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The Lithological and Geochemical Characteristics and Paleoclimatic Conditions of the Formation of Upper Cretaceous Sediments of the Russian Plate Epicontinental Basin in the Region of the Ul'yanovsk–Saratov Trough

R. R. Gabdullin[a, *], A. Yu. Puzik[b, **], S. I. Merenkova[a, *], I. R. Migranov[a, ****], N. V. Badulina[a, *****], A. V. Ivanov[c, ******], and M. D. Kazurov[a, *******]**

[a] *Department of Geology, Moscow State University, Moscow, 119991 Russia*
[b] *Institute of Natural Sciences, Permian State University, 4 Genkelya str, Perm, 614990 Russia*
[c] *Institute of Geography, Russian Academy of Sciences, 29 Staromonetny, Moscow, 119017 Russia*
**e-mail: mosgorsun@rambler.ru*
***e-mail: alex.puzik@mail.ru*
****e-mail: koshelevasof@mail.ru*
*****e-mail: iskandermig@mail.ru*
******e-mail: nvbadulina@mail.ru*
*******e-mail: yashkovia@mail.ru*
********e-mail: max.kazurov@yandex.ru*

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Abstract—The results of a geochemical, paleogeographic, and paleoclimatic study of a cyclically constructed section of upper Cretaceous deposits near Vol'sk city (Saratov oblast) are presented. Elementary layered cyclites and cyclic variations of several certain parameters were associated with the Milankovich astronomical-climatic cycles. Paleotemperature, humidity, and paleobathymetry curves were compiled. Paleotemperatures of the land surface in the denudation areas were obtained from the chemical index of alteration (CIA). Climatic cyclicity was established in the Turonian–Campanian interval, including a period of relative cooling (Turonian–Coniacian) with a paleotemperature of approximately 20°C, the period of relative warming in the mid–late Campanian (20–24°C), the cooling time at the end of the late Campanian (19–21°C) and the period of warming at the turn of the Campanian and Maastrichtian and in the early Maastrichtian time, there are two climatic cycles in Maastrichtian age, beginning with a time of relative cooling (approximately 19°C) and ending with a time of relative warming (approximately 20°C, at the end of Maastrichtian to 25°C). The cycles of climate humidity change are also determined: two cycles in Campanian time, three cycles in early Maastrichtian, and one cycle in late Maastrichtian. The boundary of the early and late Maastrichtian corresponds to the change of arid conditions to humid ones. The paleobatimetry curves show transgressive–regressive cycles: one in the late Turonian–Coniacian time, two in the late Campanian time, five in the early Maastrichtian time, and one in the late Maastrichtian time. Depth variations were estimated: in the Turonian–Coniacian time in the range of 70–80 m, in the Campanian–Maastrichtian time, the paleobatimetry consistently increased and changed from 100 to 200 m (on average approximately 150 m). These results provide an idea of the migration of the boundaries of the arid belt in the Late Createaceous and main features of the climatic zonation, which is important for regional and global paleoclimatic reconstructions, as well as for the history of the development the Russian Plate in the Ulyanovsk–Saratov region.

Keywords: Cretaceous, cyclicity, geochemistry, climate, Vol'sk

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INTRODUCTION

The quarry of the Bol'shevik cement plant in Vol'sk (Saratov region) contains both cyclical and visually acyclic intervals (Fig. 1). This section was studied using a complex of methods (Badulina et al., 2016; Gabdullin, 2002; Gabdullin and Ivanov, 2002; Gabdullin et al., 2014; Seltser et al., 2016); the key factors that generated cyclicity, as well as cycles of (a) bioproductivity (for the Campanian–Maastrichtian interval), (b) dilution (for the end of the Early Maastrichtian and for the Late Maastrichtian), and (c) cycles caused by variations in the eccentricity of

