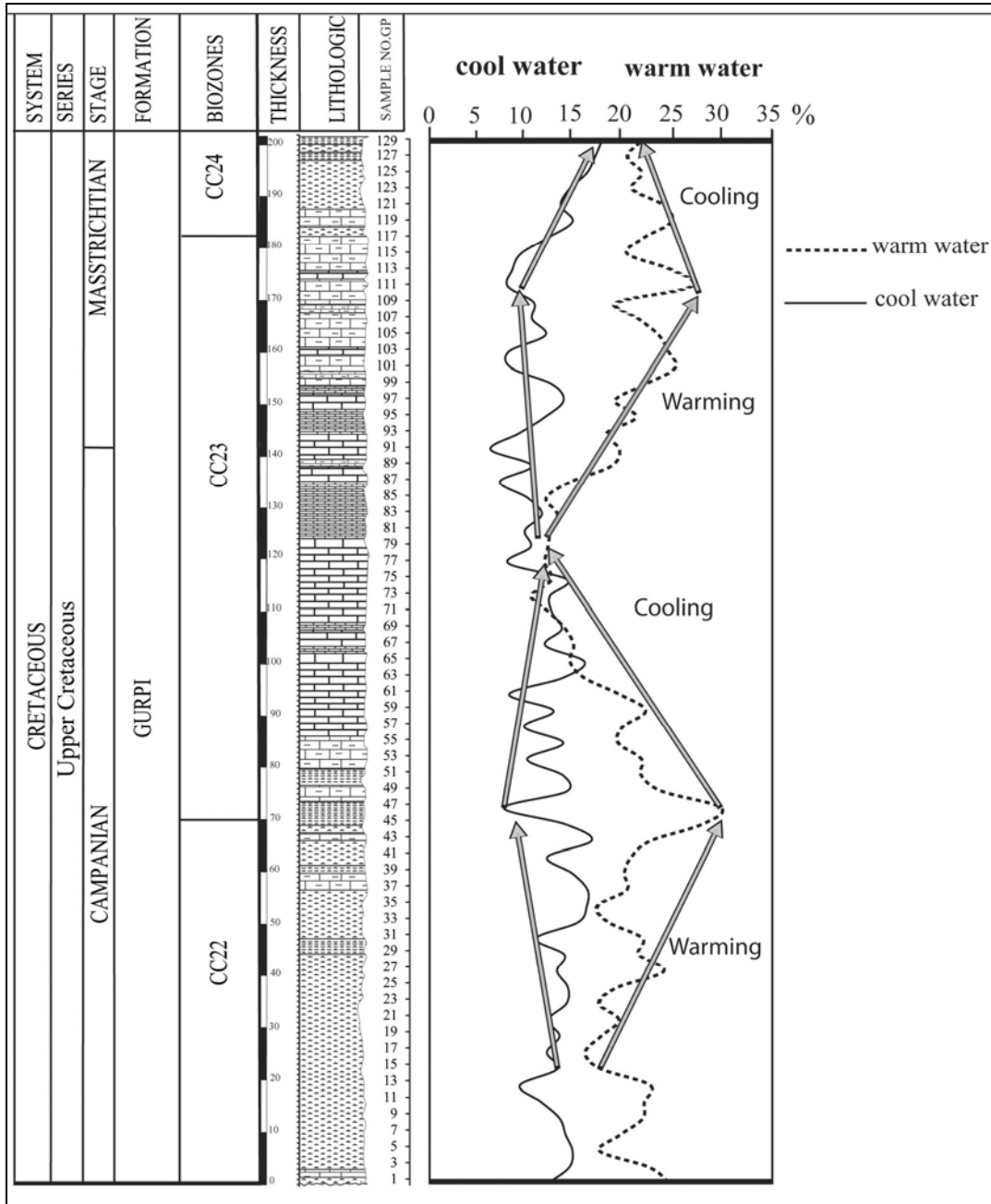

Figure 6. Fluctuations in the curves of warm and cool water calcareous nannofossil taxa along with each other
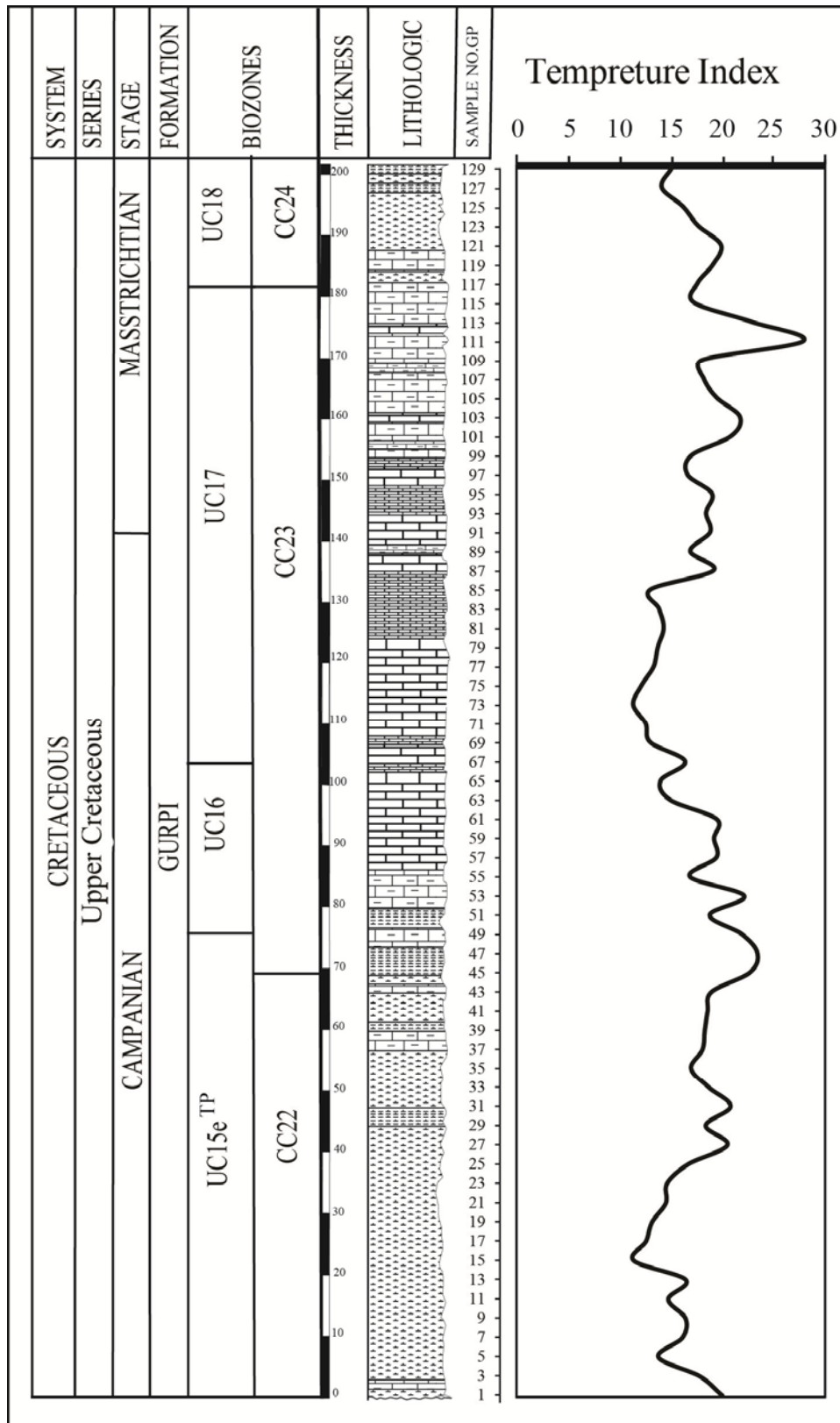
Figure 7. Vertical distribution of proposed Temperature Index (TI) calcareous nannofossil taxa at the studied interval. High values in the TI curve indicate high surface water temperature and vice versa.
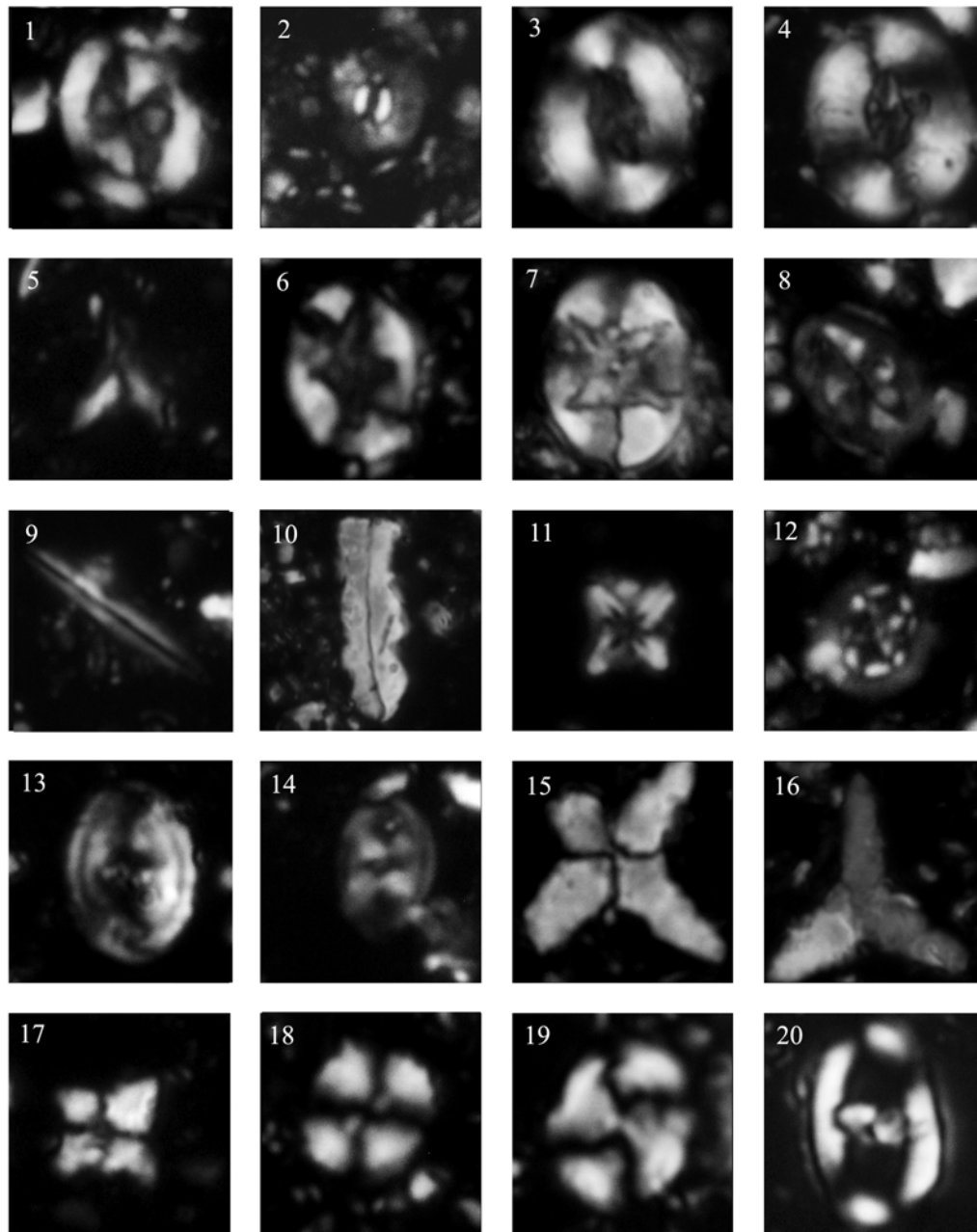
Plate 1: 1- *Arkhangelskiella cymbiformis* (Vakshina, 1959), XPL (Sample No. 76); 2- *Biscutum constans* (Gorka, 1957) Black, 1959, XPL- 20º rotated (Sample No. 72); 3- *Broinsonia parca parca* (Stradner, 1963) Bukry, 1969, XPL- 10º rotated (Sample No. 10); 4- *Broinsonia parca constricta* (Hattner