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Astronomo-Climatic Cycles in the Sequence of Upper Cretaceous Sediments of the Saratov Volga Region

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Abstract—The composition and genesis of the cyclic sequence of Upper Cretaceous sediments near the town of Volsk (Saratov Region) were first investigated using a series of analytical methods. The results were statistically processed using methods of manual counting, as well as spectral and wavelet analyses. Elementary formation cyclites and cyclic variations in several parameters are correlated with astronomo-climatic Milankovitch cycles.

Keywords: Cretaceous, Milankovich cycles, geochemistry, wavelet analysis, Volsk

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INTRODUCTION

Deposition of cyclic sequences of sedimentary rocks is often associated with cyclical variations in the Earth's orbital parameters. There is no doubt that climatic and geographic variations due to precession rotation cycles of the Earth, the obliquity of the ecliptic, and the eccentricity of the Earth's orbit affect the systems of sedimentation. There are several approaches and related problems in the identification of the relationships between elementary formation cyclicity or cyclic variations in certain parameters and astronomical cycles. We assume that along with Milankovitch cycles (the first factor) solar magnetic activity cycles (the second factor) affect sedimentation. The last factor is not considered in this work. It is most appropriate to assume that the elementary cyclicity resulted from continuous interaction between these two factors.

There is another problem in interpreting cyclites based on paleogeographical data. The analytical results cannot always be logically explained due to changing landscape and climatic conditions. Despite the fact that the cyclostratigraphic method has been widely used recently, analysis of cyclites is still problematic. The statistical processing of cyclic data sets using computer programs is not always applicable to resolve the problems that face researchers.

For the first time, we applied a comprehensive approach to clarify paleogeographic conditions in the Tethys Ocean and its periphery in the Late Cretaceous and relationships between paleogeographical variations and astronomo-climatic Milankovitch cycles using the open pit of the "Bolshevik" cement plant (Saratov Region) as an example. This sequence was chosen due to its accessibility and the long period of its study.

RESEARCH METHODS

The geological sequence was studied using a complex of methods. The results of these studies have been previously published (Gabdullin, Ivanov, 2001, 2002, 2003; Gabdullin, 2002, 2007). The following research methods have been used: petrographic (macroscopic field study of rocks and microscopic study of thin sections), chemical (determination of CO_2 concentration with a volumetric method using the Knopp–Fresenius device and determination of C_{org} concentration with a fully automated system for coulometric pH titration according to the pH value using an AN-7529 express analyzer), physical (X-ray diffraction with a DRON-4 X-ray diffractometer (the results were automatically processed using an X-ray computer program), petromagnetic (determination of magnetic susceptibility (k), NRM (Jn); residual magnetization saturation (Jrs); destructive residual magnetization field (H'cs) and an increase in the magnetic susceptibility of rocks heated to 500°C in air (dk), as well as paleoecological and paleoecological–paleontological methods.

Using petrographic studies, rhythmic and arrhythmic sequences were distinguished in the sequence and the lithotypes of carbonate rhythms were established.

Chemical studies that were performed in GIN RAS allowed us to obtain the cyclic distribution of the CO_2 and C_{org} concentrations, which confirm the validity of distinguishing the carbonate rhythms based on petrographic data. The results of chemical analysis allowed us to clarify the mineral composition of lithotypes of rhythms and determine the conditions of their formation.

The X-ray diffraction study allowed us to identify a number of clay minerals that were not established petrographically. The data on mineral composition of marly limestone and marls allowed us to reconstruct the conditions of their formation.

The goal of the paleomagnetic research was the reconstruction of sedimentation conditions in a paleobasin with a comprehensive study of magnetic minerals in the studied sequences. An advantage of this method is the ability to determine fine ferromagnetic minerals, which cannot be diagnosed by macroscopic and microscopic studies. As a result, the petromagnetic rhythmicity was identified in the sequence. This allowed us to obtain valuable information about the conditions of its formation. Comparison of the petromagnetic data that were obtained with petrographic, physicochemical, and lithological data allowed us to estimate the evolution of paleobasins (transgression and regression phases).

As a result of paleoecological and paleoecological–paleontological studies the data on the apparent temperature, depth, salinity, hydrodynamic regime, the structure of the bottom of a sedimentation basin, and the gas regime during formation of the carbonate sequences were obtained. These data are well correlated with those that were obtained with other methods.

The complex investigations allowed us to identify cyclites throughout the studied sequence (except for the Turonian-Coniacian interval), to determine the mineral composition and cyclic distribution of physical, chemical, and other parameters in the rhythms selected, to distinguish rhythms, to assess existing models of the formation conditions of carbonate rhythms, and to apply a number of models for the interpretation of the formation conditions of these rhythms.

The results of the studies were supplemented with geochemical data. A full geochemical analysis of ten samples of Turonian and Coniacian sediments collected by R.R. Gabdullin in the Volsk sequence was carried out using a MARC.GV X-ray fluorescent spectrometer (NGO Spectron, St. Petersburg) at the Faculty of Engineering Geology of the Geology Department of Moscow State University (analyst E.N. Samarin). Cyclicity in these sediments was not previously identified.

Based on the calculated ratios and the concentrations of several chemical elements that indicate the changes in the sedimentation conditions (the depth of the sedimentation basin, hydrodynamics, climate, etc.), it became possible to clarify the understanding of the regime of sedimentation.

Analysis of the formation cyclicity and its relation to astronomo-climatic Milankovitch cycles was previously made by the "manual" counting of a number of oscillations on parametric curves and the computer method of mathematical statistics based on Fourier spectral analysis. The application of spectral Fourier analysis is constrained by the relatively large length of the numerical series being analyzed and equal time intervals. It is quite difficult to fulfill these constraints. The results were given in (Gabdullin, 2002).

The results of the analysis of the relationship between the formation cyclicity with the Milankovitch cycles that were obtained using both methods do not always correlate well and they do not clarify the origin of the studied cyclites.

In order to solve this problem, we first applied statistical processing of previously obtained wavelet-based parametric data.

A Description of the Sequence in the Open Pit of the Bolshevik Cement Plant (Town of Volsk, Saratov Region)

The sequence (Fig. 1) is situated in the northwestern side of the open pit of the Bolshevik cement plant (Volsk, Saratov Region). Sequences in environs of the town of Volsk have been studied and described in detail (Archangelskii, 1912; Matesova, 1930; Milanovskii, 1940, Volga-Ural'skaya..., 1959; Gerasimov et al., 1962; Kamysheva-Elpat'evskii, 1967; Glazunov, 1972; Yakushin and Ivanov, 2001; Akhlestina and Ivanov, 1
2000; Yanochkina et al., 2009; Olfer'ev et al., 2009a, b; and Seltser and Ivanov, 2010). The stratigraphic subdivision of the Upper Cretaceous sediments of the Russian Platform is based on the stratigraphic scheme in (Alekseev, Olfer'ev, and Schick, 1995). The distribution of the studied parameters throughout the sequence is shown in Figures 2 and 3.

Middle–Upper substages, Turonian Stage. Turonian deposits are represented by carbonate rocks of the Middle–Upper substage with *Inoceramus lamarki* and echinoid shells, which rest erosively on Albian dark gray sandy clays.

Member I. A marl with phosphorite nodules and beds of rock fragments from a 2 m prismatic-shaped bed. The thickness of inoceramus beds decreases from the bottom to the top of the sequence (from 0.1–0.25 to 0.04–0.05 m). Ferruginized fragments of chalk occur. At the bottom of the member, there is a horizon that is analogous to a "phosphorite plate" (0.3 m) made of marl with abundant mostly subrounded phosphorite concretions of various shapes. The maximum concentration of concretions is confined to the central part of this horizon.

Member II. Yellowish-gray chalk, sometimes silicified, the thickness is ~2.5 m. Microscopically, the rocks of member II are presented by biocrystalloclastic limestone. The sediments contain *Inoceramus lamarki*, *In. apicalis*, *Micraster corbovis*, *M. leskei*, *Conulus subrotundus*, *C. subconicus*, *Scaphites geitnitzi*, *Lewesiceras peramplum*, *Micraster corstetudinarium*, and *Holaster planus*. A Middle Turonian age of the sediments was established based on the occurrence of zonal species of *Inoceramus lamarki* and *In. apicalis* and Late Turonian was established by the occurrence of echinoderms of *Micraster corstetudinarium* and *Holaster planus*. The Turonian sediments contain abundant oysters, brachiopods, teeth, and calcified vertebrae of selachians (Matesova, 1930). The Turonian sediments show trace fossils of *Chondrites*, *Teichichnus*, and *Planolites*. There are no visual traces of cyclicity.

Lower substage, Coniacian Stage. Member III. Yellowish-gray chalk (microscopically, biocrystalloclastic limestone), thickness of 1.5–2 m. The upper part contains greenish gray marly chalk with phosphorite nodules and glauconite, thickness of 0.5 m. The total thickness of Coniacian sediments is 2–2.5 m. The belonging of sediments to the Lower substage of the Coniacian Stage is confirmed by the occurrence of *Cremnoceramus wandereri* Andert. Echinoderms are in abundance in sequences near the town of Volsk (Matesova, 1930, 1935; Gerasimov, 1962). Oysters and ammonites occur as well (Matesova, 1930). There are no visual traces of cyclicity.

Upper substage, Campanian Stage. Member IV (the second horizon of the Campanian). Loose writing chalk with abundant echinoderm skeletons. The silica content increases from bottom to top. The thickness of the Member is 2–3 m. Member IV contains macrofossils of *Belemnitella mucronata* Schlot., *Belemnitella mucronata senior*, *Isomicraster sp.* et al.

Campanian sediments rest unconformably and erosively over Coniacian sediments. The crenulation amplitude of the erosion surface can be up to 5 cm. Campanian sediments are presented by Upper Campanian carbonate rocks (a thickness of 6 m).