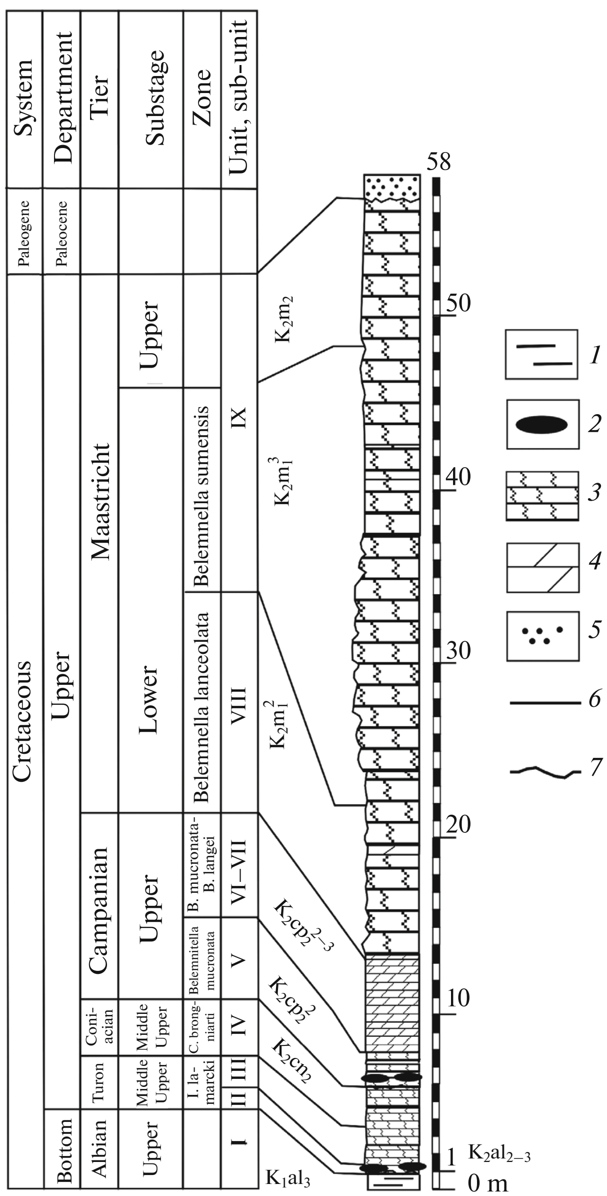

Fig. 1. The section of the Upper Cretaceous deposits of the quarry of the Bol'shevik cement plant, Vol'sk, Saratov region: (*1*) clays; (*2*) phosphorites; (*3*) writing chalk; (*4*) marls; (*5*) sands; (*6*) consonant stratigraphic boundaries; (*7*) discordant stratigraphic boundaries.

the Earth's orbit of the second order (lasting approximately 400000 years), third order (approximately 1290 thousand years) and fourth order (approximately 2030 thousand years), were determined. In these works, models of the formation of the deposits were proposed, and individual parameters (salinity, depth, and temperature) were estimated either qualitatively (except for the paleo–depth) or quantitatively for individual intervals of the section, for example, the values of paleotemperature for the Maastrichtian. Quantitative values were given for the units, as a rule, on average. This article presents curves of changes in temperature, depth, salinity, and climate type for the entire interval of the Upper Cretaceous part of the section in much more detail. The data are new and interesting from the standpoint of reconstructing the climatic and paleogeographic history of the epicontinental seas that covered the Russian Plate in the region of the evolution of the Ulyanovsk–Saratov trough. In addition, the obtained values provide an idea of the migration of the boundaries of the arid belt in the Late Cretaceous time and, in general, of the climatic zoning, which is important for regional and global paleoclimatic reconstructions.

MATERIALS AND METHODS

The geological section was previously studied using several methods. A review of the results of these studies and their interpretation was published earlier in (Gabdullin et al., 2014); it contains a list of publications by our and other research teams that studied these issues.

The emphasis of our work is on the results of geochemical studies of the section using 37 rock samples previously collected by R.R. Gabdullin, and their paleogeographic and paleoclimatic interpretation.

A complete geochemical analysis of elements for these 37 samples collected from visually noncyclic Turonian and Coniacian deposits and cyclically constructed Campanian and Maastrichtian deposits of the section was carried out on an S8 Tiger wave-dispersive X-ray fluorescence spectrometer of the sequential action type (Bruker).

Based on these results, the ratios and contents of some chemical elements were calculated, indicating a change in the conditions of sedimentation (depth of the basin, hydrodynamics, climate, etc.), which allowed us to clarify the previously formulated ideas about the sedimentation regime.

To analyze **variations in paleotemperature values**, the following values of element concentrations and their ratios were used: V, Ca, Ni, Ca/Sr, the titanium modulus (TM), Mn, and Si/Al. Temperature variations can also be estimated using the Ca/Mg, Sr/Ba, Zn/Nb, and (Ce, Nd, La, Ba)/Yb(Y, Zr) ratios.

An increase in the concentrations of Ca, Sr, Mg may indicate an arid type of climate, while an increase in the contents of Sc, Ni, Zn, Y, W, U, Cu, V, and rare earth elements (REE) may indicate humid sedimentation conditions.

