ISSN: 1698-6180
www.ucm.es\JIG

Journal of Iberian Geology 31 (1) 2005: 149-165

Journal of Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

Quantitative changes of calcareous nannoflora in the Saratov region (Russian Platform) during the late Maastrichtian warming event

Cambios cuantitativos en la nanoflora calcárea en la región de Saratov (Plataforma rusa) durante el evento cálido del Maastrichtiense superior

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Received: 23/10/03 / Accepted: 10/06/04

Abstract

Calcareous nannoplankton from three high latitude sections in the Volga River Region near Saratov (Lokh, Klyuchi 1, and Klyuchi 2) are described. Subzone CC23a, Subzone CC23b-Zone CC24 (Lokh Formation) and Zones CC25a-b and CC26 (Nikolaevka Formation) are recognised. The Lower and Upper Maastrichtian sequences have been analysed quantitatively. New data on calcareous nannoplankton confirm a cooling, during the Early Maastrichtian and a considerable warming at 500–100 Kyr before the K/T boundary. The dominance of cold-water species is characteristic of the Early Maastrichtian, where warm-water taxa constitute only 3–6 %. An increase of warm-water species up to 15–20 % is characteristic of the Late Maastrichtian (CC26 Zone). Three maxima of substantial warming are recognised at 68.35 Myr, 66.25 Myr, and 65.5 Myr.

Keywords: Calcareous nannofossils, quantitative analysis, Maastrichtian, biostratigraphy, Russian Platform, palaeotemperature.

Resumen

Se describe el nanoplancton calcáreo de tres secciones de altas latitudes (Lokh, Klyuchi 1 y Klyuchi 2) en la región del Río Volga, cerca de Saratov. Se han reconocido las Subzonas CC23a, CC23b y la Zona CC24 en la Fm. Lokh y las Zonas CC25a-b y CC26 en la Fm. Nikolaevka. Se han analizado cuantitativament las secuencias del Maastrichtiense. Los nuevos datos del nanoplancton calcáreo confirman un enfriamiento durante los comienzos del Maastrichtiense y un calentamiento considerable hacia los 500-100 ka antes del límite K/T. El predominio de las especies de aguas frías caracteriza la parte inferior del Maastrichtiense, con presencia de especies de aguas cálidas entre el 3 y el 6%. La parte superior del Maasrtrichtiense (Zona CC26) se caracteriza por un incremento de esas especies hasta el 15-20%. Reconociéndose hasta tres máximos cálidos importantes hacia los 68,35, 66,25 y 65,5 Ma, respectivamente.

Palabras clave: nanofósiles calcáreos, análisis cuantitativo, Maastrichtiense, bioestratigrafía, Plataforma Rusa, paleotemperatura.

1. Introduction

Due to their microscopic size and the near-global distribution of many taxa, calcareous nannoplankton have become very popular for solving various stratigraphic problems, and many studies have been devoted to that end. Furthermore, nannofossils are sensitive indicators of changes in the temperature and salinity of the ocean and sea surface water. To reveal such changes, quantitative analysis of calcareous nannoplankton assemblages is essential. Quantitative analysis is a relatively new approach in nannoplankton research. A quantitative study has recently been carried out for the Campanian of the Russian Platform (Belgorod Region), which confirmed the global

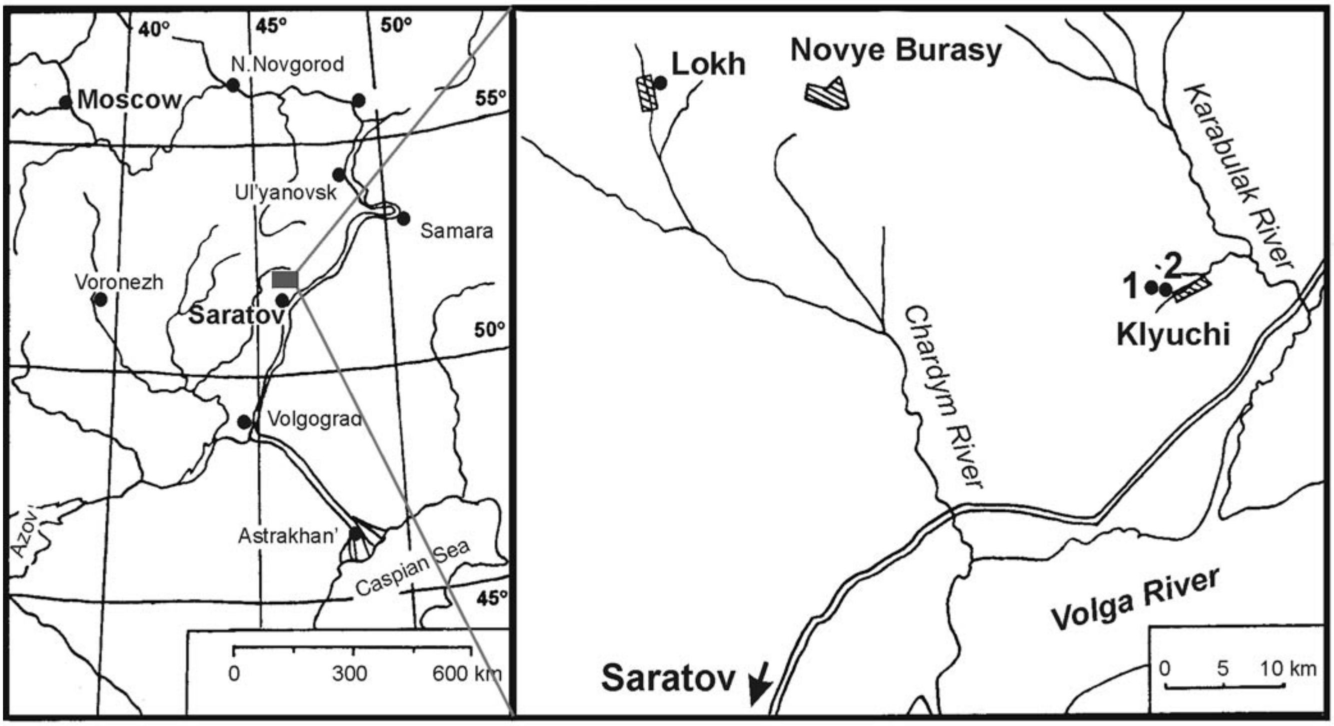

Fig. 1.- Location of the sections studied.
Fig. 1.- Situación de las secciones estudiadas.

pattern of cooling during this period (Ovechkina and Alekseev, 2002).

The climate was fairly cold at high latitudes during the Maastrichtian, and the temperature of the surface water reached 7–9º C at its minimum (Barrera, 1994; Huber, 2002). Despite the general trend toward cooling, considerably warmer periods are recognised during the Maastrichtian (Alekseev *et al.*,1999; Barrera and Savin, 1999; Olsson *et al.*, 2001).

The purpose of the present work is to analyse nannoplankton quantitatively and to reconstruct palaeotemperature oscillations for the Maastrichtian of the Volga River Region near Saratov. Clay and marl deposits of the Maastrichtian of this region were accumulated at the northern periphery of Peritethys, which occupied the southern part of the Russian Platform at relatively high latitudes (50–55ºN).

The calcareous nannoplankton of the Maastrichtian of the Saratov Region have been studied previously (Shumenko, 1970, 1976; Alekseev *et al.*, 1999). However, those studies were mainly stratigraphic.

2. Materials and Methods

Quantitative analysis has been performed for three high latitude (52°N) sections of the Maastrichtian of the Saratov Region (Lokh, Klyuchi 1, and Klyuchi 2), situated 65 km NE and NW of Saratov city (Fig. 1). These sections and their sequencing on the basis of the calcareous nannoplankton, foraminifera and molluscs have been published earlier (Alekseev *et al.*,1999).

Approximately 130 samples were taken at 0.4–1.5 m intervals. The nannoplankton were studied in permanent slides, that had been prepared in the following way. A small piece of the sample (ca. 5 g) was powdered in a glass container, where distilled water (20 ml) was added. We used the standard techniques of decantation at 5 min intervals. A drop of the suspension obtained was put onto a slide, dried out, and covered with a cover-slip with a drop of the Canada Balsam. Then the preparation was heated and the cover slip held with a pin to eliminate air bubbles. Samples were inspected under a Zeiss Axiolab light microscope at x1500 magnification. Photographs were taken under SEM.

An average state of preservation was assigned to each sample according to the following criteria: G – good (most specimens exhibit little or no secondary alteration); M – moderate (specimens exhibit some effects of secondary alteration from etching and overgrowth); P – poor (specimens exhibit profound effects of secondary alteration from etching and overgrowth).

For the purpose of the quantitative analysis, 200 specimens were counted in each sample (100 from several random fields of view in the centre of the slide, 100 from

warm-water taxa (lower and middle latitudes)																
Previous attribution	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Biscutum constans					+											
Ceratolithoides aculeus				+			+					+		+		+
Cretarhabdus surirellus							+					+				
Cylindralithus serratus	+						+					+				+
Lithraphidites carniolensis				+								+			+	
L. praequadratus				+								+				
L. quadratus							+					+	+			+
M. murus			+				+					+		+		+
M. prinsii													+			+
Octolithus multiplus													+			
Uniplanarius sissinghii				+								+		+		
U. trifidum	+						+					+		+		
Watznaueria barnesae		+			+		+	+				+	+		+	
cold-water taxa (high latitudes)																
Ahmuellerella octoradiata			+		+		+		+		+	+			+	
Arkhangelsk. cymbiformis		+			+		+	+		+	+	+	+		+	
A. specillata									+		+	+			+	
Biscutum magnum					+				+		+	+			+	
Broinsonia parca constricta															+	
Br. parca parca									+						+	
Calculites obscurus			+					+	+		+			+		
Cribrosphaer. ehrenbergii									+		+	+			+	
Eiffellithus eximius								+	+			+			+	
E. turriseiffelii				+	+		+		+	+	+	+			+	
Gartnerago spp.			+		+		+				+					
Kamptnerius magnificus		+	+	+	+	+	+	+	+	+	+	+		+	+	+
Lucianorhabdus cayeuxii			+		+	+	+		+		+	+		+	+	
Micula concava													+	+	+	
M. decussata			+		+		+	+	+		+	+	+		+	
Nephrolithus frequens	+	+	+	+	+	+	+	+	+		+	+		+		+
Prediscosphaera cretacea					+				+		+	+			+	
Pr. grandis									+					+		
Pr. spinosa					+		+		+		+	+			+	
Pr. stoveri											+	+				+
Reinhardtites antophorus					+		+								+	
R. levis										+	+	+		+		+
Tranolithus phacelosus					+				+		+	+			+	

Table 1.- Taxa previously attributed to either warm-water or cold-water forms. References or attributions are as follows: 1 - Worsley and Martini (1970); 2 – Bukry (1973); 3 – Thierstein (1976); 4 - Wise and Wind (1977); 5 - Wind (1979); 6 – Perch-Nielsen (1979); 7 - Thierstein, 1981; 8 – Doeven (1983); 9 – Wise (1983); 10 - Wagreich (1987); 11 – Pospichal, Wise (1990); 12 - Watkins (1992); 13 - Lamolda and Gorostidi (1994); 14 - Burnett (1998); 15 - Ovechkina and Alekseev (2002); 16 – Melinte, Lamolda and Kaiho (2003).