White chalk (microscopically, biocrystalloclastic limestone) with thin greenish-gray chalk-like marl interbeds (banded chalk after (Matesova,1930)), a thickness of 2 m. The boundary between the upper and lower members is erosional. The member of "banded chalk" ($K_2cp_2^1$) that is situated near the town of Volsk is characterized by the occurrence of *Belemnitella mucronata* Schlot. and *Isomicraster sp.* This member is referred to the lower Belemnitella mucronata senior zone of the Upper Campanian. The member of "banded chalk" near the Volsk town contains *Echinocorys sp.*, *In. dariensis*, *B. m. volgensis* (Gerasimov et al., 1962).

Members V–VI (the second–third horizons of the Campanian). A sequence of nodular white biocrystalloclastic marl enclosed in gray-green biocrystallolithoclastic marl (*brecciated chalk* after M.N. Matesova), a thickness of 4 m. In the middle of the upper member there is an erosion surface with echinoderm shells that trickled into erosional niches. It is possibly that this surface is the boundary between members V

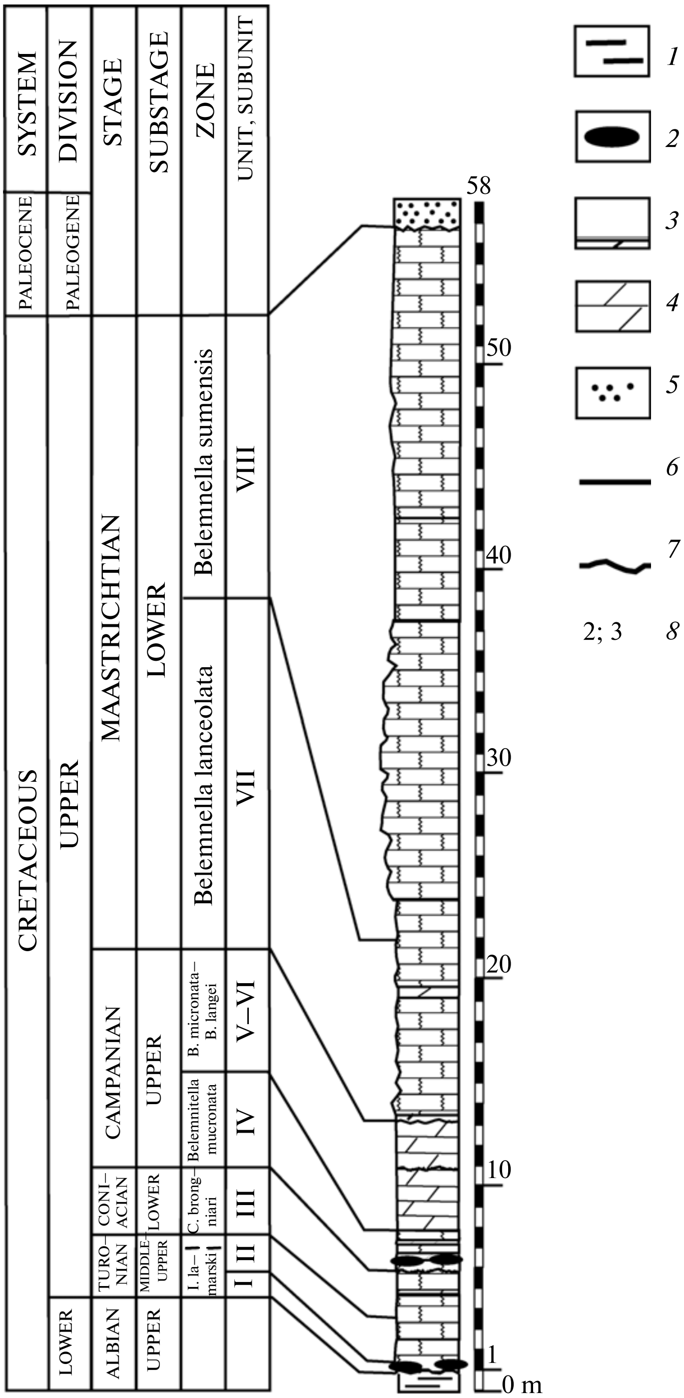

Fig. 1 Sequence of the Upper Cretaceous sediments in the open pit of the cement plant Bolshevik (Volsk, Saratov Region): *1*, clay; *2*, phosphorites; *3*, chalk; *4*, marl; *5*, sand; *6*, concordant stratigraphic boundaries; *7*, discordant stratigraphic boundaries; *8*, the type of rhythms, a number of rhythms.

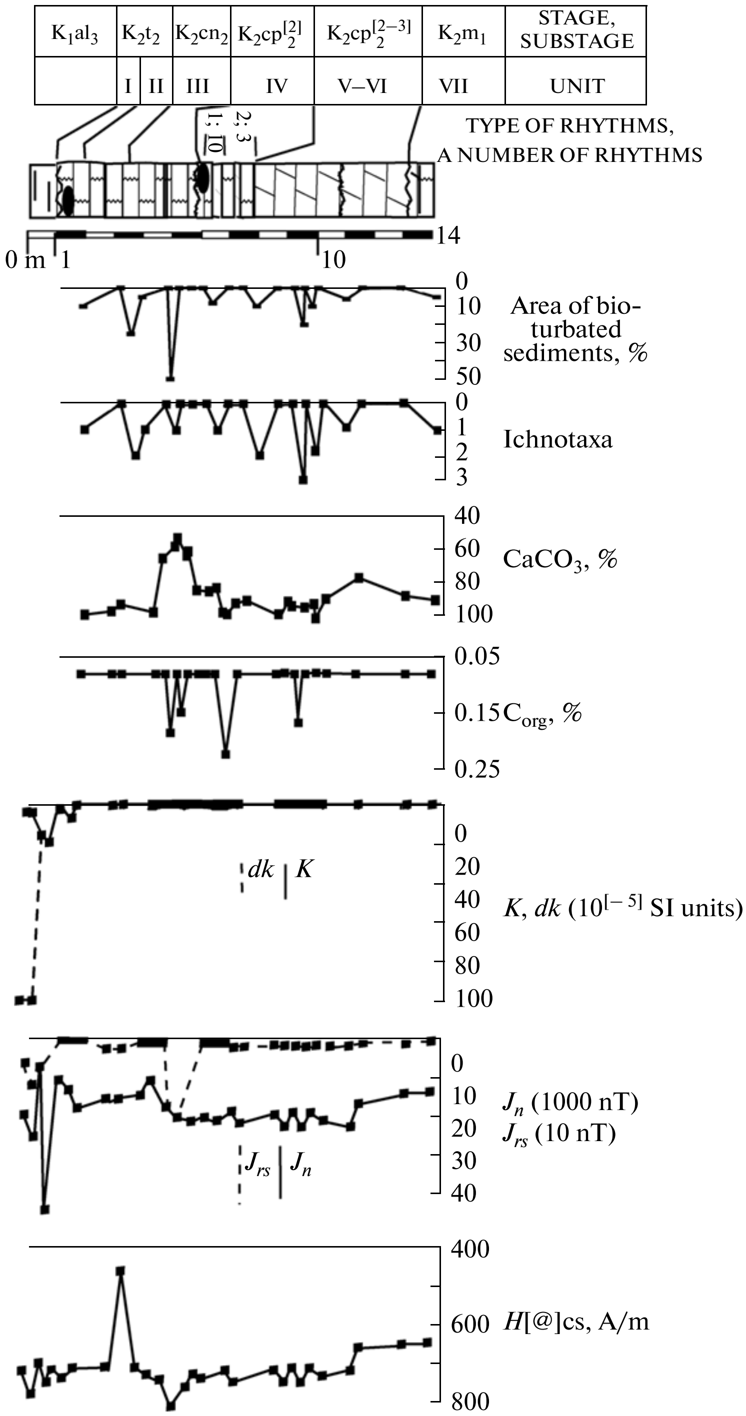

Fig. 2 The distribution of bioturbated sediments, ichnotaxa, $CaCO_3$, C_{org}, magnetic susceptibility and its growth, natural remanent magnetization, residual saturation magnetization, and destructive magnetization residual field in Albian–Lower Maastrichtian sediments in the open pit of the Bolshevik cement plant (Volsk, Saratov Region). The legend was given in Figure 1.

and VI. The sequence of "brecciated chalk" ($K_2cp_2^{2-3}$) in the Volsk area contains rostra of *Belemnitella langei* Shatsk., *B. t. mucronata*, *B. t. senior*, as well as echinoderms of *Micraster grimmensis* Nietsch. and *Coraster cubanicus* Posi. According to this find, this sequence is referred to the Upper Campanian (the second and third horizons of the Campanian) (Gerasimov et al., 1962). Thus, this stratigraphic interval is characterized by mucronata and langei zones.