The titanium modulus (TM), that is, the ratio of the content of TiO_2 and Al_2O_3, depends both on the dynamic facies of sedimentation and on the titanium content of the petrofund; therefore, if we fix the facies factor, TM serves as an excellent indicator of the petrofund of basic or acidic composition. The difference in TM values indicates different climatic conditions. The sandy–silty rocks that formed in a humid climate are characterized by higher TM values than arid rocks.

The same ratio is observed for clay rocks. The use of the TM to restore climatic features is possible only under conditions of a constant source of drift. In some cases, the dynamic sorting of material and the petrofund composition affect the TM value much more strongly than the climatic factor. In summary, we can say that TM value increases during the transition from the arid zone to the humid zone, and within the latter, as it moves from deep-water zones to coastal–marine and continental ones (Engalychev and Panova, 2011).

The indicators of depth changes of the basin include the Fe/Mn ratio, Ti/Mn, TM, the sodium modulus (SM), and the potassium modulus (PM), as well as the elements Zn, Pb, Al, Mn, Cu, Sr, and Ba showing the displacement of facies.

The Fe/Mn ratio. A decrease in this ratio corresponds to an increase in depth, as well as a transition from shelf to pelagic facies. The tendency towards a decrease in this ratio with the sedimentation depth is due to the absorption of manganese by sedimentary deposits from sea waters, which is more pronounced in deepwater conditions. According to the value of the Fe/Mn ratio, sedimentary rocks can be divided into deep-water (<40), shallow-water (<80), and shallow-water-coastal with a predominantly terrigenous source of drift (>160). The Fe/Mn ratio is quite applicable to clay or clay-containing sediments, and to a lesser extent to carbonate ones (Sklyarov, 2001).

The potassium modulus ($KM = K_2O/Al_2O_3$) is determined by the intensity of the chemical weathering in the erosion area. Potassium is a component of feldspars and accumulates during their destruction in continental sediments in an arid climate. In humid climates, it is transported in the form of solutions and suspended matter and is concentrated in marine and lacustrine sediments. Aluminum is associated with the clay part of the rocks. Its content in sediments increases towards the open basin. Low values of the potassium modulus are characteristic of continental sediments, while in coastal marine and pelagic sediments its values increase (Engalychev and Panova, 2011).

The sodium modulus ($HM = Na_2O/Al_2O_3$). Sodium is usually carried in the form of solutions and suspensions. Its maximum concentration is observed in continental sediments in an arid climate, as well as in marine and lacustrine sediments in a humid climate. The coastal marine formations are the poorest in sodium (Engalychev and Panova, 2011).

The Sr and Ba contents. An increase in the strontium content indicates distance from the source of drift of terrigenous material, while an increase in the concentration of barium, in contrast, indicates an approaching source of drift. With increasing depth of the basin Ba dissolves increasingly; however, at a depth of 4–5 km, its concentration can reach maximum values, since it reacts with the environment and precipitates.

The contents of Pb and Zn. The increase in lead and zinc concentration is caused by the approach to the source of drift and/or an increase in the salinity of the basin.

For **the analysis of salinity changes**, the Sr/Ba and Ca/Sr ratios were used. When the physicochemical equilibrium of the saline solution is shifted, which is caused by its burial, some minerals in this system dissolve (for example, calcite) and others appear (dolomite), which leads to a deep transformation of the composition of brines. In this case, selective concentration of chemical elements occurs in the solution, including Ca, Sr, and Ba. This is also clearly seen in super-saline solutions, where the Ca content is reduced to almost zero, since with an increase in salinity, it is replaced by Mg, which was previously contained in the sediment. Consequently, an increase in the Sr/Ba and Ca/Sr indices indicates an increase in the salinity of the solution.

The concentrations of B, Ba, S, Cr, Cu, Ga, Ni, and V in marine sediments are higher than in freshwater.

Zn and Cu are also indicators of the salinity of the solution. The mobility of these elements directly depends on salinity. The Cu content is almost always constant in river waters; therefore, when river water mixes with sea water, the rate of Cu precipitation decreases with increasing salinity of the resulting solution. The mobility of Zn also decreases with increasing salinity.