Tabla 1.- Taxones atribuidos previamente a aguas cálidas o aguas frías. Referencias o atribuciones: 1 - Worsley y Martini (1970); 2 – Bukry (1973); 3 – Thierstein (1976); 4 - Wise y Wind (1977); 5 - Wind (1979); 6 – Perch-Nielsen (1979); 7 - Thierstein, 1981; 8 – Doeven (1983); 9 – Wise (1983); 10 - Wagreich (1987); 11 – Pospichal, Wise (1990); 12 - Watkins (1992); 13 - Lamolda y Gorostidi (1994); 14 - Burnett (1998); 15 - Ovechkina y Alekseev (2002); 16 – Melinte, Lamolda y Kaiho (2003)

several random fields of view along the margin).

To recognise temperature changes, all nannofossil taxa have been divided according to their association with warm or cold waters. There are few data on this problem. For the first time, peculiarities of the latitudinal distribution of Late Cretaceous nannoplankton species were reported by Bukry (1973). He noted, for example, that the species *Watznaueria barnesae* is absent from high latitudes, where the surface water was obviously colder than in the tropics. In support of his conclusion, he mentioned results of his own examination of two samples from the Maastrichtian of a reference borehole drilled in the vicinity of Omsk, Western Siberia, which demonstrated the absence of *W. barnesae*. However, our study of the nannoplankton assemblages of the Upper Maastrichtian from a borehole near the village of Chistoozernyi, about 200 km east of Omsk and approximately at the same latitude as Omsk (ca. 55ºN), has revealed a constant presence of this species, although in small numbers (Benjamovski *et al*., 2002). It is also recorded in the Upper Cretaceous deposits of the Northern Atlantic and in the Maastrichtian of Denmark (57ºN). At the same time, assumptions have been made that the proportion of *W. barnesae* increases under low productivity conditions (Erba *et al*., 1992) or that it is an ecologically tolerant species which occupies new ecological niches first (Mutterlose, 1996). However, neither interpretation implies that *W. barnesae* is indifferent to temperature; on the contrary, available data show rarity or complete absence of this species at high latitudes of the Southern Hemisphere (Pospichal and Wise, 1990; Resiwati, 1991; Watkins, 1992).

Watznaueria barnesae is the main warm-water species. *Ceratolithoides aculeus*, species of the genera *Lithraphidites* (*L. praequadratus*, *L. carniolensis*, and *L. quadra-*

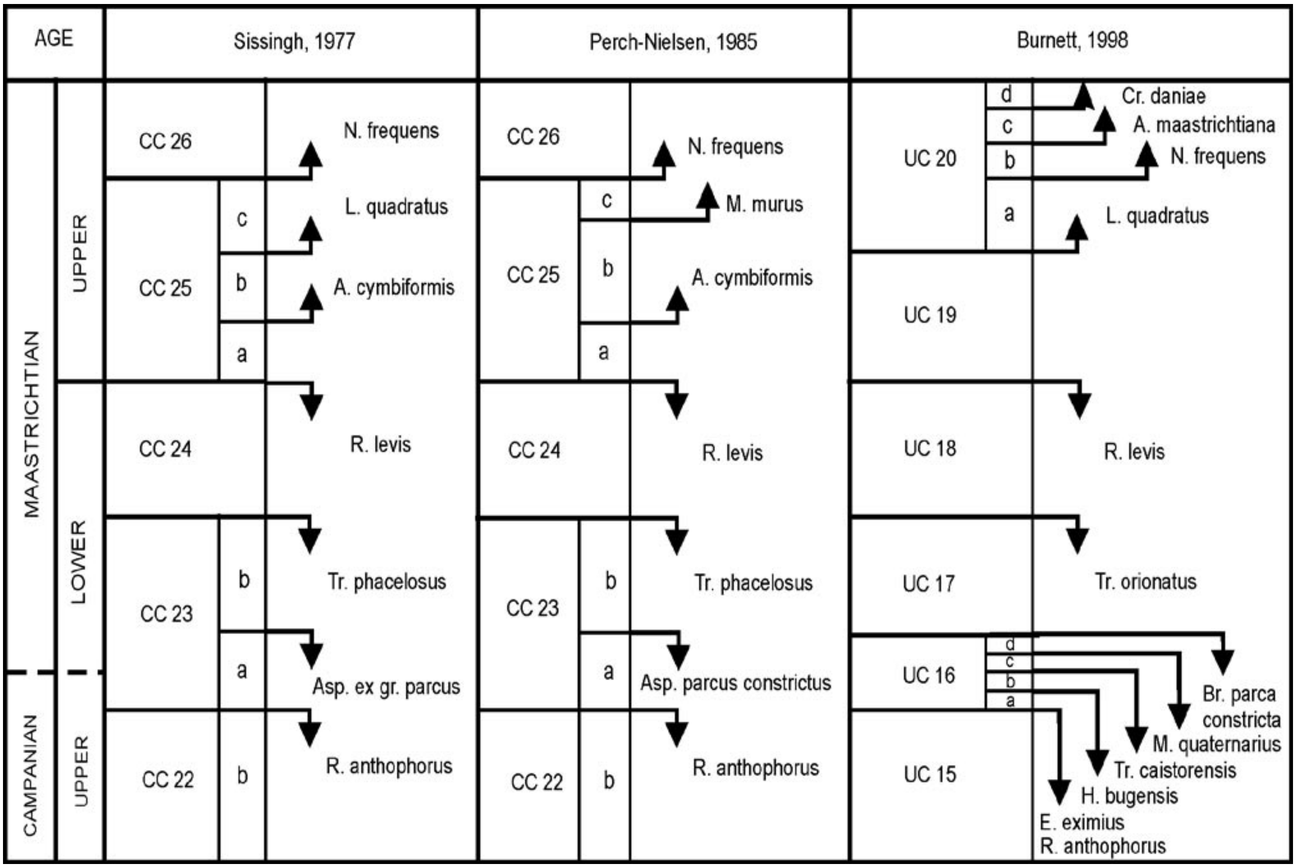

Fig. 2.- Summary of the nannofossil biozonation of Sissingh (1977), Perch-Nielsen (1985) and Burnett (1998).
Fig. 2.- Resumen de las biozonaciones de Sissingh (1977), Perch-Nielsen (1985) y Burnett (1998).

tus), *Micula murus*, *M. prinsii*, *Uniplanarius sissinghii*, *U. trifidum*, *Biscutum constans*, *Cretarhabdus surirellus*, *Cylindralithus serratus*, and *Octolithus multiplus* should be also considered as warm-water species (Table 1).

Such forms as *Micula decussata*, *M. concava*, *Lucianorhabdus cayeuxii*, *Kamptnerius magnificus*, *Nephrolithus frequens*, *Arkhangelskiella cymbiformis*, *A. specillata*, *Eiffellithus eximius*, *E. turriseiffelii*, *Reinhardtites antophorus, R. levis*, *Gartnerago* spp., *Calculites obscurus*, *Broinsonia parca parca*, *B. parca constricta*, *Cribrosphaerella ehrenbergii*, *Prediscosphaera cretacea*, *P. spinosa*, *P. stoveri*, *P. grandis*, and *Tranolithus phacelosus* should be considered as relatively cold-water species.

Some of these taxa could be more exactly defined as eurythermal (and cosmopolitan), i.e. independent of the water temperature, but this is not possible due to the small number of quantitative studies of nannofossils carried out so far. Such forms as *Cribrosphaerella ehrenbergii* and *Eiffellithus turriseiffelii* most probably belong to this group (Thierstein, 1981).

For quantitative analysis of the Upper Cretaceous we used *Watznaueria barnesae*, *Lithraphidites carniolensis*, and *L. quadratus* as warm-water taxa and *Micula decussata, M. concava, Kamptnerius magnificus*, *Nephrolithus frequens*, *Arkhangelskiella cymbiformis*, *A. specillata*, *Reinhardtites levis*, *Prediscosphaera stoveri*, *P. grandis*, and *P. spinosa* as relatively cold-water taxa. *Prediscosphaera cretacea* is a eurythermal species, which is the commonest at high latitudes, although it has been recorded at low latitudes as well. It is considered as a cosmopolitan species. We counted the total number of species of the genus *Prediscosphaera*, given that species of this genus can be assumed to have been relatively cold-water tolerant. *Eiffellithus turriseiffelii* and *Cribrosphaerella ehrenbergii* belong to the cosmopolitan taxa.

The warm-water coefficient for each sample was evaluated as the percentage of warm-water taxa in the assemblage for each sample.

Beside the percentage of warm- and cold-water forms, such an important criterion as the ratio of *Micula* spp./ *Watznaueria barnesae* is essential for revealing palaeoenvironments. The group *Micula* spp. includes the species *Micula decussata* and *M. concava*. The ratio *Micula staurophora* (= *M. decussata*)/ *W. barnesae* was used to detect palaeotemperature variations (Wind, 1979; Doeven, 1983). The ratio *Micula* spp./ *W. barnesae* was used by Gorostidi and Lamolda (1995) and Pospichal