The Campanian sediments of the Volsk area also contain cephalopods (*Bostrychoceras*), bivalves

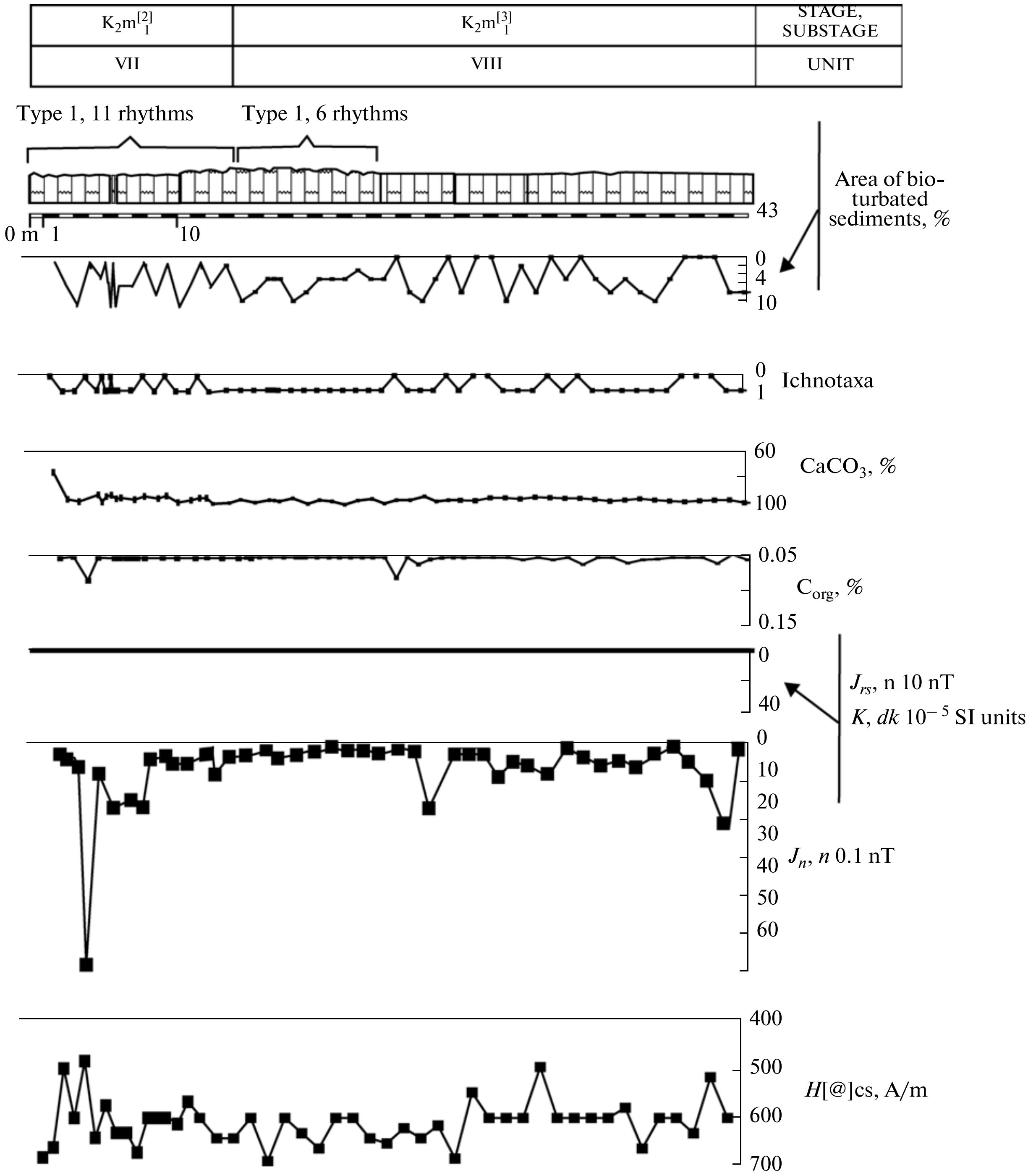

Fig. 3 Distribution of bioturbated sediments, ichnotaxa, $CaCO_3$, C_{org}, magnetic susceptibility and its growth, natural remanent magnetization, residual magnetization saturation, and destructive magnetization residual field in Lower Maastrichtian sediments in the open pit of the Bolshevik cement plant (Volsk, Saratov Region). The legend was given in Figure 1.

(*Spondylus*), scaphopods (*Dentalium*), brachiopods, and solitary corals (*Parasmilia*). This interval is named the "Mikrastrovo Cemetery" because of an abundance of echinoderm shells (Matesova, 1930). The Campanian sediments of the Volsk sequence contain trace fossils of *Thalassinoides*, *Teichichnus*, and *Planolites*.

Cyclicity in the "banded chalk" sequence is presented by ten cyclites of type 1: chalk (0.4–0.1 m)–clayey marl (0.02–0.05 m). The more carbonate elements of a rhythm, viz., chalk beds, in the top of the sequence are separated by a few erosional surfaces. Rhythmicity in "brecciated chalk" is alternation of

Table 1. Correlation of different geochronological scales

Age	Authors, year									
	Hinte, 1975	Harland. 1982	Palmer, 1983	Haq, 1987	Harland, 1989	Cowie, 1989	Odin, 1990	Obradovich, 1993	Gradstein and Ogg, 1994	Hardenbol et al., 1998
	Duration, Ma									
Maastrichtian	5	8	8.5	7	9	10	7	6	6.3	6.3
Campanian	8	10	9.5	10	9	8	10	12	12.2	12.2
Santonian	4	5	3	4	4	3	5	3	2.3	2.3
Coniacian	4	1	2	1	2	2	1	3	3.2	4.5
Turonian	6	2	3	3	3	3	3	4	4.5	4.5
Cenomanian	8	6.1	6	4	5.5	4	5	5	5.4	5.4

massive (2.5–0.6 m) and clayey (0.03–0.05 m) marls. Three cyclites classified as type 2 were established.

Lower substage, Maastrichtian Stage. The thickness of the Lower Maastrichtian sediments in the Volsk sequence is 40–60 m. It should be noted that the sequence in the open pit of the "Kommunar" cement plant (Volsk) comprises sediments of the very first subzone ($K_2m_1^1$), *Belemnella licharewi*, but they were not found in the studied sequence. The sediments are represented by grayish-white sandy chalk with thin clay interbeds (0.3–0.4 m).

Member VII. White writing chalk with greenish-gray marl interbeds (10–15 m). The Lower Maastrichtian age of the sediments is confirmed by finds of *Bel. lanceolata*, *Baculites anceps leopoldensis*, *Acanthoscaphites tridens*, and *Hoploscaphites constrictus* (Gerasimov et al., 1962). This assemblage is typical of the middle subzone of the lower Maastrichtian ($K_2m_1^2$). Member VII comprises cyclites of type 1: chalk (2.5–0.2 m)–clayey marl (0.03–0.17 m). Cyclites are outlined by the weathering profile and irregular thickness (0.35–2.6 m).

Member VIII. White chalk with clay and marl interbeds; higher in succession, glauconite sandy marl, thicknesses of 30–57 m. Member VIII is presented by white chalk (>30 m). Within the sequence the third subzone of Lower Maastrichtian ($K_2m_1^3$) was distinguished based on finds of *Bel. lanceolata sumensis*, *Bac. anceps leopoldensis*, *Asc. tridens*, *H. constrictus*, and *In. balticus* Boehm.

The Member comprises cyclites of type I: writing chalk (1.1–2 m)–clayey marl, clay (0.03–0.05 m). The results of the X-ray analysis show that the most of the visually distinguished clayey interbeds are made of clayey chalk (Table 1). Cyclites are clearly seen in the weathering profile and characterized by stable thicknesses (1.15–2.05 m). Moreover, it is possible to distinguish rhythms of higher order by grouping rhythms in pairs. In other words, rhythms 1-m thick alternate regularly with 2-m cyclites. Thus, we distinguish eight cyclites of the third order and four cyclites of the second order in the 12 m interval from the base of the member. Higher in the section, the succession is acyclic in the interval of 11 m, then there are two chalk-clay cyclites of the third order (rhythms of 1–2.5 m thick) or one cycle of the second order. During the next 10 m the sequence is acyclic again. It is possible that the acyclic intervals of 10–12 m thickness are elements of the cyclite of the first order, alternating with cyclic intervals.

Lower Maastrichtian sediments also contain echinoderms-cidaroids (*Cidaris*, *Salenia*), spatangoids (*Echinocorys*), oysters (*Spondylus*, *Ostrea*), pectenids (*Janira*), sponges (Ventriculites), and corals (*Cylicosmila*), as well as rare brachiopods, gastropods (*Pleurotomaria?*) (Matesova, 1930, 1935). Maastrichtian sediments of the Volsk sequence contain trace fossilis of *Thalassinoides*, *Teichichnus*, and *Planolites.*

The geochemical data for the Turonian–Coniacian interval of the sequence make it possible to calculate the eight relationships (modules) that are necessary to clarify the sedimentation conditions and origin of cyclicity (Fig. 4).

The *Ti/Mn ratio* is a factor of the shallowness of deposition of sediments. It decreases with distance from a provenance area and increases when approaching the land. The Ti/Mn ratio for continental environments is 110–150. Due to resistance of titanium minerals to chemical weathering they accumulate in alluvial and coastal marine environments. In a marine basin with normal salinity, the Ti content is low due to an absence of the true solutions (Yudovich, Ketris, 2011). The low Ti/Mn ratio values that were obtained for the Coniacian sediments are evidence of the existence of a normal-salinity water basin in the Coniacian, as well as large depths and a distance from a provenance area (relative to Turonian sediments). The values of other factors are higher, which is evidence that sedimentation occurred under shallow-water condi-