Determination of paleotemperature values by the weathering index. Weathering indices usually show the degree of depletion of volatile elements during chemical weathering. The CIA index was first proposed in (Nesbitt, Young, 1982) and is widely used as an indicator of the intensity of chemical weathering:

$$CIA = 100Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O),$$

where CaO* is noncarbonate CaO and all variables are molar amounts of oxides of basic elements. CaO * is the proportion of CaO in silicate minerals, which is used instead of total CaO to avoid the contribution of CaO from carbonate and phosphate minerals that are not associated with weathering processes (Nesbitt, Young, 1982).

In sediments that contain large amounts of carbonates or phosphates, it is necessary to estimate the amount of CaO*. This is usually done by calculating corrections for the measured CO_2 and P_2O_5 content. In the absence of measured CO_2 values, corrections can be calculated based on the Ca/Na ratio in the silicate material. For this, the CaO values are corrected for P_2O_5. If the phosphate corrected CaO* value exceeds the Na_2O concentration (also in molar fractions), CaO* is set equal to Na_2O (McLennan, 1993). With increasing weathering, the bases are gradually lost, which leads to high CIA values that approach 100 due to the accumulation of Al_2O_3 in the weathering products.

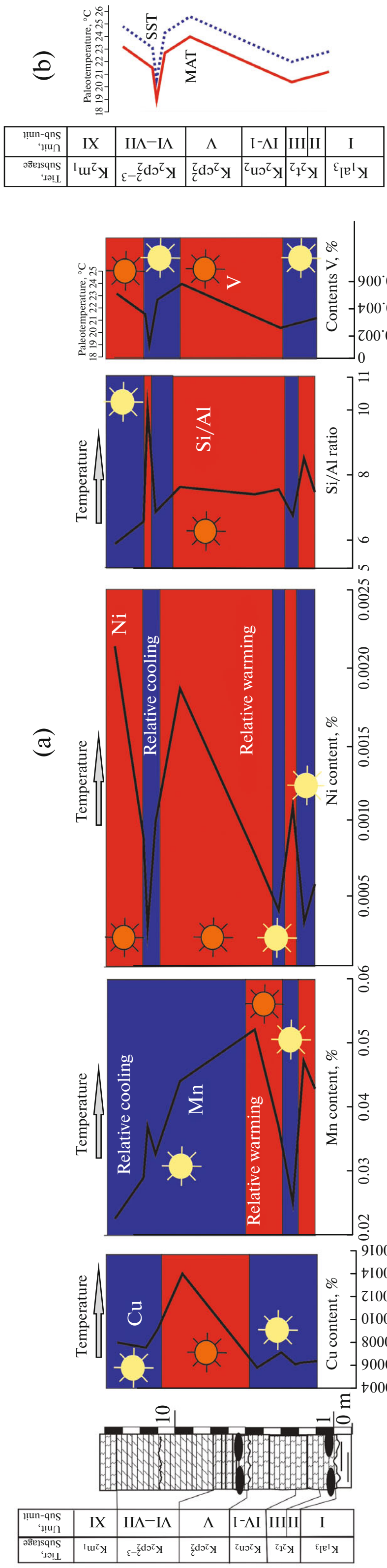

Fig. 2. Variations in paleotemperature for the Upper Turonian–Lower Maastrichtian: (a) in areas of denudation (obtained by us from geochemical data); (b) paleotemperature curves (MAT, annual average; SWT, surface waters).

The CIA index of 70 is a criterion for distinguishing between sediments formed in warm and cold climates.

Relatively high air temperatures lead to more intense chemical weathering, which can potentially be measured. In (Li and Yang, 2010), it was suggested that the CIA values of suspended sediments in modern estuaries of large rivers change as a function of the latitude and the land surface temperature. The authors of (Yang et al., 2014) demonstrated that the earth's surface temperature changes linearly with CIA on a global scale. This relationship is:

$$T = 0.56\text{CIA} - 25.7\ (r^2 = 0.05),$$

where T is the temperature, °C. It was shown in (Yang et al., 2014) that this ratio is stable in the CIA range from ~50 to 90, which corresponds to the paleotemperature range from ~3 to 25°C. The data obtained from the CIA correspond to the paleotemperature of the earth's surface (but not the air!).

The lithological and paleontological characteristics of the section. The section (Fig. 1) is in the northwestern side of the quarry of the Bol'shevik cement plant. Sections of the environs of Vol'sk and quarries of cement plants have been studied in detail by many researchers; their description has been given in dozens of works. A list of these publications was given in (Gabdullin et al., 2014). The stratigraphic subdivision of the Upper Cretaceous deposits of the Russian Plate is based on the scheme of A.S. Alekseev, A.G. Olfer'ev, and S.M. Shik (1995). The distribution of the studied parameters along the section is shown in Fig. 2-10.