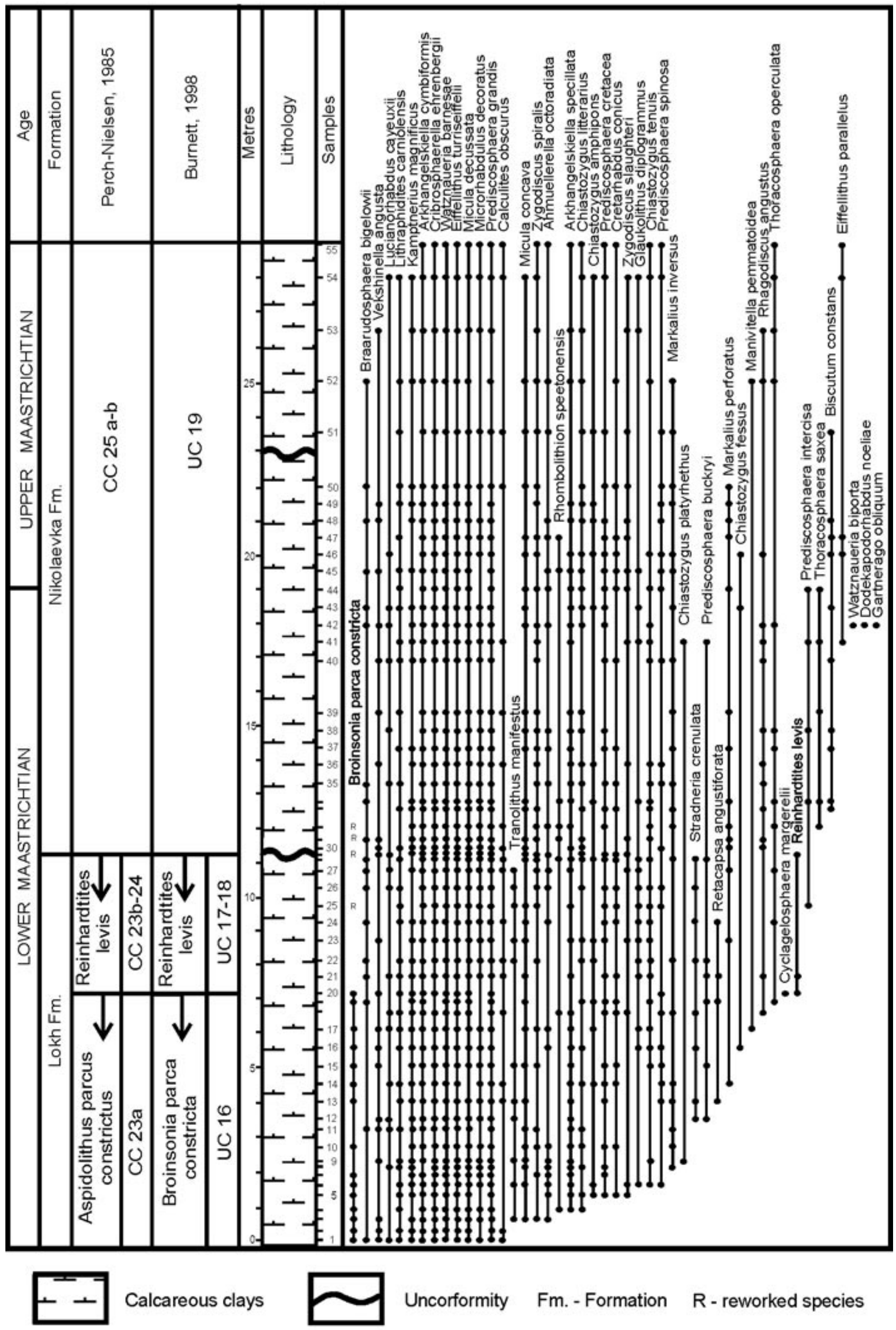

Fig. 3.- Stratigraphic distribution of calcareous nannofossils in the Maastrichtian, Lokh section.

Fig. 3.- Distribución estratigráfica de los nanofósiles calcáreos en el Maastrichtiense de la sección de Lokh.

(1996) to determining cooling episodes in late Maastrichtian in the sections at Bidart (southwestern France) and Agost (southeastern Spain).

3. Results

3.1. Stratigraphy

Columns of the studied sections as well as their sequencing using calcareous nannoplankton, benthic foraminifera, and molluscs have been published elsewhere (Alekseev *et al.*, 1999). Originally, a standard nannoplankton zonation (Sissingh, 1977) corrected by Perch-Nielsen (1985) was used. In the present work we also tried to sequence Maastrichtian deposits in the sections studied using a zonation proposed for the Boreal Region (Burnett, 1998) (Fig. 2).

3.1.1. The Lokh section

The lower part of the Maastrichtian is represented in the Lokh section, situated on the left bank of the Lokh River, near the village of Lokh, Novye Burasy District (Fig. 1). The base of the Lower Maastrichtian Lokh Formation is not visible in the small quarry, but, most probably, this formation overlies a deeply eroded, washed out Santonian sponge bed or rests on the Turonian, sandy chalk of which is exposed in a quarry below the cemetery, or directly on Cenomanian sands (Bondarenko, 1975).

A nannoplankton assemblage consisting of a relatively small number of species (47) has been identified in this section (Fig. 3). The state of nannofossil preservation is good in the lower part of the section (samples 1–3), but it deteriorates up section due to secondary alteration. Coccoliths are rather heavily broken and dissolved.

The whole calcareous nannoplankton assemblage is characteristic of the Maastrichtian. This is indicated by high proportions of *Arkhangelskiella cymbiformis, A. specillata*, and *Cribrosphaerella ehrenbergii*. The Lokh Formation (Fig. 3, samples 1–29) is characterised by the dominance of *A. cymbiformis* and *A. specillata*.

The nannofossil assemblage is identified from the visible base of the 11.3 m thick Lokh Formation, which is composed of calcareous clays and very clayey marls (22–35% $CaCO_3$). The lower 7.3 m of the Lokh Formation, prior to sample 20, can be assigned to Subzone CC23a or Zone UC16 on the grounds of the constant presence of *Broinsonia parca constricta*, the disappearance of which demarcates the top of this subzone. Isolated specimens occur up section (samples 25-29); however, they are considered to be redeposited, since they are particularly rare and heavily dissolved. In this case, the upper part of the Lokh Formation should be assigned to Subzone CC23b or Zone UC17, despite the absence of *Tranolithus phacelosus*. At the same time, *R. levis* disappears at the top of this formation (sample 29), which indicates that this interval is not younger than zones CC24 or UC18. These data on nannofossil distribution and the absence of lithological signs of discontinuity in the upper part of the Lokh Formation, allow assignment of this interval to Subzone CC23b–Zone CC24 or zones UC17–18.

The finding of *R. levis* in sample 19 cannot be considered as the first occurrence, for this species is rather rare in the Boreal Region and usually appears at the base of Subzone CC22b.

The lowermost part of the Lokh Formation (samples 1–19 prior to the occurrence of *R. levis*) does not belong to the Upper Campanian Subzone CC22b. This is supported by the absence of typical Campanian forms such as *Eiffellithus eximius*, *Tranolithus phacelosus*, and *Reinhardtites anthophorus* as well as by the presence of a large number of representatives of the genus *Arkhangelskiella*. Rostra of *Belemnella lanceolata* found at this level (sample 9) are typical for the Lower Maastrichtian (Alekseev *et al.*, 1999). It is further confirmed by the foraminiferan species *Rugoglobigerina rugosa, Globotruncanella petaloidea, Bolivina decurrens*, and *B. incrassata* (B. decurrens Zone, which incorporates the whole Lower Maastrichtian) (Alekseev *et al.*, 1999).

In the Lokh section, the Nikolaevka Formation is represented only by its lower part and is composed by very clay-rich marls (23-32% $CaCO_3$). It lies with distinct erosion on marls of the Lokh Formation and is enriched basally with sandy material and glauconite (Fig. 3). On the basis of a small hiatus in the middle part (appearance of rather abundant kidney-shaped glauconite grains in sample Lkh-51), the Nikolaevka Formation is subdivided into two members. The lower member is 11.6 m thick, the upper member 6 m thick. The basal layer of the lower member contains eroded belemnite rostra of *Belemnella sumensis* Jeletzky, which are typical of the upper part of the Lower Maastrichtian. Here, the nannoplankton assemblage which consists of a small number of species (36) is identified as well. The number of nannoplankton species reduces to 31 in the upper member. Both members of the Nikolaevka Formation are assigned to Zone UC19 of the upper part of the Lower Maastrichtian, since *Reinhardtites levis* is already absent and *Lithraphidites quadratus* has not yet appeared, and corresponds to the undivided subzones CC25a and b.

Two other sections have been studied in the Bazar-Karabulak District, on the left slope of the Malyi Klyuch Valley near the northern environs of the Klyuchi village (Fig. 1).

3.1.2. The Klyuchi 2 section

In the Klyuchi 2 section, which is closer to the village of Klyuchi, the upper part of the Lokh Formation which is composed of distinctly calcareous clays and 3.2 m thick is exposed at the base of the section. A nannofossil assemblage, consisting of a small number of species (32) (Fig. 4) and essentially identical to the assemblage of this formation in the Lokh section, has been identified in this part of the section. It allows recognition of Zone UC16 or Subzone CC23a.

At the base of the overlying Nikolaevka Formation, a relatively thin (0.8–0.9 m) greenish yellow bed of weakly calcareous (16–20% $CaCO_3$) clays is clearly distinguished by its colour. Apparently, it discontinuously overlies clays of the Lokh Formation. It contains a nannofossil assemblage, which is similar to that from the underlying beds and does not allow identification of the zone with certainty. However, these clays represent a condensed part of the section encompassing the upper part of the Lower Maastrichtian and the lower part of the Upper Maastrichtian according to the benthic foraminifera (Alekseev *et al.*, 1999). This conclusion is supported by the discovery of rostra of *Belemnella sumensis praearkhangelskii* Naidin in the talus on the clay bed. Al-

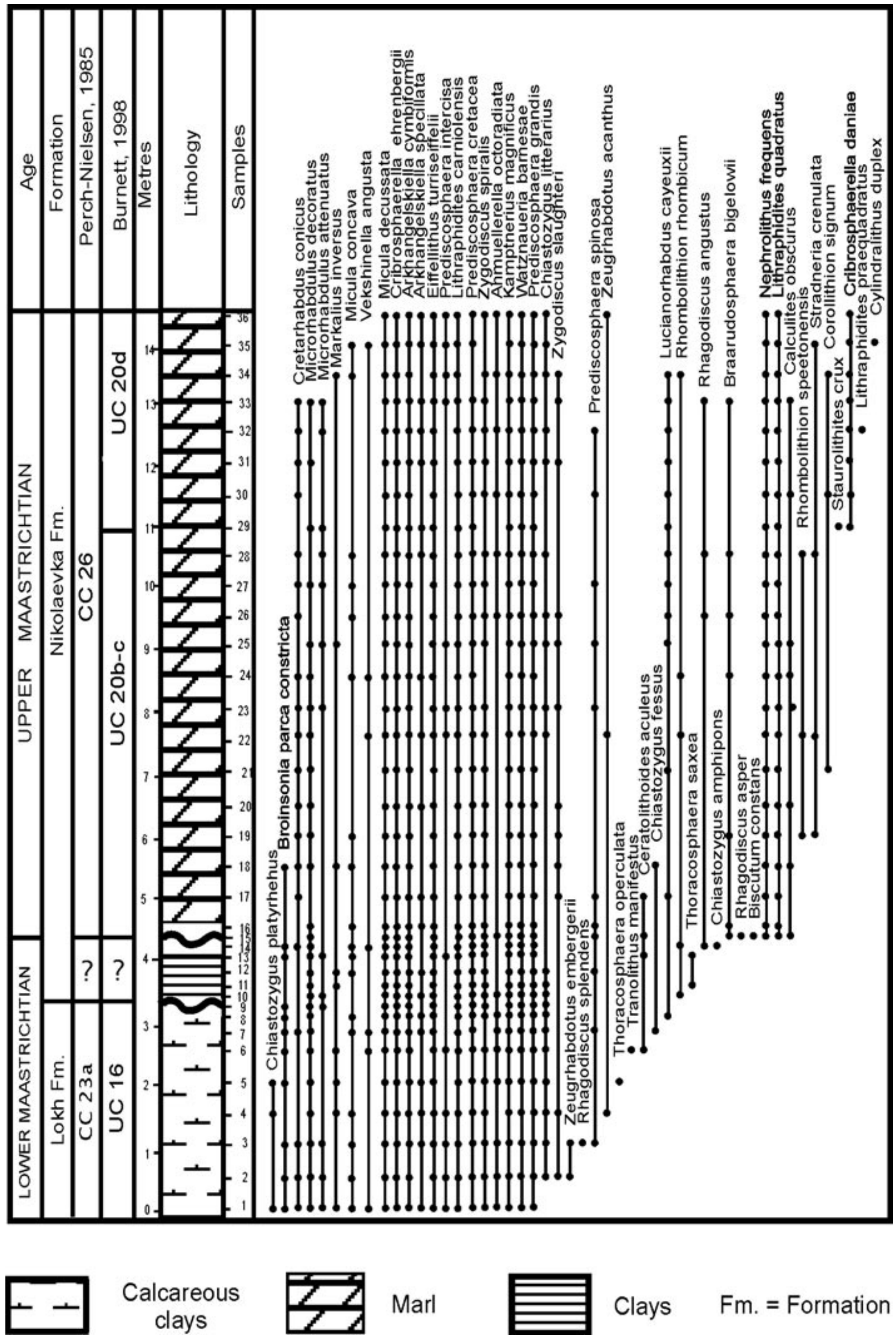

Fig. 4.- Stratigraphic distribution of calcareous nannofossils in the Maastrichtian, Klyuchi 2 section.