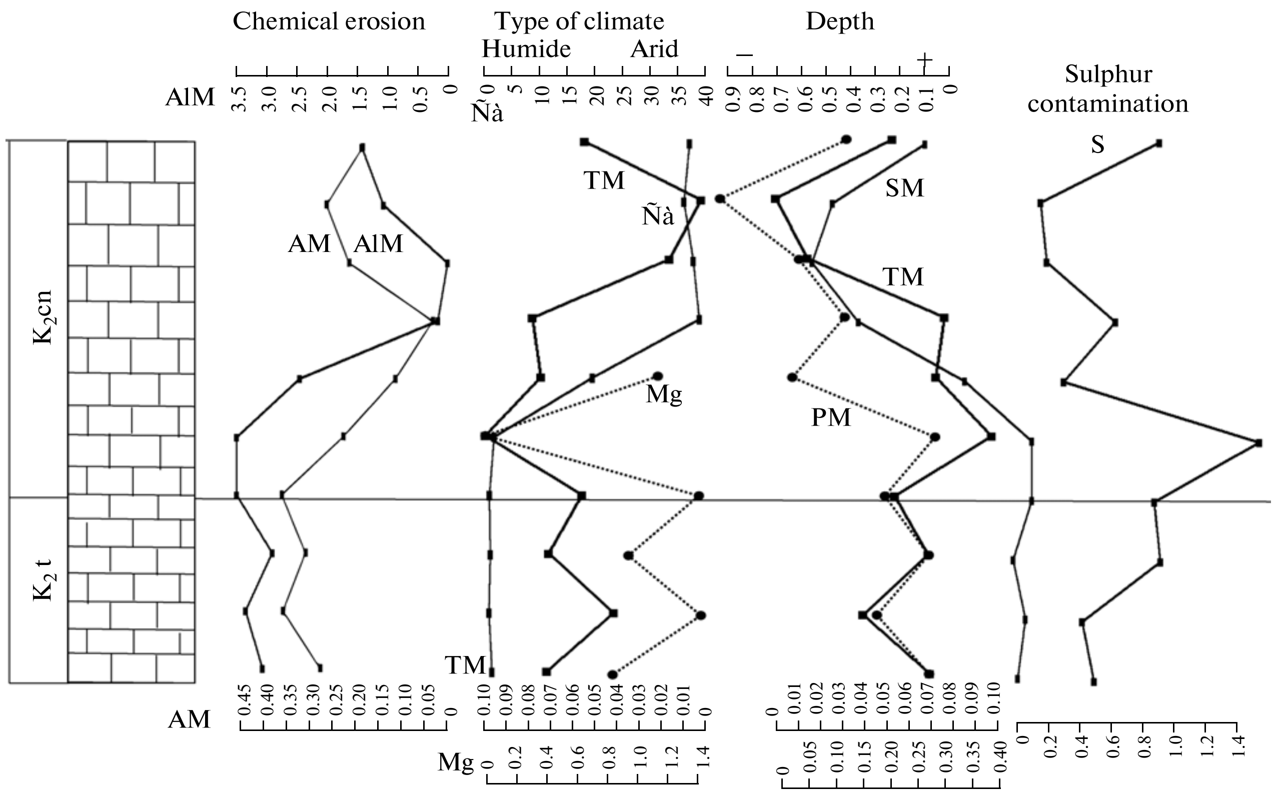

Fig. 4. The geochemical characteristics of the Turonian–Coniacian interval of the sequence in the open pit of the Bolshevik cement plant (Volsk, Saratov Region). Contents of the elements are given in percent. Explanation, see the text.

tions. Sample no.7 yields abnormally high Ti/Mn ratio values. This fact is interpreted below.

The *alumosilicate module (AM)*, the Al_2O_3/SiO_2 ratio, shows the degree of chemical weathering of rocks. Higher alumina content of sedimentary rocks and the high AM values (>0.35, for example) tend to indicate that humid weathering crusts or chemical
2 weathering rocks were eroded (Engalychev, Panov, 2011). Sample no. 1, with respect to sample no. 2 (Turonian sediments and higher in the section) yields higher AM values, which is evidence of the gradual reduction of the role of chemical weathering. However, these variations are cyclical, viz., discontinuous variations in AM values are repeated (samples 3–5). Starting with sample no. 6, the variations become less significant and the influence of chemical weathering increases. In samples 8–10 the AM value decreases sharply to the same level, indicating the reduction in the role of chemical weathering.

The *alkaline module (AlM),* the Na_2O/K_2O ratio, characterizes the intensity of chemical weathering in a provenance area. Its value decreases in the period of increased weathering and increases in the period of reduction of weathering. This module is often considered together with the sodium and potassium modules. The alkaline module value provides additional information about the relative proportion of clayey material in the composition of a sediment (Engalychev, Panov, 2
2011).

The variations in the intensity of chemical weathering are the same as in case with the AM module. Relatively higher AlM module values in samples 1–3, 8, and 10 indicate the insignificant role of chemical weathering. The remaining samples yield significantly lower values, which indicates an increase in the intensity of the chemical weathering. The AlM value for sample no. 9 is anomalous, probably due to the very important role of chemical weathering.

The *potassium module (PM)*, the K_2O/Al_2O_3 ratio, depends on the intensity of chemical weathering in a provenance area. Potassium enters feldspars and accumulates upon their destruction in continental deposits under arid climate conditions. Under humid conditions, it is transported in the form of solutions and suspensions and concentrated in marine and lacustrine sediments. Aluminum is associated with the clayey part of sediments. Its content in the sediments increases toward an open basin. Low PM values are characteristic of continental sediments, whereas in?littoral and pelagic sediments its value increases
(Engalychev, Panov, 2011). 2

The potassium module values in the studied samples are quite low, which is typical of the coastal marine depositional environment and the relative proximity of the area of denudation. The PM values in samples 1–6 are actually the same (dominating role of chemical weathering). In the next samples, the PM values sharply decrease, which indicates an increase in coastal denudation (relative shallowing of a basin).

Sodium module (SM) is Na_2O/Al_2O_3 ratio. Sodium is usually transported in the form of solutions, which reach their maximum concentrations in continental sediments under arid climate conditions, as well as in marine and lacustrine sediments under humid conditions. The aluminum content in the sediments increases towards an open basin. Coastal marine sedi-
2 ments are highly depleted in sodium (Engalychev, Panov, 2011).

The SM values for samples 2–4, 7, 8, and 10 are high; for samples 1, 5, 6, and 9 the SM values are significantly lower, which is evidence of variations in hydrodynamics of a sedimentation basin and its paleodepth.

The *titanium module (TM)*, TiO_2/Al_2O_3 ratio, depends on the dynamic facies sedimentation and the Ti content in samples of the petrology fund. Thus, if a facies factor is established, the TM is an excellent indicator of a petrology fund of basic or acidic composition. Variations in TM values indicate different climatic environments. Humid sandy–silty sediments have a TM module that is higher than in arid sediments. The same ratio is established in the clayey rocks. It is possible to use this module to reconstruct the climatic features only in the case of a permanent provenance area. In some cases, dynamic sorting of clastic material and the composition of the petrology fund can affect the TM value much more strongly than the climatic factor. In summary, the titanium module value increases with the transition from the arid zone to the humid one; within the humid zone, it increases from deep water zones to coastal marine and conti-
2 nental facies zones (Engalychev, Panov, 2011). Based on the TM values in samples 1–6 we assume that sedimentation occurred in a shallow water basin under humid climate conditions. This conclusion, which is based on geochemical data, is consistent with the previously published data.

The titanium module values that were obtained in samples 7–10 are significantly lower due to the change of the humid climate into an arid one, but not the shallowing of a basin and predominance of coastal marine depositional environment.

The S content increases seaward, which is evidence of an oxygen deficiency in the bottom waters. In the studied samples, the value of the sulfur content is highly variable, probably due to variations in the water level or variations in the oxygen content in the bottom waters.

The maximum S values were measured in samples 3 and 5 (Turonian sediments, the effects of the OAE-2 event); the lowest S values were found in samples 6, 7, and 9 (Coniacian sediments).

The Ca and Mg contents increased under arid climate conditions. This is evidence of aridization of the territory, viz. a decrease in a humidity degree, which causes a reduction in the biological productivity of ecosystems due to a reduction in the difference between precipitation and evaporation.

The lower Ca content values in samples 1–5 indicate that sedimentation occurred under a relatively humid climate. In sample no. 6 the Ca content sharply increases by 16 times. This indicates the existence of a transitional phase that is probably associated with the restructuring of the climate. The Ca value then increases by 2 times in samples 7–10 compared with the sample 6. Accordingly, it is 32 times higher than the Ca content values in samples 1–5. This distribution of Ca values is probably due to the sharply growing aridization in the studied area.

The *Ca/Mg ratio* decreases with increasing temperature. In the samples we studied it is approximately the same. However, sample 6 has an anomalous Ca/Mg ratio value. In samples 8–10 the Mg content values are below the detection limit. Due to this, calculation of this ratio for the given interval of the sequence is hardly possible.

DISCUSSION OF THE RESULTS OF THE GEOCHEMICAL STUDY

The dynamics of chemical weathering under humid climate conditions are shown on the AM and AlM plots (Fig. 4). The role of chemical weathering increases with increasing AM values and decreasing AlM values. It is evident that the trend of an increase in this type of weathering was the same during the Late Turonian. The role of this type of weathering began to decline gradually in the Late Coniacian.

Aridization of the climate conditions is indicated by an increase in the Ca and Mg contents. Comparison of the Ca and Mg distribution plots, however, gives a mixed picture, viz., an inverse relationship (an increase in the Ca content with a decrease in the Mg content, which is apparently due to the variable calcite/dolomite ratio). Nevertheless, arid epochs (with a relatively high Mg content) are clearly contrasted to humid epochs (AM and AlM).

The eustatic variations in the level of the sedimentation basin on the TM and PM plots are very similar in shape. This fact allows us to assume with a great confidence that the paleodepth was increasing from Turonian to Coniacian. Based on PM values, cyclic variations in the Late Turonian are clearly distinguished.

The normal salinity conditions in the paleobasin are confirmed by low Ti/Mn values on the plot. The temperature conditions of marine water can be determined on the basis of the Ca/Mg dependence plot, which demonstrates that there was gradual warming from the Turonian to Coniacian.