et al., 1980), XPL (Sample No. 15); 5- *Ceratolithoides aculeus* (Stradner, 1961) Prins and Sissingh, 1977, XPL (Sample No. 25); 6- *Eiffellithus eximius* (Stover, 1966) Perch-Nielsen 1968, XPL (Sample No. 32); 7- *Eiffellithus turriseiffelii* (Deflandre in Deflandre and Fertm 1954), XPL (Sample No. 23); 8- *Gartnerago segmentatum* (Stradner, 1963) Noel, 1970 or Reinhardt, 1970a, XPL- 10º rotated (Sample No. 36); 9- *Lithraphidites carniolensis* Deflandre (1963), XPL- 45º rotated (Sample No. No. 38); 10- *Lucianorhabdus cayeuxii* (Deflandre, 1959), XPL (Sample No. 38); 11- *Micula staurophora* (Gardet, 1955) Stradner, 1963, XPL (Sample No. 60); 12- *Prediscosphaera cretacea* (Arkhangelsky, 1912) Gartner, 1968, XPL- 40º rotated (Sample No. 52); 13- *Reinhardtites levis* Prins and Sissingh in Sissingh (1977), XPL (Sample No. 42); 14- *Tranolithus orionatus* (Reinhardt, 1966), XPL (Sample No. 34); 15- *Uniplanarius sissingii* (Perch-Nielsen, 1986b), XPL (Sample No. 35); 16- *Uniplanarius trifidus*-long (Stradner in Stradner and Papp 1961) Hattner and Wise 1980, XPL (Sample No. 24); 17- *Uniplanarius gothicus* (Deflandre, 1959) Hattner and Wise, 1980, XPL (Sample No. 38); 18- *Watznaueria barnesae* (Black, 1959) Perch- Nielsen, 1968, XPL- 45º rotated (Sample No. 42); 19- *Watznaueria biporta* (Bukry, 1969), XPL- 25º rotated (Sample No. 32); 20- *Zeugrhabdotus embergeri* (Noël, 1958) Perch-Nielsen, 1984, XPL (Sample No. 28); 2000x.