Fig. 4.- Distribución estratigráfica de los nanofósiles calcáreos en el Maastrichtiense de la sección de Klyuchi 2.

though these rostra might be washed out from the base of the overlying member, this subspecies is characteristic of the terminal part of the Lower Maastrichtian (Kopaevich *et al*., 1987).

Almost white, chalk-like marls of the Nikolaevka Formation which is about 10 m thick discontinuously overlie the clay bed. However, their contact with overlapping Palaeocene Syzran Formation is not visible in this section. *Nephrolithus frequens* and *Lithraphidites quadratus* are recorded from the base of the marls. This indicates that these marls are not older than Subzone UC20b. The nannoplankton assemblage is still not very diverse (37 species). The first *Cribrosphaerella daniae* appear approximately 6 m above the base of the chalk-like marls (sample Kl 2-29). Thus the uppermost 2.5 m of the section can be assigned to Subzone UC20d that ends the Maastrichtian. The nannofossil assemblage of Subzone UC20d is essentially unchanged and includes 35 species. The presence of Subzone UC20c cannot be established in this section, as its index species *Arkhangelskiella maastrichtiana* has not been recorded here. According to the standard zonation, this part of the Nikolaevka Formation in the Klyuchi 2 section is referred to Zone CC26 of the Upper Maastrichtian.

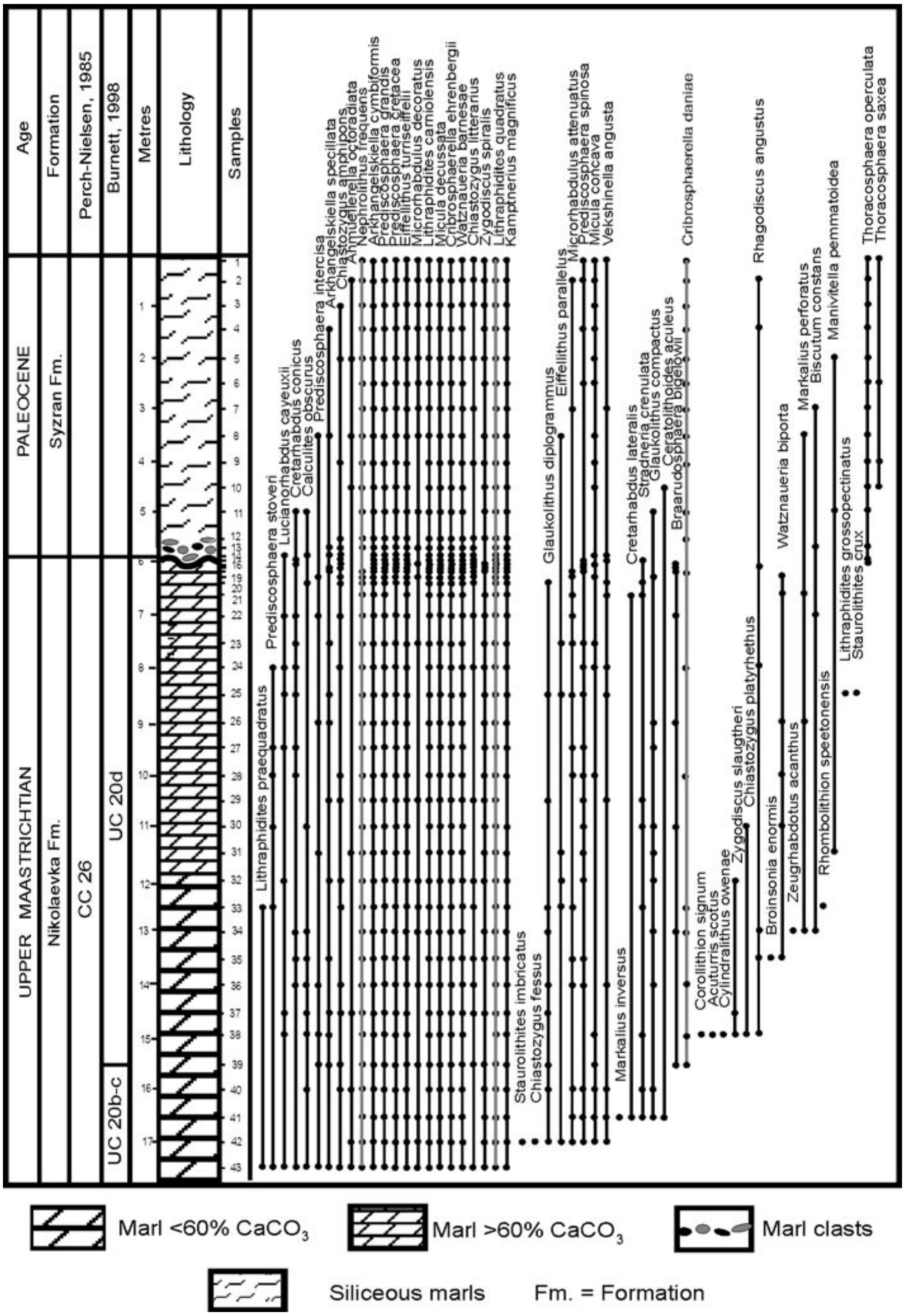

Fig. 5.- Stratigraphic distribution of calcareous nannofossils in the Maastrichtian, Klyuchi 1 section.

Fig. 5.- Distribución estratigráfica de los nanofósiles calcáreos en el Maastrichtiense de la sección de Klyuchi 1.

3.1.3. The Klyuchi 1 section

In the Klyuchi 1 section, only the upper 11.5 m of the Nikolaevka Formation and 5.8 m of the Palaeocene siliceous marls of the Syzran Formation are exposed. The Nikolaevka Formation is represented in this section by 5.5 m of more carbonate-rich (62–65 % $CaCO_3$) marls below and 6.0 m of marls with 55–59 % carbonate above. These marls are unconformably overlain by 6 m of Palaeocene siliceous marls with a phosphorite layer at the base. In this section, 55 calcareous nannoplankton species have been identified (Fig. 5). Nannofossil preservation is poor to moderate, although it improves up section. The assemblage is basically identical to the nannofossil assemblage of the Nikolaevka Formation in the Klyuchi 2 section. This is not surprising for these two sections are situated only 0.5 km apart. The lower part of the section (ca. 2.5 m) is referred to subzones UC20b-c, whereas the other 9.5 m, starting from sample KL1-39, are assigned to Subzone UC20d. The first occurrence of *C. daniae* in sample 39 allows correlation of these two sections, indicating that the level of samples Klyuchi 1-39 and Klyuchi 2-29 is the same.

Some Upper Cretaceous species (*Lucianorhabdus cayeuxii, Glaukolithus diplogrammus, Cretarhabdus*

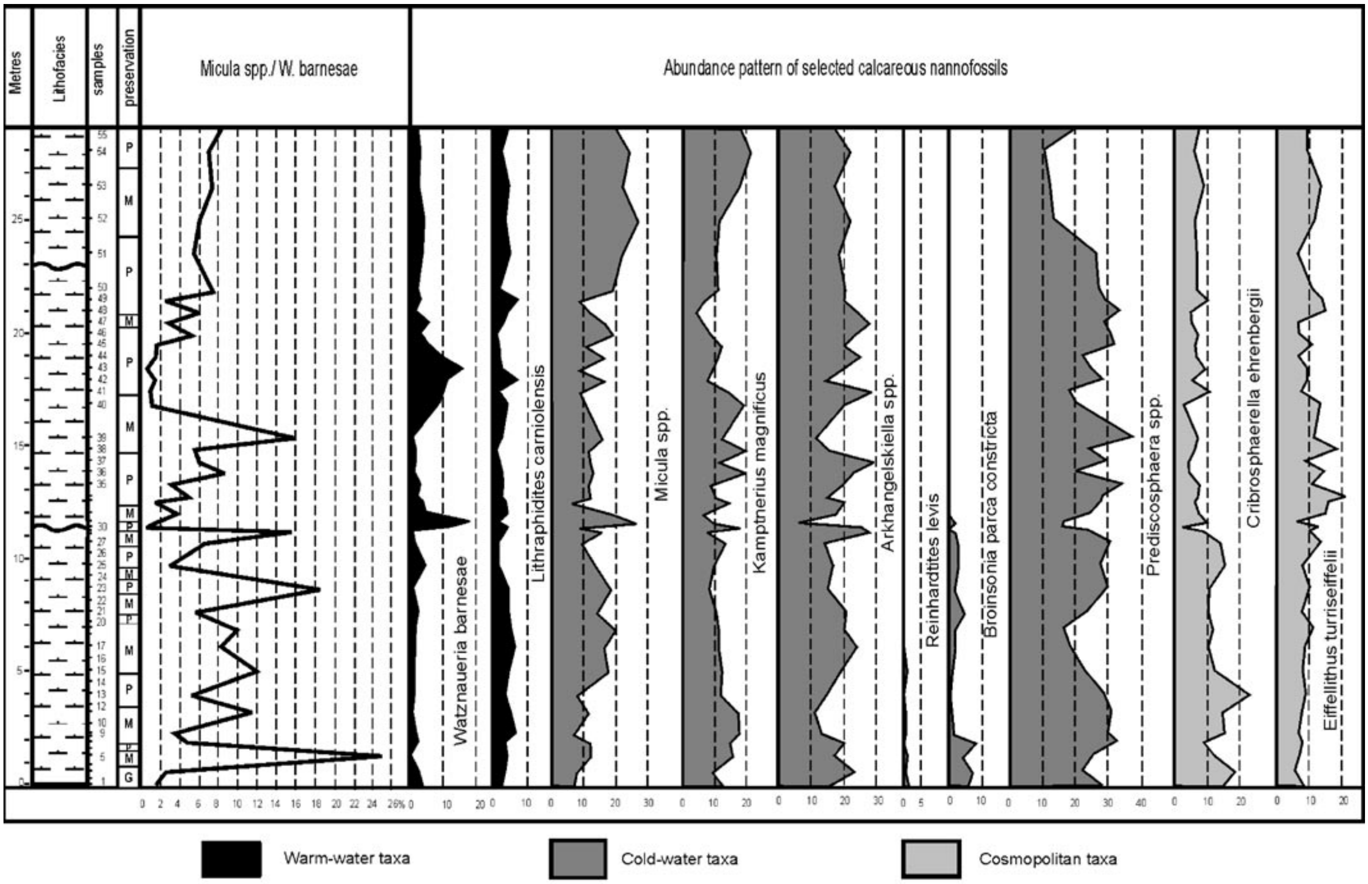

Fig. 6.- Quantitative analysis of calcareous nannofossil distribution in the Maastrichtian, Lokh section.
Fig. 6.- Análisis cuantitativo de la distribución de los nanofósiles calcáreos en el Maastrichtiense de la sección de Lokh.