Table 2. The calculation results for ten time scales of duration of the proposed astronomo-climatic cycles for Lower Maastrichtian sediments in the open pit of the Bolshevik cement plant (Volsk, Saratov Region)

Number of scale	Duration of Lower Maastrichtian, Ma	Duration (2/3) of Lower Maastrichtian, Ma	$T_{cycle} = T_{time}/37$ bioturbation oscillations	$T_{cycle} = T_{time}/25$ ichnocenosis oscillations	$T_{cycle} = T_{time}/29$ oscillations of maximum burrow diameter (mm) and $CaCO_3$ concentration	$T_{cycle} = T_{time}/26$ @	$T_{cycle} = T_{time}/17$ oscillations of C_{org} content	$T_{cycle} = T_{time}/36$ H'cs oscillations	$T_{cycle} = T_{time}$/total number of oscillations (28.4)
1	2.5	1.7	**45946 (cycles O_2)**	68000	58621	65385	**100000 (cycles E_1)**	47222	59859
2	4	2.7	72973	**108000 (cycles E_1)**	**93103 (cycles E_1)**	**103846 (cycles E_1)**	158823	75000	95070
3	4.25	2.8	75676	**112000 (cycles E_1)**	**96552 (cycles E_1)**	**107692 (cycles E_1)**	164706	77778	**98592 (cycles E_1)**
4	3.5	2.3	62162	**92000 (cycles E_1)**	79310	88462	135294	63889	80986
5	4.5	2.9	78378	**116000 (cycles E_1)**	**100000 (cycles E_1)**	**111538 (cycles E_1)**	170588	80556	**102113 (cycles E_1)**
6	5	3.3	89189	132000	**113793 (cycles E_1)**	126923	194117	91667	**116197 (cycles E_1)**
7	4.5	2.9	78378	**116000 (cycles E_1)**	**100000 (cycles E_1)**	**111538 (cycles E_1)**	170588	80556	**102113 (cycles E_1)**
8	3	1.9	51351	76000	65517	73077	**111765 (cycles E_1)**	52778	66902
9	3.15	2.09	56486	83600	72069	80385	122941	58055	73592
10	3.15	2.09	56486	83600	72069	80385	122941	58055	73592

The calculated values of the durations of cycles, which are close to the known ones, are given in semi-bold.

The sulfur content varies cyclically, due to a simultaneous change in the paleodepth and the content of dissolved oxygen in the bottom waters.

As a result, one can state that there was a relatively shallow basin at the studied territory during the Turonian. Its depth gradually increased to the Coniacian and it became a deep-water basin in the Early Coniacian. During the Turonian and Coniacian, the paleobasin had normal salinity. The humid climate in the Turonian was followed by arid climatic conditions in the Coniacian, which lasted until the second half of the Coniacian. Nevertheless, relative climate aridization of the region continued later, but it was not as significant. Relative cooling in the Early Turonian was followed by warming at the end of century and this trend continued throughout the Coniacian.

The genesis of the formation cyclites was revealed by methods of "manual" counting and spectral Fourier analysis. Below, we briefly discuss some of the previously published results (Gabdullin, 2002). Comparison of ten geochronological time scales (Table 1) clearly shows that the durations of some centuries may differ by two times or more according to different authors (as for the durations of Milankovitch cycles). One of the problems that arises here lies in the difficulty of solving the problem of clarification of geological time: with the use of different time scales the cycles of one order or the same genesis "pass" into another order or another genesis is proposed. For example, eccentricity cycles of about 20 ky can change into the cycles of obliquity of the ecliptic lasting about 40 ky or the eccentricity cycles of the first order with duration of 100 ky can change into the cycles of second order with a duration of 400 ky.

Along with a geochronological time scale one can use a sedimentometric method, which allows one to connect the duration of cyclites and the possible sedimentation rate. The latter can be determined experimentally or one can use a sedimentation rate that is determined for similar sediments. Such a strategy makes sense only for sequences that comprise frequent hiatuses whose durations are difficult to determine.

"Manual" counting results are given in Table 2. It is seen that if the duration of a century (or its part) is subdivided into a number of oscillations, then we obtain a wide range of values, from ecliptic cycles to eccentricity.

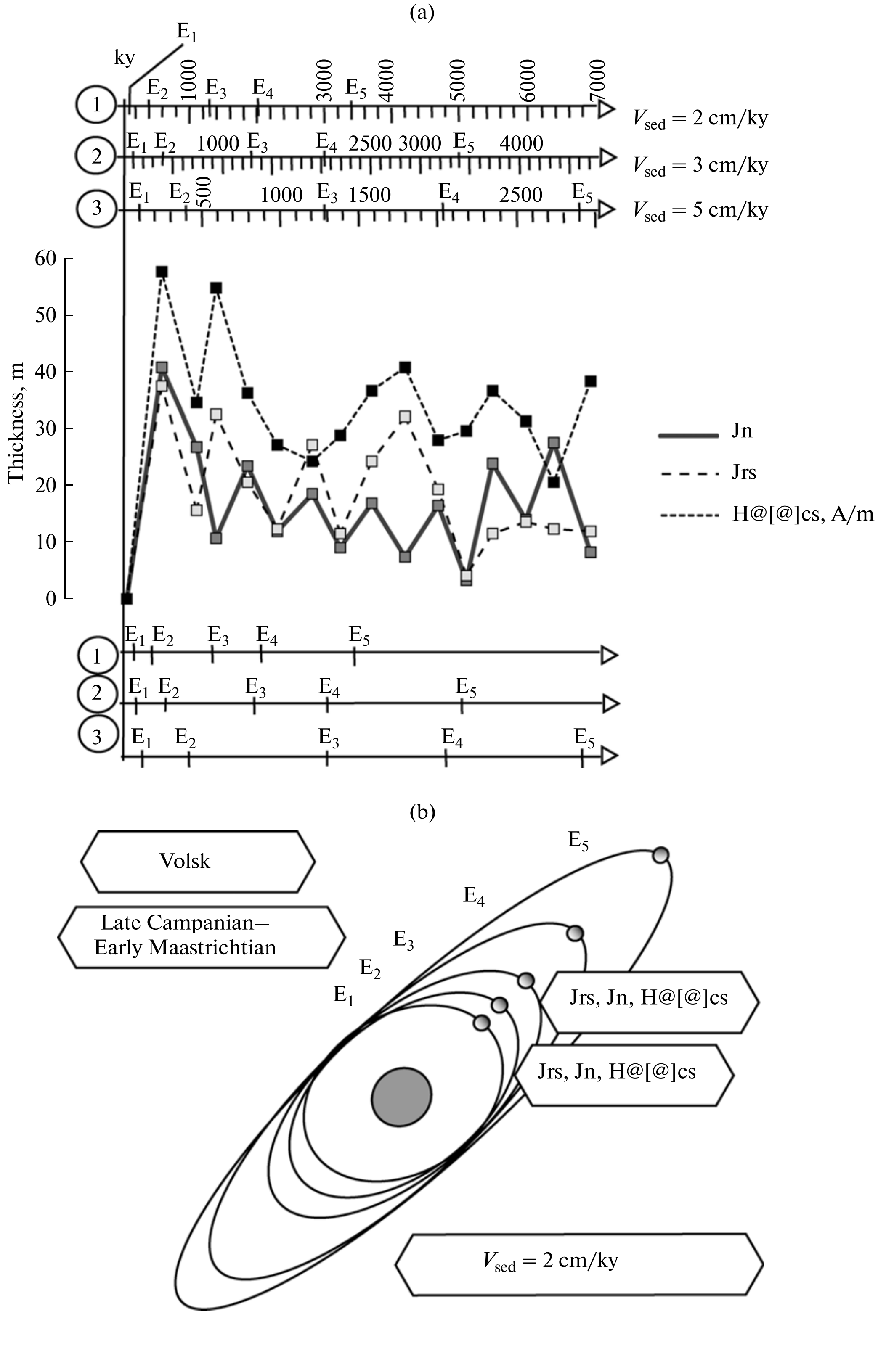

Fig. 5. The Fourier spectral distribution of a number of parameters in Upper Campanian–Lower Maastrichtian sediments in the open pit of the Bolshevik cement plant (Volsk, Saratov Region) (a) and final diagram of study results (b).

In some cases, the duration of the variations do not correspond to the Milankovitch cycles (Gabdullin, 2002).

Spectral analysis was used to determine a number of parameters for sediments of the Upper Campanian and Lower Maastrichtian (Fig. 5a) that were collected in the open pit of the Bolshevik cement plant (town of Volsk, Saratov Region) (Gabdullin, 2002). The Fourier spectral distribution was linked to the different time intervals that were studied (an analog of different geochronological time scales or different sedimentation rates) using original software and consultations by S.V. Borisov, Candidate in Biology (Department of Biology, Moscow State University). Thus, at the sedimentation rate of 2 cm/ky the variations of three petromagnetic parameters (Jrs, Jn, H'cs) can be associated with the eccentricity cycles of the second (0.4 Ma) and third (1.29 Ma) orders (see Fig. 5b). The relationship of these oscillations with astronomo-climatic cycles is not identified in the case of other sedimentation rate values or some other parameters. The absence of a distinct relationship between cyclic variations and Milankovitch cycles stimulated us to use a new method.

Wavelet Analysis

In order to clarify the connection between specific changes in climate and paleogeographic conditions and long-period Milankovitch cycles, the curves of cyclic variations of different parameters were statistically processed using computer software. In particular, the wavelet spectral analysis of the patterns of distribution of a number of parameters was first applied to the Late Campanian–Early Maastricht interval: the *Belemnella sumensis* zone, in the interval of 70.04–69.42 Ma, samples 103–62; in the *Belemnella lanceolata* zone, the interval of 70.67–70.04 Ma, samples 61–45; in the interval of 77.69–71.29 Ma (the mucronata and langei zones, the second half of the mucronata zone, samples 51–60) and in the interval of 80.42–77.69 Ma (the first half of the mucronata zone, samples 24–50).

The interval of 71.29–70.67 Ma corresponds to a hiatus. The chronostratigraphic scale was used to
3 estimate the duration of biozones (Hardenbol et al., 1998).