At the first part of the studied interval, there are some fluctuations in the number of warm and cool water taxa, then an increase in abundance of warm water taxa along with a decrease in abundance of cool water taxa is recorded. After this phase, a major negative trend in the number of warm water taxa along with a major positive trend in the number of cool water taxa is recorded at the uppermost part of the Campanian up to the CMB. At the first part of the Maastrichtian, the trend of the cool and warm water taxa is changing and a negative trend in the number of cool water taxa along with a positive trend in the number of warm water taxa have been observed. Another change in the trend of cool and warm water taxa is recorded towards the uppermost part of the section (Early Maastrichtian), where the second positive shift in the number of cool water taxa along with a negative shift in the number of warm water taxa is recorded.

Based on the above mentioned data, it is evident that calcareous nannofossils experienced a significant fluctuation in response to climate variations during the Late Campanian- Early Maastrichtian at the studied interval, which is located at the low latitude sites in the Tethyan realm. According to these data, two cooling phases are recorded at the studied interval as follows: 1) at the uppermost part of the Campanian and the CMB and 2) at the uppermost part of the section in the Early Maastrichtian. The number of cool water taxa at the Early Maastrichtian is higher than the Late Campanian time, so the cooling phase of the Early Maastrichtian is more intensive than the Late Campanian. Barrera and Savin (1999) assumed that the cooling trend of the Campanian through Maastrichtian interval was accompanied by several cooling events. The Early Maastrichtian cooling event is also considered rapid and one of the most intensive cooling events compared to the Late Campanian (Barrera, 1994; Macleod and Huber, 1996). In the Equatorial Atlantic (Demarara Rise, ODP Leg 207 Hole 1258A), Thibault and Gardin (2006) delineated a major cooling event in the Early Maastrichtian. This climate changes observed inside the magnetochron C31r. Watkins *et al.* (1996) also recorded an increase in the number of cool water taxa during the latest Campanian in the southern high latitude. The cooling event of this time interval is also reported with regard to foraminifera (Li &

Keller, 1998; Friedrich *et al*., 2005; Friedrich & Hemleben, 2007), calcareous nannofossils (Watkins *et al*., 1996; Thibault and Gardin, 2006) and geochemical data (Voigt *et al*., 2010; Friedrich *et al*., 2009) at the other parts of the world. Another matter is the decreasing trend of species diversity in modern high latitude sites which is associated with an increase in abundance of cold water taxa (Okada and Honjo, 1973). At the Maud Rise and the Kerguelen Plateau in the Antarctica, a general decrease in the Shannon Index is recorded in the earliest Oligocene and a correspondence can be observed between species diversity and oxygen isotope curve, reflecting surface water cooling at that time (Persico and Villa, 2004). At the studied interval also, the decrease in the shannon diversity, simple diversity and absolute abundance towards the uppermost part of the section is associated with an increase in abundance of cool water taxa and can be indicative of a decrease in surface water temperature. As a whole, our results seem to fit very well with previous findings on the Late Campanian- Early Maastrichtian climate and faunal turnovers with regard to the calcareous nannofossils and at least two important cooling events are recorded at the studied interval.