lateralis, Stradneria crenulata, Watznaueria biporta) disappear near the eroded top of the Maastrichtian in the Klyuchi 1 section, although the majority of them pass through into the assemblage of the Lower Palaeocene Syzran Formation, where they are undoubtedly redeposited. At the same time, *Thoracosphaera saxea* and *Th. operculata*, i.e. species indicating unfavourable environments, become rather abundant in Palaeogene siliceous marls.

3.2. Time resolution

The duration of the Lokh Formation interval composed of clayey marls (11.3 m) is more than 700 Kyr. In the Lokh section, the lower part of the Lokh Formation (7.3 m) is assigned to Subzone CC23a *Tranolithus phacelosus*, the top of which is dated at 70.73 Myr (Hardenbol *et al.*, 1998). The disappearance of *R. levis* coincides with the discontinuity between the Lokh and Nikolaevka formations, and this species cannot be taken into account as well. We hypothesise that the base of this interval of the Lokh Formation can be dated not earlier than as 71.40 Myr, because the lower boundary of CC23a is 71.40 Myr (Hardenbol *et al.*, 1998). However, the upper 4 m have no precise dating. If we assume the same rate of sedimentation, which is confirmed by the monotonous lithology, then the total duration would be approximately 1.1 Myr.

Taking into account the lithological uniformity of this interval and dates of nannozone boundaries established for the Upper Cretaceous of the Western Europe (Hardenbol *et al.*, 1998), we can estimate the age of each sample in Myr. In the Boreal Region, the first occurrence of *N. frequens* is dated at 67.65 Myr and that of *C. daniae* is dated at 66.77 (Hardenbol *et al.*, 1998). The latter is 1.77 Myr before the K/T boundary. In the Nikolaevka Formation of the Klyuchi 2 section, an incomplete thickness of Zone CC26 is observed prior to the first occurrence of *C. daniae*, since *N. frequens* appears at the base of this formation. The average sedimentation rate was more than 0.76 cm/Kyr. One metre of marls accumulated in 131.6 Kyr.

The top of the Maastrichtian is eroded and probably not less the 0.1 Myr is absent in the succession. In the Klyuchi 1 section, the thickness of the interval of occurrences of *C. daniae* is 9.5 m and the average rate of sedimentation is 0.54 cm/Kyr.

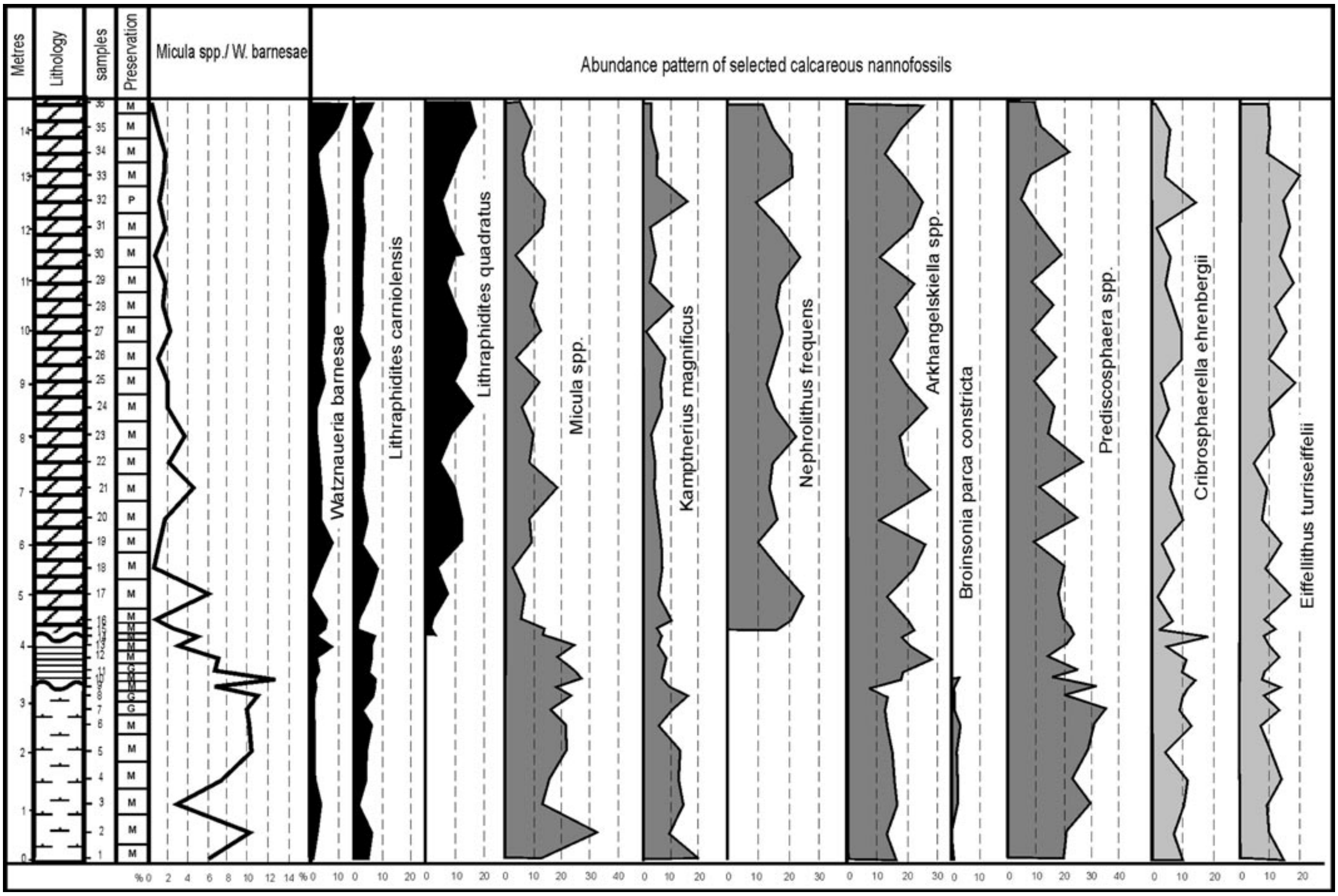

Fig. 7.- Quantitative analysis of calcareous nannofossil distribution in the Maastrichtian, Klyuchi 2 section.
Fig. 7.- Análisis cuantitativo de la distribución de los nanofósiles calcáreos en el Maastrichtiense de la sección de Klyuchi 2.

3.3. Quantitative analysis

The following groups have been recognised on the basis of the quantitative analysis of nannoplankton from the Lokh Formation (Fig. 6):

1. A group of dominant forms (average): *Prediscosphaera* spp. 26.1%, *Arkhangelskiella* spp. 18.1%.

2. A group of subdominant forms (average): *Cribrosphaerella ehrenbergii* 13.5%, *Micula* spp. 12.8%, *Kamptnerius magnificus* 12%, *Eiffellithus turriseiffelii* 8.7%.

3. The group of rare forms (average): *Lithraphidites carniolensis* 4%, *Watznaueria barnesae* 2.1%, *Broinsonia parca constricta* 3.2%, *Reinhardtites levis* 0.9%.

The proportion of the warm water species *W. barnesae* is mainly ca. 2%, with a sharp increase to 10% at 70.86 Myr (sample Lkh 17). The proportions of another warm water species, *L. carniolensis*, constitute 1–7% without significant oscillations throughout the whole interval.

Cold water species of genus *Prediscosphaera* dominate the assemblage and constitute about 20–30%. Sharp cyclic oscillations from 16 through 32% are characteristic. The proportion of the genus *Arkhangelskiella*, which is also a dominant, is 15–20% on average, with abrupt oscillations from 6 to 25%. *Micula* is about 13% on average, varying from 5 to 10% in the lower part of the interval and increasing up to 15–20% up section. *K. magnificus* forms about 12%, varying from 15% in the lower part and decreasing to 8–10% up section.

Abrupt oscillations from 3 through 23% are typical of *Cribrosphaerella ehrenbergii*, although its proportion averages 10–13%. *Eiffellithus turriseiffelii* does not fluctuate significantly and constitutes about 10%.

The following groups are recognised in the Nikolaevka Formation (Figs. 7, 8):

1. A group of dominant forms (average): *Arkhangelskiella* spp.18.8%, *Prediscosphaera* spp. 17.3%, *Nephrolithus frequens* 15.5 %.

2. A group of subdominant forms (average): *Micula* spp. 12%, *Eiffellithus turriseiffelii* 11%.

3. A group of rare forms (average): *Lithraphidites quadratus* 7.6%, *Cribrosphaerella ehrenbergii* 6.5%, *Kamptnerius magnificus* 6.4%, *Watznaueria barnesae* 6.1%, *Lithraphidites carniolensis* 4%.

The average proportion of the warm-water species *W. barnesae* is ca. 4% in the lower part of the interval and increases to 8% in the upper part. There are some sharp increases, to 18% at 68.68 Myr (sample Lkh 30), to 15% at 68.35 Myr (sample Lkh 43) (Fig. 6), to 24% at 66.25 Myr (sample KL1/33), and again to 15% at 65.5 Myr (sample KL1/25) (Fig. 8). *L. carniolensis* forms ca. 4–5% in the lower part of the interval, with gradual cyclic fluctuations from 0.5 up to 6.5%. *L. quadratus*, which appears at approximately 67.7 Myr (sample KL2/14) (Fig. 7), constitutes a larger proportion of the assemblages compared to the two previous species, viz. 9.5%, fluctuating sharply from 1 up to 17.5% with two distinct maxima of 17.5% at 66.38 Myr (sample KL1/34), and 15.5% at 65.5 Myr (sample KL1/25) (Fig. 8).