Many processes are non-stationary and demonstrate changes in their statistical characteristics over time. The analysis of the relevant experimental data based on the classical probabilistic and spectral methods (in particular, the traditional standard Fourier analysis) often creates problems when interpreting the results. By the present time, significant progress in the development of more effective methods for studying non-stationary processes has been achieved; wavelet analysis is considered to be the most effective (Koronovskii, Khramov, 2003; Koronovskii et al., 2013; Astafieva, 1996). It was first proposed as a method as an alternative to the classical spectral analysis. However, with the implementation of wavelet analysis it started to be used as a tool for applied research in almost all of the natural sciences and in various fields of engineering. This mathematical apparatus, which is mainly used in the natural sciences, is the processing of non-stationary (in time) and/or non-uniform (in space) non-stationary complex and chaotic processes (Runnova et al., 2013; Filatova et al., 2010). Wavelet analysis allows one to obtain a time–frequency dynamic pattern of cycles in a time series that is being analyzed.

This is the reason that wavelet analysis is of considerable interest to geologists and geophysicists, as it offers new possibilities for digital data processing, including parametric data (logging data, for example). In order to interpret parametric data it is necessary to analyze short (and sometimes ultra-short) time series, which includes a few oscillation periods of a particular parameter that is analyzed throughout the sequence.

In this situation, the use of methods of spectral analysis is incorrect due to the influence of the edge effects of a short time series (Farge et al., 1995), which can significantly distort the results of the analysis of cycles.

Therefore, wavelet analysis is regarded as a more correct method for analyzing short-term processes with a weak influence of edge effects. Wavelet analysis is time limited, due to this, the zone of influence of edge effects is constrained by a narrow zone near the boundaries in the time series (the width of the zone of the edge influence is defined by the analyzed time scale) (Torrence, Compo, 1998).

The nature of the distribution of natural remanent magnetization Jn (nT) has been investigated using a continuous wavelet transform (Koronovskii, Khramov, 2003; Koronovskii et al., 2013; Astafieva, 1996).

The standard complex Morlet wavelet with the center frequency parameter $\Omega = 12$ was used as the mother wavelet. This choice of the Morlet mother function provides improved frequency resolution of the wavelet transform with the preservation of a good temporary resolution compared to the traditional choice $\Omega = 2\pi$. The time–frequency spectra were calculated with the wavelet transform using a computer program that was previously developed for the analysis of rhythmic components in non-stationary signals (Torrence, Compo, 1998). The time series that was obtained with the analysis of the parametric curve Jn (nT) and used to calculate the wavelet spectrum is shown in Figure 6 (the time intervals are shown in millions of years). The non-equidistance of the intervals between time series readings, which is connected with the features of sedimentation over time, should be noted. The corresponding wavelet spectrum is shown in Figure 7: time is on the horizontal axis and the time scale of geological cycles that were distinguished in the analyzed data (Ma) is on the vertical axis. The spectrum-intensity distribution over the time scale is shown in gray (oscillations with a non-existent period are shown in white), the maximum intensity of the

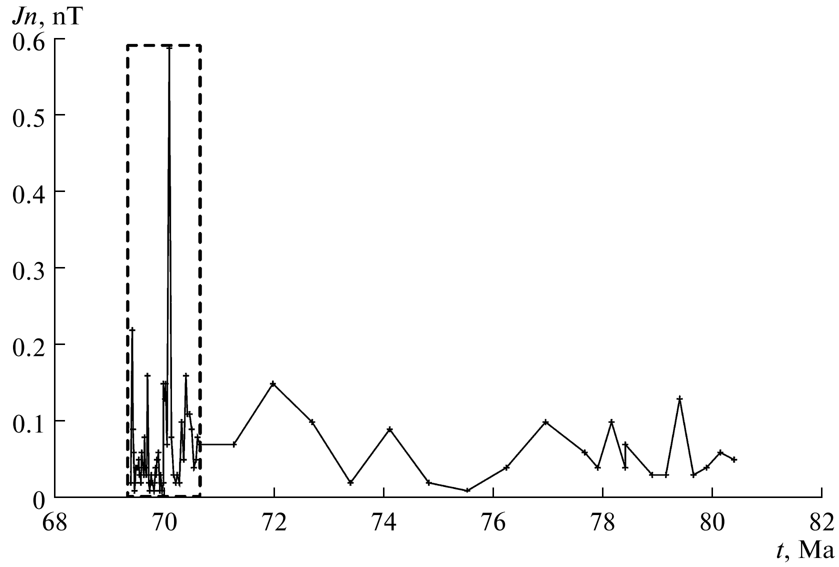

Fig. 6. The interval of the analyzed time series with parametric data.

rhythm at a specific time is shown in black. The duration of the analyzed time series corresponds to ~12 Ma, the minimum sampling frequency was 1.4 Ma^{-1}, the minimum frequency was 66.6 Ma^{-1}. Accordingly, the rhythms in the entire parametric data set in the time scale $s = [0.4; 8]$ Ma were analyzed.

In addition, the integral wavelet spectrum E (s) (scalogram), which is a time-averaged instant wavelet spectrum, was calculated using the same program

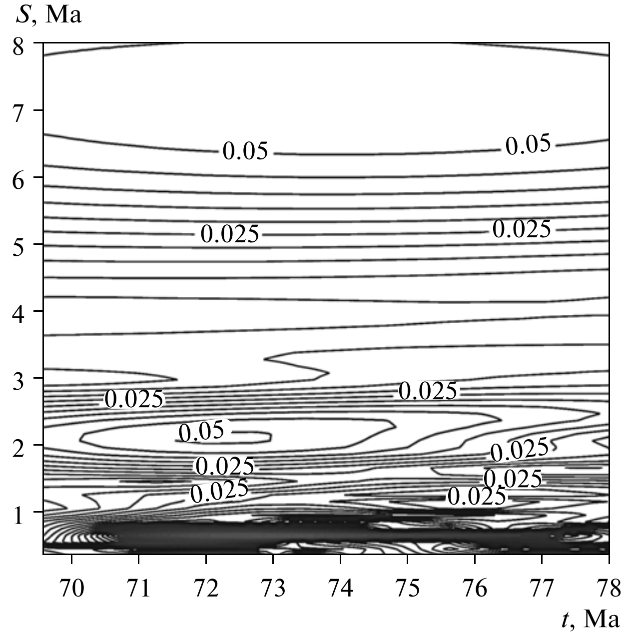

Fig. 7. A wavelet spectrum, constructed with a basic Morlet wavelet ($\omega = 12$) based on the data (Fig. 6).

(Koronovskii, Khramov, 2003; Koronovskii et al., 2013). The obtained scalogram is shown in Figure 8. It is clearly seen that the time series comprises distinct cycles with durations: $T_1 = 0.9$ Ma (by comparison with the plot on Figure 7, one can make the conclusion that this rhythm is the most pronounced in the interval), $T_2 = 2.2$ Ma (expressed in the interval of 71–73 Ma), and $T_3 = 7.4$ Ma (due to the long period this rhythm cannot be distinguished) (the duration of the time series is 8.5 Ma). These cycles are similar in duration to the cycles of the Earth's orbital eccentricity of the third order E_3 (a duration of 1.29 Ma; T_1) and the fourth order (a duration of 2.03 Ma, T_2). In addition, this segment was analyzed using the wavelet transform.

Let us note the segment of the time series in the time interval of 69.4–70.7 Ma (Early Maastrichtian, *Belemnella sumensis* zone, outlined in Figure 6), which is characterized by short-wave rhythms (Fig. 9). The results, which are presented in the form of a scalogram in Figure 10, show that this interval comprises several rhythms. The most pronounced rhythms are 0.04 Ma (O-cycles or cycles of obliquity of the ecliptic) and 0.4 Ma (E_2 cycles or cycles of eccentricity of the second order).

Conditions of sedimentation. Based on the complex of the analytical and partly statistically processed data, we will describe the paleogeographic environment for the studied sequence.

The *Turonian Stage. Late epoch.* In the Turonian the accumulation of predominantly carbonate silts and clastic phosphorite sediments within the Ulyanovsk–Saratov Basin occurred under shallow-water marine conditions (Gerasimov et al., 1962). The characteristics of the sedimentation basin are given below.

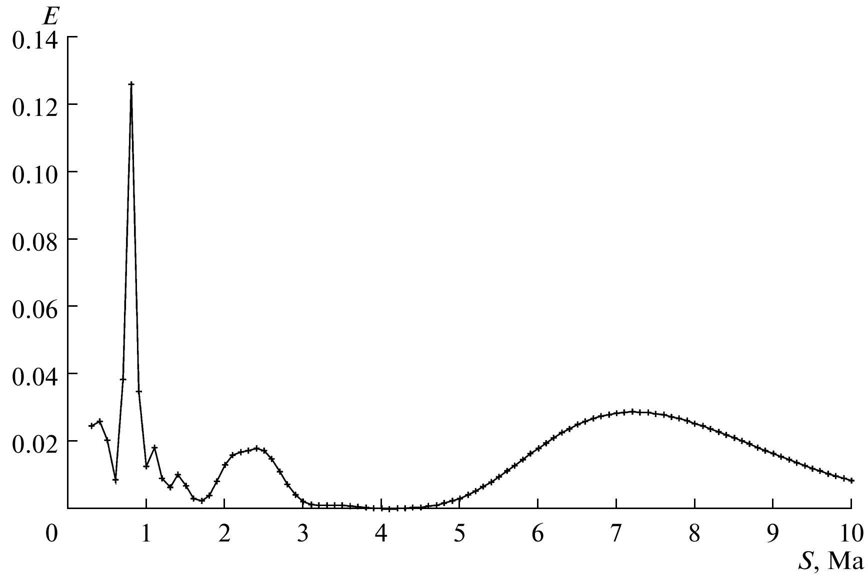

Fig. 8. The wavelet spectrum scalogram of the time series that was analyzed.