Conclusions

Quantitative calcareous nannofossil analyses were performed on the lower part of the Gurpi Formation in the Zagros sedimentary basin in SW Iran. The nannofossil species have been assigned to different paleoecological groups with respect to the sea surface temperature. Variations in the number of temperature index species are inferred to be primarily indicative of sea surface temperature fluctuation in response to climate changes. The calcareous nannofossil assemblage records indicate the climatic trends from the Late Campanian to the Early Maastrichtian, allowing us to recognize two cooling event within this time interval. In the uppermost part of the Campanian and the CMB, a major increase in the number of cool water calcareous nannofossil taxa is associated with the cooling event recorded with regard to foraminifera, calcareous nannofossils and stable isotopes at the other parts of the world. At the uppermost part of the interval in the Early Maastrichtian, the second cooling event is recorded.

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Appendix

Alphabetical list of calcareous nannofossil species cited in the text and figures are given below. References are not cited in this paper and can be found in Perch-Nielsen (1985) and Bown (1998).

Ahmuellerella octoradiata (Gorka, 1975) Reinhardt, 1964.
Arkhangelskiella confusa (Burnett, 1997).
Arkhangelskiella cymbiformis (Vakshina, 1959).
Biscutum constans (Gorka, 1957) Black, 1959.
Broinsonia parca parca (Stradner, 1963) Bukry, 1969.
Broinsonia parca constricta (Hattner et al.,1980) Perch-Nielsen, 1984.
Ceratolithoides aculeus (Stradner, 1961) Prins and Sissingh, 1977.
Ceratolithoides amplector (Burnett, 1998a).
Ceratolithoides indiensis (Burnett, 1997).
Cribrosphaerella ehrenbergii (Arkhangelsky, 1912) Deflandre in Piveteau, 1952.
Discorhabdus ignotus (Gorka, 1957) Perch- Nielsen, 1968.

Eiffellithus eximius (Stover, 1966) Perch-Nielsen 1968.
Eiffellithus gorkae (Reinhardt, 1965).
Eiffellithus parallelus (Perch-Nielsen, 1973).
Eiffellithus turriseiffelii (Deflandre and Fertm. 1954).
Gartnerago segmentatum (Stradner, 1963) Noel, 1970 and Reinhardt, 1970a.
Kamptnerius magnificus (Deflandre, 1959).
Lucianorhabdus cayeuxii (Deflandre 1959).
Microrhabdulus attenuatus (Perch-Nie lsen, 1973).
Microrhabdulus decoratus (Deflandre, 1959).
Micula concava (Stradner in Martini and Stradner, 1960) Verbeek, 1976.
Micula praemurus （Bukry, 1973）Stradner and Steinmetz, 1984.
Micula staurophora （Gardet, 1955）(Stradner, 1963).
Micula swastica (Stradner and Steinmetz, 1984).
Nephrolithus frequens (Gorka, 1957).
Placozygus fibuliformis (Reinhardt, 1964) Haffmann, 1970b.
Prediscosphaera cretacea (Arkhangelsky, 1912) Gartner, 1968.
Reinhardtites anthophorus (Deflandre, 1959) Perch-Nielsen, 1968.
Reinhardtites levis (Prins and Sissingh in Sissingh, 1977).
Retecapsa angustiforata (Black, 1971a).
Retecapsa crenulata (Bramlette and Martini, 1964) Grun in Grun and Allemann, 1975.
Retecapsa ficula (stover, 1966) Burnett, 1998.
Retecapsa surirella (Deflandre and Fert, 1954) Grun in Grun and Allemann, 1975.
Tranolithus orionatus (Reinhardt, 1966).
Uniplanarius gothicus (Deflandre,1959).
Uniplanarius sissinghii (Perch-Nielsen, 1986b).
Uniplanarius trifidus (Stradner, 1961).
Watznaueria barnesae (Black, 1959) Perch- Nielsen, 1968.
Watznaueria biporta (Bukry, 1969).
Watznaueria fossacincta (Black, 1971) Bown, 1989.
Zeugrhabdotus bicrescenticus (Stover, 1966) Burnett in Gale et al., 1996.
Zeugrhabdotus diplogrammus (Deflandre in Deflandre and Fert, 1954) Burnett in Gale *et al*.,
1996.
Zeugrhabdotus embergeri (Noël, 1958) Perch-Nielsen, 1984.
Zeugrhabdotus sigmoides (Bramlette and Sullivan, 1961) Bown and young, 1997 =
*Placozygus sigmoide*s (Bramlette and Sullivan, 1961) Romein, 1979.