A gradual decrease up section from the base is characteristic of the relatively cold-water *Prediscosphaera* spp. Their proportion is 20–35% in the lower part of the interval, reducing to 15–20% in the upper part. Sharp fluctuations from 5.5% up to 25% are characteristic as well. Abrupt cyclic oscillations from 3 through 27% are typical for the genus *Micula*, the proportion of which is ca. 11% on average. The genus *Arkhangelskiella* forms a substantial part of the assemblage and its share fluctuates from 6 to 36%. The proportion of the cold-water species *K. magnificus* decreases constantly up section from 6–18% to 1–5%. Cyclic oscillations from 4.5 to 26.5% are typical for *N. frequens*, which appeared at 67.65 Myr (sample KL2/15) (Fig. 7). On average it forms ca. 15%.

The average share of *Cr. ehrenbergii* is 7%, oscillating from 2 through 18% with an abrupt increase to 18% at 67.7 Myr (sample KL2/14) (Fig. 7). Similarly, cyclic oscillations from 4.5 to 18% are typical for *Eiffellithus turriseiffelii*, with an average proportion of ca. 12%.

4. Discussion

Owing to the correlation of closely situated sections, we are able to trace quantitative fluctuations of various nannoplankton taxa in both the Lower and Upper Maastrichtian.

The proportion of the warm water species *W. barnesae* constitutes 4.4% in the Lower Maastrichtian and gradually increases to 18% in the Upper Maastrichtian. That of *L. carniolensis* oscillates cyclically from 3.5 to 4.1%. Among three warm water species in the Upper Maastrichtian, *L. quadratus* is the most abundant species, comprising 9.5% and gradually decreasing to 5.7% with rather sharp fluctuations (Figs. 5-7).

Prediscosphaera dominates the cold water forms. Its proportion decreases gradually from 25% in the Lower Maastrichtian, to 15% in the Upper Maastrichtian. *Arkhangelskiella* is the second most abundant genus in the sections. It is characterised by sharp cyclic oscillations. Its share decreases slightly from 19.3% in the Lower Maastrichtian, to 17.8% in the Upper Maastrichtian. The genus *Micula* is characterised by abrupt cyclic fluctuations with a gradual decrease from 14.5% in the Lower Maastrichtian to 11.5% in the Upper Maastrichtian. The proportion of *K. magnificus* is 12.1% in the Lower Maastrichtian and declines significantly to 5.4% in the Upper Maastrichtian. The abundance of this species is also characterised by sharp fluctuations. Slight fluctuations are typical of *Cribrosphaerella ehrenbergii*, which comprises 9.4% in the Lower Maastrichtian and decreases gradually to 5.9% in the Upper Maastrichtian. In the upper part of the Upper Maastrichtian, a considerable part of the nannoplankton assemblage is represented by *N. frequens*. Generally, it forms about 17%, decreasing slightly to 13.8% toward the Cretaceous/ Palaeogene boundary. The propoprtion of *Eiffellithus turriseiffelii* fluctuates cyclically from 5.5 to 18% throughout the entire Lower and Upper Maastrichtian.

Maastrichtian and, in particular, Late Maastrichtian palaeotemperatures have been studied extensively in recent years (Teis and Naidin, 1973; Alekseev *et al.*, 1998; Barrera and Savin, 1999; Olsson *et al.*, 2001; Huber *et al.* 2002; Wilson *et al.*, 2002) (Fig. 8). Alekseev *et al.* (1999) carried out quantitative analyses of the planktonic foraminiferan *Globotruncana* in the Klyuchi 1 section (upper part of zone CC26). Their results indicated an intense warming event during the interval of 65.55–65.20 Myr, with a maximum at 65.30–65.23 Myr, about 0.3 to 0.23 Myr before the K/T boundary.

Olsson *et al.* (2001) studied $\delta^{18}O$ changes and the distribution of planktonic foraminifera in the Upper Maastrichtian (upper part of zone CC26) in the Bass River basin. The general pattern of $\delta^{18}O$ oscillations revealed a progressive warming with small fluctuations. A global warming event was established in the interval 65.450–65.022 Myr with its maximum at 65.15 Myr, about 0.45 to 0.022 Myr before the K/T boundary.

Barrera and Savin (1999) investigated $\delta^{18}O$ oscillations for the Southern and Northern Atlantic, Indian and Pacific oceans and discovered that global temperatures increased by 3–4º C between 65.5 and 65.3 Myr, after which there was a period of cooling at 65.2 Myr, about 0.5 to 0.3 Myr before the K/T boundary.

Huber *et al.* (2002) studied Albian–Maastrichtian palaeotemperatures using isotopic analyses of foraminiferans from Blake Nose. Warming periods were revealed in the Maastrichtian against a background of global cooling with minimum temperatures of about 9º C. The most no-

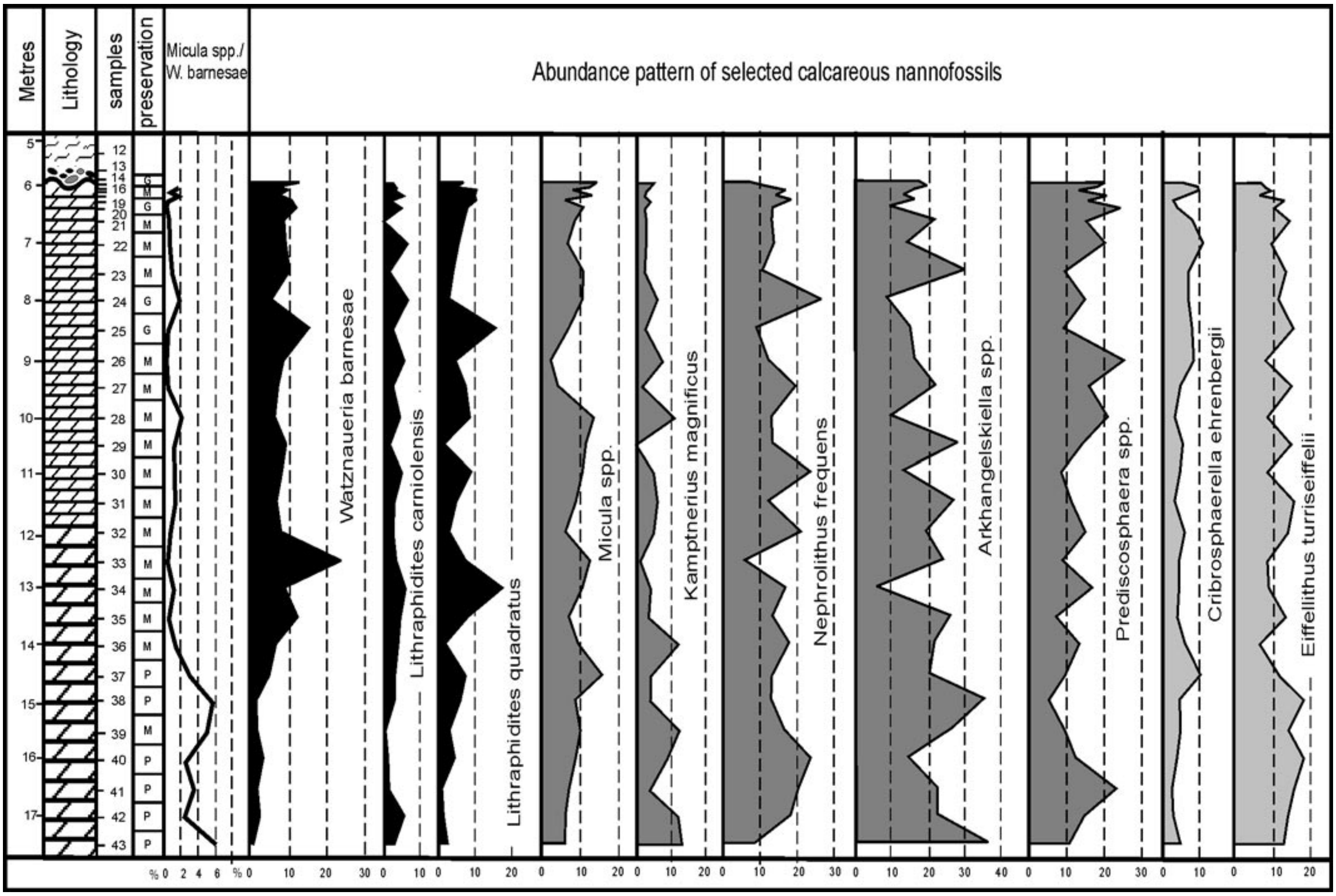

Fig. 8.- Quantitative analysis of calcareous nannofossil distribution in the Maastrichtian, Klyuchi 1 section.
Fig. 8.- Análisis cuantitativo de la distribución de los nanofósiles calcáreos en el Maastrichtiense de la sección de Klyuchi 1.

ticeable warming maximum occurred during the interval from 65.80 to 65.55 Myr, 0.8–0.55 Myr before the K/T boundary, when the temperature increased to 13º C.

Teis and Naidin (1973) estimated marine isotopic temperatures on the basis of the belemnite fauna from the Russian Platform. They pointed that the only significant change revealed by their data is a cooling event in the Early Maastrichtian and our data generally confirm this.

Our analysis of quantitative fluctuations in the proportions of calcareous nannoplankton suggests a generally cold environment during the Maastrichtian. However, periods of significant warming of surface water can be recognised against a general background cooling. Three maxima are established; the first coincides with the 68.35 Myr level, the second one occurs at 66.25 Myr, and the last maximum is detected at 65.5 Myr (Fig. 8). The third maximum coincides with the beginning of the global warming event revealed by Olsson *et al*. (2001), although the maximum established using nannoplankton occurred a little earlier than the maximum established on the basis of planktonic foraminiferans. Similarly, the maximum estimated from planktonic foraminiferans in the Klyuchi 1 section occurs somewhat later than the maximum established on the basis of the nannoplankton.

As a result of our quantitative analysis, we can subdivide the combined section into five parts and propose the following phases based on the ratio of the warm- to cold-water taxa (Fig. 8).

Phase 1 (interval 71.4–70.3 Myr) corresponds to the lower part of the Lokh Formation. It is characterised by the dominance of cold water forms. *Prediscosphaera* constitutes ca. 25%, *Arkhangelskiella*, ca. 15–20%, *Cribrosphaerella*, 10–13% and *K. magnificus* ca. 12%. The warm water coefficient varies within 3–8.5%. The ratio *Micula* spp./ *W. barnesae* is generally high (ca. 10–12), with very sharp fluctuations from 2–4 up to 25. The lowest and the most distinct peak is formed due to abrupt changes in the preservation from good to poor.

Phase 2 (interval 70.3–68.8 Myr). Maximum of regression and hiatus in the succession related with sea-level fall and the coolest episode.