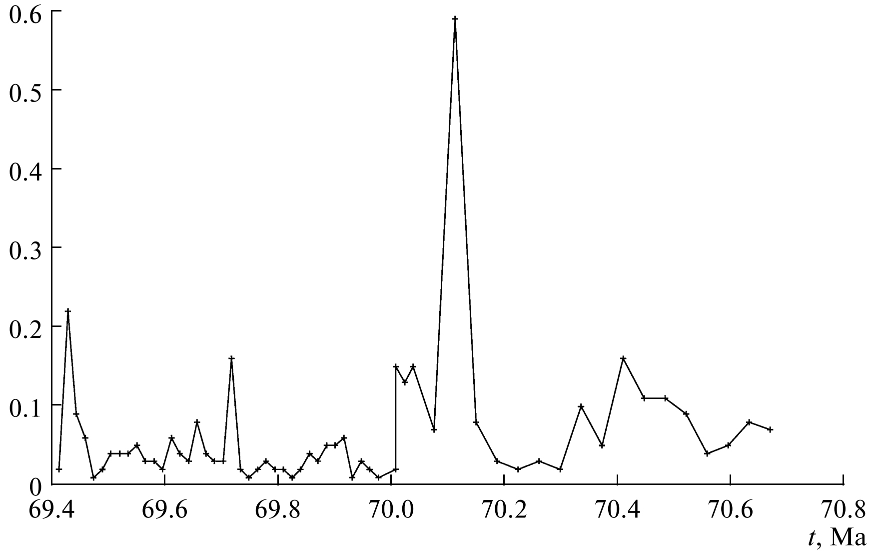

Fig. 9. An interval of the time series with the parametric data, corresponding to the area outlined in Figure 1.

The composition of the paleocenosis. Benthic forms (echinoderms, pelecypods, brachiopods) and plankton with carbonate skeletons sharply predominate over nekton (belemnites and sharks). The trace fossil *Planolites* can belong both to echinoderms and pelecypods. The trace fossil *Thalassinoides* indicates the presence of crustaceans in the composition of the paleocenosis.

Depth. The basin was shallow water, which is confirmed by the Ti/Mn ratio and TM values. However, eustatic variations occurred (SM, AlM, TM, PM, S content).

The gas regime. An abundance of echinoderms, crustaceans (trace fossils *Thalassinoides*), and cartilaginous fish are evidence of the common content of dissolved oxygen in the water.

However, variations in the S content indicate oxygen content variations.

Salinity. The occurrence of echinoderms and brachiopods, as well as the Ti/Mn ratio value confirm the normal salinity conditions in the basin.

Type of substratum. The presence of a loose substrate is confirmed by the occurrence of spatangoids—echinoderms and the trace fossils *Planolites*, *Thalassinoides*, and *Chondrites*. The remains of oysters and brachiopods indicate a solid substrate. It is most likely

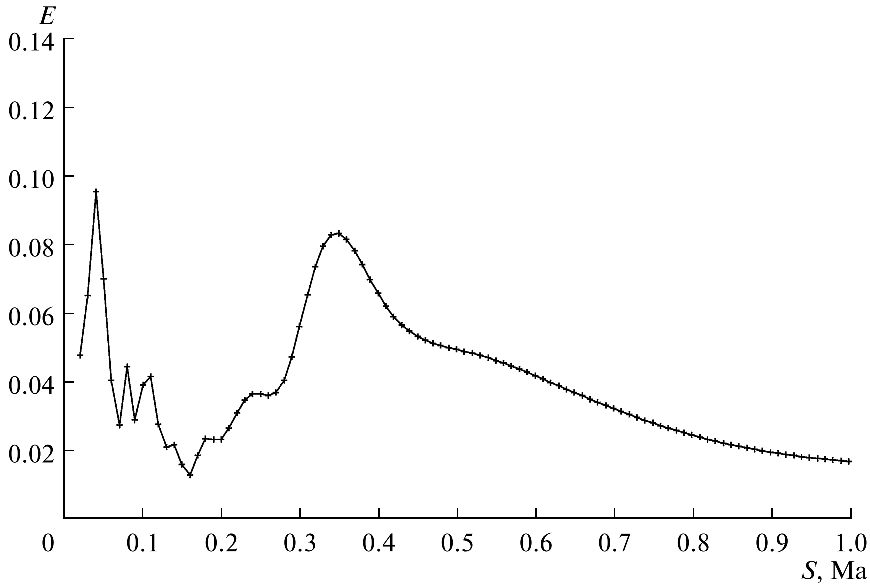

Fig. 10. The wavelet scalogram of an interval of the time series corresponding to the dynamics in the period of 69–71 Ma (see Fig. 9).

that the bottom of the basin was loose with rocky ledges.

Hydrodynamics. The occurrence of oysters suggests that active hydrodynamic processes occurred in the basin.

The water temperature (Teiss, Naidin, 1973) is estimated to have been 14–15°C in the Saratov Volga Region in the second half of the Turonian, based on finds of belemnites.

Relatively cold waters were gradually heated to the Coniacian, which is confirmed by the Ca and Mg contents, and Ca/Mg ratio value. Based on TM, AM, and AlM values, as well as the Mg content, the humid climate in the Turonian was followed by an arid climate in the Coniacian.

The Coniacian Stage. In the Coniacian, predominantly carbonate sedimentation took place within the Ulyanovsk–Saratov Basin (Gerasimov et al., 1962).

The composition of the paleocenosis. The biocenosis was represented by plankton with carbonate skeletons, crustaceans, and the trace fossils *Thalassinoides*, inoceramids, and echinoderms. There are no finds of nekton forms of microfauna.

Foraminiferal assemblages are represented by anomalines. Such a poor assemblage composition is probably evidence of unfavorable environmental conditions.

Depth. A relatively deep basin, which is confirmed by TM and Ti/Mn ratio values. However, eustatic variations occurred (SM, AlM, TM, PM, S content).

Salinity. The occurrence of crustaceans (trace fossil *Thalassinoides*) and rare pelecypods, as well as the Ti/Mn ratio, confirm the assumption of normal salinity conditions in the paleobasin.

Gas regime. Trace fossils of crustaceans (*Thalassinoides*) provide evidence of the common content of dissolved oxygen in the water. At the same time, the trace fossil *Chondrites* indicates a reducing environment. The sequence contains pyrite nodules, indicating the deficiency of dissolved oxygen in the water. Variations in the distribution of trace fossils and the concentration of organic carbon indicate fluctuations in the gas regime, which is also confirmed by the variation in the sulfur content.

The type of substratum. The existence of a loose soft substrate is a necessary condition for the existence of spatangoid echinoderms of the genus *Micraster*. It is probable that the bottom of the basin was composed of a loose substratum, which is confirmed by the occurrence of the trace fossils *Thalassinoides* and *Chondrites*. Inoceramids could colonize different types of soils.

Hydrodynamics. The presence of waters with an oxygen deficiency indicates stagnation and the collapse of water circulation.

The water temperature in the basin of the Russian Plate estimated based on belemnites was 13–15°C in the Late Coniacian (Teiss, Naidin, 1973). Nevertheless, the geochemical data (the Ca and Mg contents, as well as the Ca/Mg ratio) indicate that the water in the Coniacian was warmer than in the Turonian. From the beginning of the Coniacian the aridization of the climate occurred as indicated by the values of TM, AM, AlM, and the Mg content.

Cyclicity was not visually identified in the sequence of the Turonian and Coniacian sediments. However, there were eustatic variations and fluctuations in the gas regime.

The Campanian Stage, the Last Epoch

In the Campanian, carbonate sedimentation dominated within the Ulyanovsk–Saratov basin. In the south of the Ulyanovsk–Saratov trough siliceous–terrigenous sediments were deposited under shallow-water marine conditions; within the rest of the trough carbonate sediments were deposited.

The Belemnitella mucronata Zone. The Composition of the Paleocenosis

Plankton with a carbonate skeleton. A poor complex of macrofossils, which are presented by benthic forms: several species of echinoderms, pelecypods (inoceramids), and belemnites.

Depth. According to N.A. Bondarenko's data [1990], these sediments accumulated in the pelagic zone.

Gas regime. There were insignificant variations in the gas regime, which is confirmed by the cyclic distribution of the C_{org} concentration, the volume of bioturbation, and the presence of pyrite nodules in the sequence.

Type of substratum. Benthic organisms are presented by spatangoid echinoderms, which inhabited loose muddy ground, and inoceramids, which inhabited all types of ground. Therefore, it is most likely that the ground was soft and muddy.

Temperature. Based on the temperature determination on the belemnite rostra (Teiss, Naidin, 1973), the water temperature in the paleobasin was 13–14°C.

Data on the salinity and hydrodynamics of the paleobasin are absent.

Formation of rhythmicity in the open pit of the Bolshevik cement plant. The lack of supply of magnetic terrigenous minerals (Gabdullin et al., 1998) is confirmed by the low values of the petromagnetic parameters and the absence of oscillations on most of the distribution curves of petromagnetic parameters. There are no traces of dissolution of $CaCO_3$. Thus, cycles of dissolution and dilution cannot be considered as the mechanisms of the formation of rhythms.

It is most likely that the origin of the ten rhythms of type 1 is associated with the cycles of bioproductivity (in a basin with carbonate sedimentation) and climate variations.

Evaluation of the connection between these rhythms and the Milankovitch cycles using the spectral analysis allowed us to identify the eccentricity cycles E_2 and E_3 after Jrs, Jn, H'cs at V_{sed} = 2 cm/1000 years in the interval from the Late Campanian to Early Maastrichtian. In the same interval the duration of these cycles was estimated with wavelet analysis. They are similar in duration to the eccentricity cycles of the Earth's orbit of the third order (E_3, 1.29 Ma) and fourth order (E_4, 2.03 Ma).

The Belemnitella mucronata Phase–Belemnitella langei Zone. The Composition of the Paleocenosis

Plankton with carbonate skeletons, nekton forms, which are presented as belemnites and ammonites, occur. Benthic forms: corals, scaphopods and bivalves, brachiopods and echinoderms (seven genera and seven species, in total) are predominant.

The occurrence of pelecypods is confirmed by the trace fossil *Teichichnus*; the trace fossil *Thalassinoides* indicates the occurrence of crustaceans in the biocenosis.

Depth. In these sediments an assemblage of macrofossils, presented by two inoceramus species, was established. The sediments formed in the pelagic zone [Bondarenko, 1990].

Salinity. Corals found in the sediments of this member are evidence of normal salinity in the sedimentation basin. The occurrence of the remains of stenohaline echinoderms and crustaceans (trace fossils *Thalassinoides*) should be noted

Gas regime. The presence of pyrite nodules and the trace fossil *Chondrites* indicate a reducing environment. There are finds of single corals. The weak fluctuations in the dissolved oxygen concentration in the water are confirmed by cyclic distribution of the C_{org} concentration and the volume of bioturbation.

Temperature. The occurrence of corals indicates that the water in the basin was rather warm. Based on the temperature determination on belemnite rostra [Teiss, Naidin, 1973], the water temperature in the paleobasin was 14–16°C.

Type of substratum. The occurrence of a large amount of shells of spatangoids–echinoderms ("Mikrastrovo Cemetery"): *Micraster grimmensis* and *Coraster cubanicus*, as well as tooth shells *Dentalium* and trace fossil *Teichnichus*, *Thalassinoides*, *Chondrites*, cyclically distributed throughout the sequence is evidence of the loose substrate. A solid substrate is required for the corals *Parasmilia* and bivalves *Spondylus*. Thus, it is most likely that the bottom of the basin was represented by loose sediments with rock ledges.

Hydrodynamics. Finds of single corals are evidence of active hydrodynamic conditions.

Modeling of sedimentation conditions. A formation of three rhythms of type 2 is associated with bioproductivity cycles (in a basin with carbonate sedimentation) and climate variations.

Maastrichtian Stage. Early epoch. In the south of the Ulyanovsk–Saratov trough siliceous–terrigenous sediments deposited under shallow water–marine conditions; in the rest of the territory, carbonate sedimentation took place.

The Belemnella lanceolata Zone. The Composition of the Paleocenosis

A paleocenosis with predominance of plankton with carbonate skeleton and benthic macrofossils over nekton macrofossils. Trace fossils of *Planolites* may belong pelecypods, gastropods, and echinoderms. The occurrence of the trace fossil *Thalassinoides* indicate the presence of crustaceans.

Salinity. The sediments contain the sponge (*Ventriculites*), which inhabited normal-salinity water basins.

Gas regime. The presence of pyrite nodules is evidence of reducing conditions. At the same time, the poor biocenosis includes stenoxybiotic sponges and euryoxybiotic oysters. The rhythmic distribution of trace fossils (volume of bioturbation) and the C_{org} concentration give possible confirmation that there were slight fluctuations in the gas regime.

Type of substratum. Spatangoids (*Echinocorus*), cidaroids, and crustaceans (trace fossil *Thalassinoides*) live in loose and soft ground. A solid substrate is favorable for sponges and terebratullids. Gastropods can live on any type of substrate. The bottom was probably muddy with rock ledges.

Hydrodynamics. The occurrence of oysters and sponges is evidence of active hydrodynamic processes (flows).

Depth. According to N.A. Bondarenko's data (Bondarenko, 1990), sediments were deposited in the pelagic zone (viz., deeper than 130–200 m). Ventriculitid sponges lived at depths varying from several hundred meters to 6 km. Oysters of genus *Ostrea* inhabit depths of 40–100 m. Echinoderms–cidaroids inhabited depths of 75–100 m (sometimes up to 4 km), where they fed on sponges. Thus, echinoderms (cidaroids and sponges) likely lived together. In our view, the basin could be >100 m deep (lower sublittoral–bathyal). Relatively shallow-water organisms (pectenids, for example) probably settled in allochtonous sediments.

The temperature in the paleobasin, according to a study of the sequence near the town of Khvalynsk (Teiss, Naidin, 1973), is estimated at 12.9°C.

Formation of rhythmicity. We assume that there was no supply of magnetic terrigenous minerals, which is confirmed by the low values of petromagnetic parameters and the absence of oscillations on most of the curves. There is no correlation between Jrs and H'cs values. There are no data on the stratification of water in the sedimentation basin. It is assumed that formation of the rhythms of type 1 (Gabdullin, 1998) was associated with bioproductivity cycles in a relatively deep water basin with carbonate sedimentation.

The Belemnella sumensis Zone.
The Composition of the Paleocenosis

Plankton with carbonate skeletons, benthic forms predominate over macrofossils and nekton macrofossils.

The occurrence of pelecypods is confirmed by the trace fossil *Teichnichus*. The trace fossil *Thalassinoides* is evidence of the existence of crustaceans.

Depth. According to N.A. Bondarenko's data [1990] these sediments accumulated in the pelagic zone. These sediments contain an assemblage of macrofossils, including oysters *Ostrea* (40–100 m), pectenids *Janira* (2–50 m), cidaroids *Cidaris* and *Salenia* (75–100 m). The basin was probably 40–70 m deep (sublittoral). It is most likely that there were rocky ledges at the bottom, where corals, pectenids, and terebratullids settled. The latter was the "upper layer" of the community. The paleoecological analysis of modern marine invertebrates shows that any biocenosis is characterized by stratification in the distribution of organisms. In our view, it would be wrong to assume that the bottom of the sedimentation basin was always flat and such organisms as corals (attached benthos) and pectenids lived in allochtonous sediments (more than 100 m below their habitats).

Salinity. The sediments contain stenohaline pleurotomarids and corals that live under normal salinity conditions. Oysters of the genus *Ostrea* (12–30%) cannot exist under an increase in water salinity. Thus, we can assume that the sedimentation paleobasin was of normal salinity.

Gas regime. The presence of pyrite nodules is evidence that there was a dissolved oxygen deficiency in the water. At the same time, there are stenoxybiotic pectenids, corals, sponges, and euryoxybiotic oysters (*Ostrea*). It is possible that there were weak fluctuations in the gas regime, which is confirmed by the cyclical distribution of trace fossils (the volume of bioturbation) and the C_{org} concentration.

Temperature. This biocenosis includes thermophilic corals (*Cylicosmilia*) and oysters of the genus *Ostrea* (0–32°C). Pectenids (*Janira*) live at temperatures from 8.8 to 23.5°C. Accordingly, the water temperature could be 23.5°C or less.

Type of substratum. Cidaroids (*Cidaris*, *Salenia*) usually settle on muddy ground. Spatangoids and crustaceans (the trace fossil *Thalassinoides*) live in burrows inside loose sediment. A solid substrate is required for corals, pelecypods *Spondylus*. In addition, it is favorable for pectenids and terebratulids. The other members of the assemblage (gastropods) could live on any type of ground. The bottom was muddy with rock ledges.

Hydrodynamics. The occurrence of oysters and pectenids is evidence of active hydrodynamic processes (flows).

Formation of rhythmicity. We assume that there was no supply of magnetic terrigenous minerals, which is confirmed by the low values of petromagnetic parameters and an absence of oscillations on most of the curves of their distribution (Fig. 3). Since Jrs = 0, the correlation between Jrs and H'cs was not calculated.

Verification of the connection between Lower Maastrichtian rhythms and the Milankovitch cycles by spectral analysis (Fig. 5) makes it possible to identify the eccentricity cycles (E_2 and E_3) and the cycles E_1 by manual counting of an average number of oscillation parameters (coincidence on two time scales of 10, viz. 20%, Table 2). As an experiment, a number of peaks (oscillations) of individual parameters were manually counted to evaluate the duration of these oscillations in the Early Maastrichtian on 10 time scales. As a result, based on a number of ichnotaxa and $CaCO_3$ concentration (a coincidence of 40%), the distribution of pyrite nodules (coincidence of 30%), C_{org} concentration (coincidence of 20%), H'cs (coincidence of 10%) the E_1 cycles were distinguished. Based on the area of bioturbated sediments, H'cs (coincidence of 20%), and the $CaCO_3$ concentration (coincidence of 10%) O-cycles (the ecliptic) were distinguished. One can state that the arithmetic mean of a number of peaks of some parameters is not always connected with possible astronomo-climatic cycles.

The O-cycles (cycles of obliquity of the ecliptic) and E_2 cycles (eccentricity cycles of the second order) were first identified for the *Belemnella sumensis* zone via wavelet analysis. Moreover, within the Late Campanian–Early Maastrichtian interval of the sequence, cycles that were similar in duration to the cycles of the Earth's orbital eccentricity of the third order (E_3, 1.29 Ma) and fourth order (E_4, 2.03 Ma), were identified.

As a result, the presence of O-cycles was confirmed by manual counting and wavelet analysis, and the cycles of E_3 were confirmed by spectral and, possibly, wavelet analyses. The presence of other eccentricity cycles of the first, third, and fourth orders was confirmed by only one of the three methods.

Consequently, the prerequisites exist for the development of a model that can explain the formation of cyclites of type 1 based on the data on climatic variations that led to variations in bioproductivity cycles.

CONCLUSIONS

As a result of a comprehensive study, the sedimentation conditions of the sequence near the town of Volsk were first reconstructed in detail with high probability. Based on new geochemical data, in the visually acyclic Turonian–Coniacian interval of the sequence eustatic fluctuations and variations in the gas regime were established. In the Campanian–Maastrichtian cyclic sequence the types of cyclites were distinguished and mechanisms for their generation, which are closely related to astronomo-climatic Milankovitch cycles, were proposed. The Milankovitch cycles in the Volsk sequence were first identified using three methods: manual counting, and spectral and wavelet analyses. The results were correlated and discussed. For the *Belemnella sumensis* zone the cycles of inclination of the ecliptic (O-cycles) and the eccentricity cycles of the second order (E2 cycles) were established with high probability.

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