Phase 3 (interval 68.8–67.70 Myr) corresponds to the lower part of the Nikolaevka Formation. This is characterised by the dominance of cold water forms, although their proportion decreased somewhat. *Prediscosphaera* constitutes ca. 15%, *Arkhangelskiella* ca. 15–20%, *Cribrosphaerella* 4–8% and *K. magnificus* forms ca. 12%. The warm water coefficient increased slightly to 7–12%. An abrupt increase of warm water forms to 20% occurred at 68.35 Myr. Despite a decrease in the percentage of cold water species, they still dominate. The ratio of *Micula* spp./ *W. barnesae* generally decreases from 12 to 8–10, being still rather high. Sharp fluctuations, which are not related to substantial changes in nannofossil preservation but can be most probably connected to sharp palaeotemperature changes, are also observed.

Phase 4 (interval 67.69–66.5 Myr) corresponds to the middle part of the Nikolaevka Formation and is characterised by sharp cyclic quantitative oscillations of cold and warm water forms. The warm water coefficient varies from 4 to 24%. A considerable decrease of the ratio of *Micula* spp./ *W. barnesae* to 2–4 with cyclic fluctuations is also observed.

Phase 5 (interval 66.49–65.10 Myr) corresponds to the upper part of the Nikolaevka Formation and is characterised by a sharp increase of warm water forms. *W. barnesae* constitutes ca. 8%, *L. carniolensis*, ca. 6%. The role of *L. quadratus* is more significant and the latter species forms ca. 10–12%. The warm water coefficient increases to 20–25%. Two maxima for this coefficient are detected against a background of general expansion of warm water species. The coefficient rises to 35% during the first maximum that occurred at 66.25 Myr and to 34% during the second at 65.5 Myr. The ratio of *Micula* spp./ *W. barnesae* is rather low and gradually decreases to 2.

Thus late Late Maastrichtian (67.79–65.10 Myr) sea surface temperatures were much higher than earlier in the Late Maastrichtian. General warming during Late Maastrichtian in the Saratov Region could also be related to some palaeogeographic changes on the southeastern margin of the Russian Platform. The Saratov Region occupied a marginal part of the vast Boreal Peri-Tethys marine basin that was wide open to the south and supplied by tropical waters (Baraboshkin *et al*. 2003). The influence of that is obvious in western Kopet-Dagh in Turkmenia. This marine basin also had connections with the cold Western Siberian marine basin via the Turgay Strait to the south-east and several other straits in the

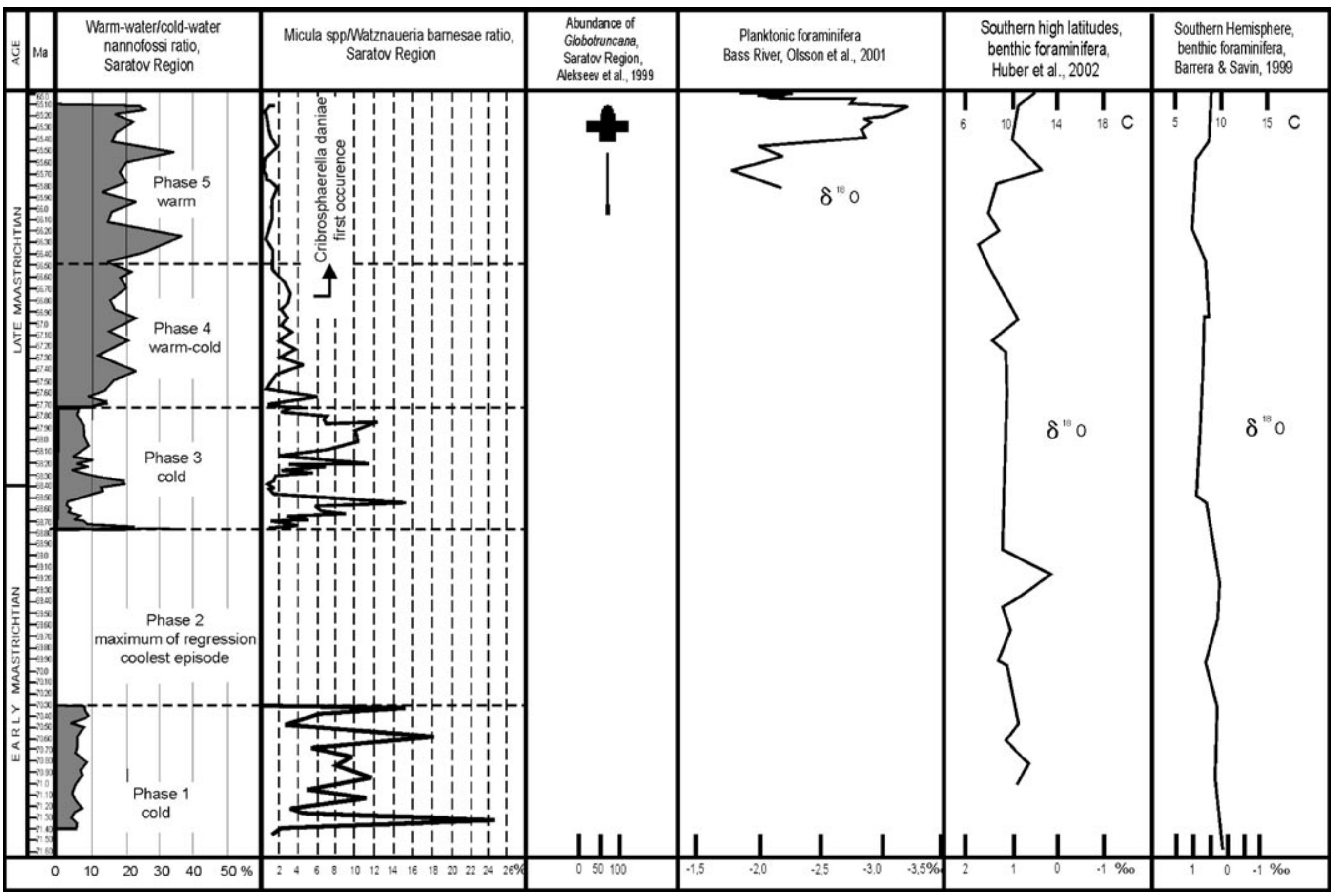

Fig. 9.- Palaeotemperature changes in the Maastrichtian of the Bass River, Russian Platform, Northern and Southern Atlantic.

Fig. 9.- Cambios en la paleotemperatura en el Maastrichtiense del Río Bass, Plataforma Rusa, Atlántico Norte y Sur.

South and Middle Urals. The warm waters from the south crossed the Turgay Strait most intensively during late Maastrichtian times (Naidin 2003) and spread over the entire Western Siberian basin. During this time relatively warm-water calcareous benthic and planktonic foraminifera migrated far to the north up to the Yamal Peninsula (68-70º N).

Several authors record a short cooling event in the latest Maastrichtian (Lamolda and Gorostidi, 1994; Gorostidi and Lamolda, 1995; Pospichal, 1996; Gardin, 2002; Keller *et al*., 2002; Melinte *et al*., 2003). However, it has not been recorded in our sections, since the uppermost part of the Maastrichtian represented in the Klyuchi 1 section is eroded and we cannot give a precise scale of this erosion. We surmise that an interval of approximately 100–150 Kyr is missing and that the cooling event observed by Lamolda and Gorostidi (1994), Gorostidi and Lamolda (1995) and other authors from changes of the ratio of *Micula* spp./ *W. barnesae* is simply not represented in our section.

5. Conclusions

The nannofossil biostratigraphy and correlation of three studied sections enabled us to construct a composite succession for the Maastrichtian in the Saratov Region. This succession represents most of time span of Maastrichtian, but there is a gap in the late Early Maastrichtian.

The composite section may be subdivided into five parts on the basis of the ratio of warm to cold-water forms (Fig. 9). During the latest Campanian, Early and early Late Maastrichtian (phases 1–3) sea surface temperatures of the marine basin were low. Warm water nannofossil taxa constitute 2–12% of the assemblages and the *Micula* spp./*W. barnesae* ratio was very high (10–12). Later (phase 4) relatively strong temperature fluctuations occurred. However in late Late Maastrchtian (phase 5) important warming took place in the area studied. Warm-water nannofossil taxa comprise 20–25% of assemblages. The *Micula* spp./*W. barnesae* ratio decreased to 2, which confirms warming of surface waters. The transition from a cold to a warm climate coincided with an increase in carbonate content of the rocks. Short-term warm maxima were also established on several levels.

Summarising the above, data obtained from nannoplankton confirm cooling during the Early Maastrichtian with minimum temperatures within Zone CC24 and considerable short-term global warming at the end of the Late Maastrichtian, 500–100 Kyr before the K/T boundary, a pettern previously established on the basis of quantitative analysis of foraminiferans (Alekseev *et al*., 1999) and foraminiferal $\delta^{18}O$ changes (Olsson *et al*., 2001; Huber *et al.* 2002). In general, sediments of the Lokh Formation accumulated during a cooling episode, and marls of the Nikolaevka Formation were deposited during a considerable warming event.

6. Acknowledgements

Our gratitude extends to Dr A.G. Olfer'iev (Paleontological Institute, Moscow) for his consultations at various stages, to Dr M.B. Mostovski and Dr J.C. Masters (both Natal Museum, South Africa) for translating and checking the manuscript, and to Dr M.S. Boiko (Paleontological Institute, Moscow) for his assistance during the field trip. The manuscript benefited from critical reviews by Dr M.A. Lamolda, Dr C.R.C. Paul and Dr M.C. Melinte. Our thanks are due to Dr M.A. Lamolda for his comments on some problems and his help in finding the literature. This work has been financed by the Russian Academy of Sciences, the Scientific School of B.S. Sokolov, grant no. 1790.2003.5.

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APENDIX

List of calcareous nannofossil taxa mentioned in our study, in alphabetical order (Fig. 10):

Acuturris scotus (Risatti, 1973) Wind et Wise in Wise and Wind, 1977
Ahmuellerella octoradiata (Gorka, 1957) Reinhardt, 1966
Arkhangelskiella cymbiformis Vekshina, 1959
Arkhangelskiella specillata Vekshina, 1959 (Fig. 10a)
Biscutum constans (Gorka, 1957) Black in Black and Barnes, 1959
Braarudosphaera bigelowii (Gran et Braarud, 1935) Deflandre, 1947
Broinsonia enormis (Shumenko, 1968) Manivit, 1971
Broinsonia parca constricta Hattner *et al*., 1980 (Fig. 10b)
Calculites obscurus (Deflandre, 1959) Prins et Sissingh in Sissingh, 1977
Ceratolithoides aculeus (Stradner, 1961) Prins et Sissingh in Sissingh, 1977
Chiastozygus amphipons (Bramlette et Martini, 1964) Gartner, 1968
Chiastozygus fessus (Stover, 1966) Shafik, 1979
Chiastozygus litterarius (Gorka, 1957) Manivit, 1971
Chiastozygus platyrhethus Hill, 1976
Chiastozygus tenuis Black, 1971
Corollithion signum Stradner, 1963
Cretarhabdus conicus Bramlette et Martini, 1964
Cretarhabdus lateralis (Black, 1971) Perch-Nielsen, 1984
Cribrosphaerella daniae Perch-Nielsen, 1973 (Fig. 10c)
Cribrosphaerella ehrenbergii (Arkhangelsky, 1912) Deflandre in Piveteau, 1952 (Fig. 10d)
Cyclagelosphaera margerelii Noel, 1965
Cylindralithus duplex Perch-Nielsen, 1973
Dodekapodorhabdus noeliae Perch-Nielsen, 1968
Eiffellithus parallelus Perch-Nielsen, 1973
Eiffellithus turriseiffelii (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1965
Gartnerago obliquum (Stradner, 1963) Noel, 1970
Glaukolithus compactus (Bukry, 1969) Perch-Nielsen, 1984
Glaukolithus diplogrammus (Deflandre in Deflandre and Fert, 1954) Reinhardt, 1964
Kamptnerius magnificus Deflandre, 1959 (Fig. 10e)
Lithraphidites carniolensis Deflandre, 1963 (Fig. 10f)
Lithraphidites grossopectinatus Bukry, 1969 (Fig. 10g)
Lithraphidites praequadratus Roth, 1978
Lithraphidites quadratus Bramlette et Martini, 1964 (Fig. 10h)
Lucianorhabdus cayeuxii Deflandre, 1959
Manivitella pemmatoidea (Deflandre in Manivit, 1965) Thierstein, 1971
Markalius inversus (Deflandre in Deflandre and Fert, 1954) Bramlette et Martini, 1964
Markalius perforatus Perch-Nielsen, 1973
Microrhabdulus attenuatus (Deflandre, 1959), Deflandre, 1963
Microrhabdulus decoratus Deflandre, 1959
Micula decussata Vekshina, 1959 (Fig. 10i)
Micula concava (Stradner in Martini and Stradner, 1960) Verbeek, 1976
Nephrolithus frequens Gorka, 1957 (Fig. 10j)
Prediscosphaera bukryi Perch-Nielsen, 1973
Prediscosphaera cretacea (Arkhangelsky, 1912) Gartner, 1968
Prediscosphaera grandis Perch-Nielsen, 1979
Prediscosphaera intercisa (Deflandre in Deflandre and Fert, 1954) Shumenko, 1976
Prediscosphaera spinosa (Bramlette et Martini, 1964) Gartner, 1968
Prediscosphaera stoveri (Perch-Nielsen, 1968) Shafik et Stradner, 1971 (Fig. 10k)
Reinhardtites levis Prins et Sissingh in Sissingh, 1977
Retacapsa angustiforata Black, 1971
Rhagodiscus angustus (Stradner, 1963) Reinhardt, 1971
Rhagodiscus asper (Stradner, 1963) Reinhardt, 1967
Rhagodiscus splendens (Deflandre, 1953) Verbeek, 1977
Rhombolithion rhombicum (Stradner et Adamiker, 1966) Black, 1973
Rhombolithion speetonensis Rood et Barnard, 1972
Staurolithites crux (Deflandre in Deflandre and Fert, 1954) Caratini, 1963
Staurolithites imbricatus (Gartner, 1968) Burnett, 1998
Stradneria crenulata (Bramlette et Martini, 1964) Noel, 1970
Thoracosphaera operculata Bramlette et Martini, 1964
Thoracosphaera saxea Stradner, 1961
Tranolithus manifestus Stover, 1966
Vekshinella angusta (Stover, 1966) Verbeek, 1977
Watznaueria barnesae (Black, 1959) Perch-Nielsen, 1968
Watznaueria biporta Bukry, 1969
Zeugrhabdotus embergeri (Noel, 1959) Perch-Nielsen, 1984
Zeugrhabdotus acanthus Reinhardt, 1967
Zigodiscus slaugtheri Bukry, 1969
Zigodiscus spiralis Bramlette et Martini, 1964

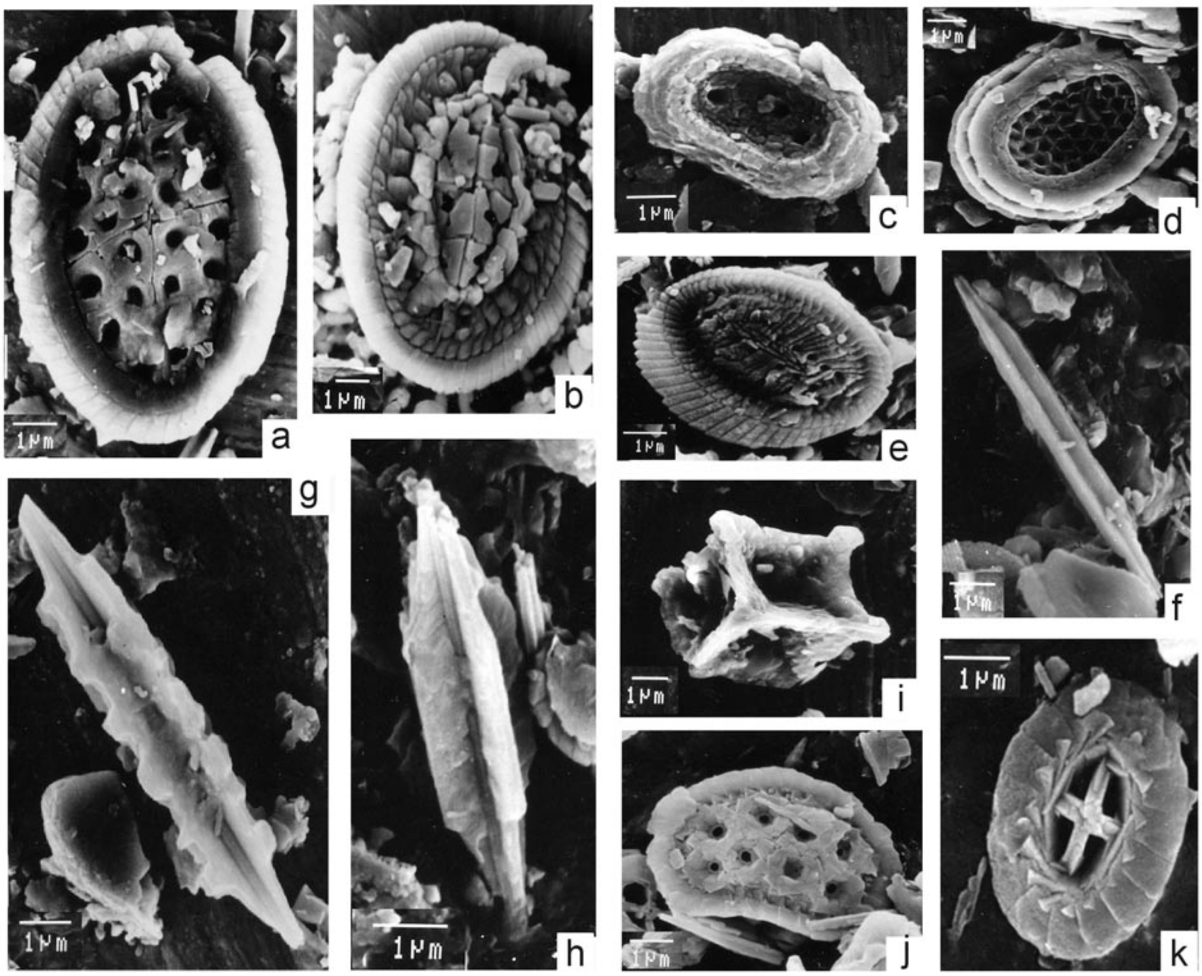

Fig. 10.- (a) *Arkhangelskiella specillata* Vekshina, Upper Maastrichtian, sample Kl2-23. Scale bar 1 µm.
(b) *Broinsonia parca constricta* Hattner *et al*., Lower Maastrichtian, sample Lkh-15. Scale bar 1 µm.
(c) *Cribrosphaerella daniae*? Perch-Nielsen, Upper Maastrichtian, sample Kl1-34. Scale bar 1 µm.
(d) *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre, Upper Maastrichtian, sample Kl1-36. Scale bar 1 µm.
(e) *Kamptnerius magnificus* Deflandre, Upper Maastrichtian, sample Kl2-24. Scale bar 1 µm.
(f) *Lithraphidites carniolensis* Deflandre, Upper Maastrichtian, sample Lkh 53. Scale bar 1 µm.
(g) *Lithraphidites grossopectinatus* Bukry, Upper Maastrichtian, sample Kl1-33. Scale bar 1 µm.
(h) *Lithraphidites quadratus* Bramlette and Martini, Upper Maastrichtian, sample Kl2-16. Scale bar 1 µm.
(i) *Micula decussata* Vekshina, Upper Maastrichtian, sample TP2-28. Scale bar 1 µm.
(j) *Nephrolithus frequens* Gorka, Upper Maastrichtian, sample Kl2-20. Scale bar 1 µm.
(k) *Prediscosphaera stoveri* (Perch-Nielsen) Shafik and Stradner, Upper Maastrichtian, sample TP2-18. Scale bar 1 µm.

Fig. 10.- (a) *Arkhangelskiella specillata* Vekshina, Maastrichtiense superior, muestra Kl2-23. Escala gráfica 1 µm.
(b) *Broinsonia parca constricta* Hattner *et al*., Maastrichtiense inferior, muestra Lkh-15. Escala gráfica 1 µm.
(c) *Cribrosphaerella daniae*? Perch-Nielsen, Maastrichtiense superior, muestra Kl1-34. Escala gráfica 1 µm.
(d) *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre, Maastrichtiense superior, muestra Kl1-36. Escala gráfica 1 µm.
(e) *Kamptnerius magnificus* Deflandre, Maastrichtiense superior, muestra Kl2-24. Escala gráfica 1 µm.
(f) *Lithraphidites carniolensis* Deflandre, Maastrichtiense superior, muestra Lkh 53. Escala gráfica 1 µm.
(g) *Lithraphidites grossopectinatus* Bukry, Maastrichtiense superior, muestra Kl1-33. Escala gráfica 1 µm.
(h) *Lithraphidites quadratus* Bramlette and Martini, Maastrichtiense superior, muestra Kl2-16. Escala gráfica 1 µm.
(i) *Micula decussata* Vekshina, Maastrichtiense superior, muestra TP2-28. Escala gráfica 1 µm.
(j) *Nephrolithus frequens* Gorka, Maastrichtiense superior, muestra Kl2-20. Escala gráfica 1 µm.
(k) *Prediscosphaera stoveri* (Perch-Nielsen) Shafik and Stradner, Maastrichtiense superior, muestra TP2-18. Escala gráfica 1 µm.