At the bottom of the quarry, the Upper Albian clay sediments (unit I) were exposed. The Upper Cretaceous (Turonian, Coniacian, Campanian, and Maastrichtian) sediments lie above the unconformity boundary.

The middle–upper substages of the Turonian stage. Turonian deposits are represented by carbonate rocks of the middle-upper stage with shells of *Inoceramus lamarki* and shells of sea urchins. These rocks with erosion overlap the Albian sandy dark gray clays.

Unit II is a marl with phosphorite nodules and levels of fragments of the incephalous prismatic layer of 2 m thick. The thickness of the inoceramic horizons decreases from 0.1–0.25 to 0.04–0.05 m from bottom to top along the section. Ferruginous chalk fragments are found. There is an analogue of a phosphorite slab (0.3 m) at the base of the unit. Marl is full of phosphorite concretions of various shapes, mostly semi-rounded. Their maximum concentration is in the middle part of the slab analogue.

Unit III is a yellow-gray chalk, sometimes silicified, 2.5 m in thickness. Microscopically, the rock is biocrystalline limestone. The sediments contain *Inoceramus lamarki*, *In. apicalis*, *Micraster corbovis*, *M. leskei*, *M. corstetudinarium*, *Conulus subrotundus*, *C. subconicus*, *Holaster planus*, *Scaphites geitnitzi*, *Lewesiceras peramplum*. The Middle Turonian age of the deposits is established by the presence of *Inoceramus lamarki*, *In. apicalis*, Late Turonian age is shown according to finds of echinoderms *Micraster corstetudinarium* and *Holaster planus*. In (Matesova, 1930) mass finds of oysters, brachiopods, teeth, and calcified vertebrae of shark fishes from the Turonian deposits are also noted. All these fossils were also found here by us. The Turonian deposits contain traces of the vital activity of *Chondrites*, *Teichichnus* and *Planolites*. There is no visual cyclicity.

The lower substage of the Coniacian tier. Unit IV. Yellow–gray chalk (microscopically biocrystalline lithoclastic limestone) 1.5–2 m thick. There is a green–gray marly chalk with phosphorite aggregates and glauconite, 0.5 m thick in the upper part. The total thickness of the Coniacian deposits is 2.5 m. The finds of *Cremnoceramus wandereri* Andert indicate that these deposits belong to the lower substage. Sea urchins are abundant in the sections of the Vol'sk region (Gerasimov et al., 1962; Matesova, 1930, 1935). Finds of oysters and ammonites was noted (Matesova, 1930). There is no visual cyclicity.

The upper substage of the Campanian Stage. Unit V. The second Campanian horizon is composed of loose writing chalk with abundant remains of sea urchins. Siliceousness to the increases roof. The unit is 2–3 m thick. The rocks contain macrofossils *Belemnitella mucronata mucronata* Schlot., *Belemnitella mucronata senior*, *Isomicraster* sp. and others.

The Campanian deposits unconformably overlap with erosion the Coniacian deposits. The amplitude of the waviness of the erosional surface can reach up to 5 cm. The deposits are represented by Upper Campanian carbonate rocks. The thickness is 6 m.

White writing chalk (microscopically biocrystalline lithoclastic limestone) with thin interlayers of greenish-gray chalk-like marl, or banded chalk, according to M.N. Matesova (1930), 2 m thickness. The boundary between the lower and upper units is erosional. The deposits composing the banded chalk unit (K_2c) are characterized in the Vol'sk region by the presence of *Belemnitella mucronata mucronata* Schlot., *Isomicraster* sp. They belong to the lower zone of the Upper Campanian *Belemnitella mucronata senior*. In the Vol'sk region, these deposits are characterized by finds of *Echinocorys* sp., *In. dariensis*, *B. m. volgensis* (Gerasimov et al., 1962).

Units VI and VII are the second–third Campanian horizons. A stratum of knotty white biocrystalline clastic marls enclosed in a gray-green biocrystalline lithoclastic marl (brecciated chalk, according to M.N. Matesova), 4-m thick. There is an erosional surface with sea urchin shells rolled into erosional niches in the middle of the upper unit. It is possible that this surface is the boundary between units V and VI. The brecciated Cretaceous sequence ($K_2cp_2^{2-3}$) in the Vol'sk region contains the rostras of *Belemnitella langei*

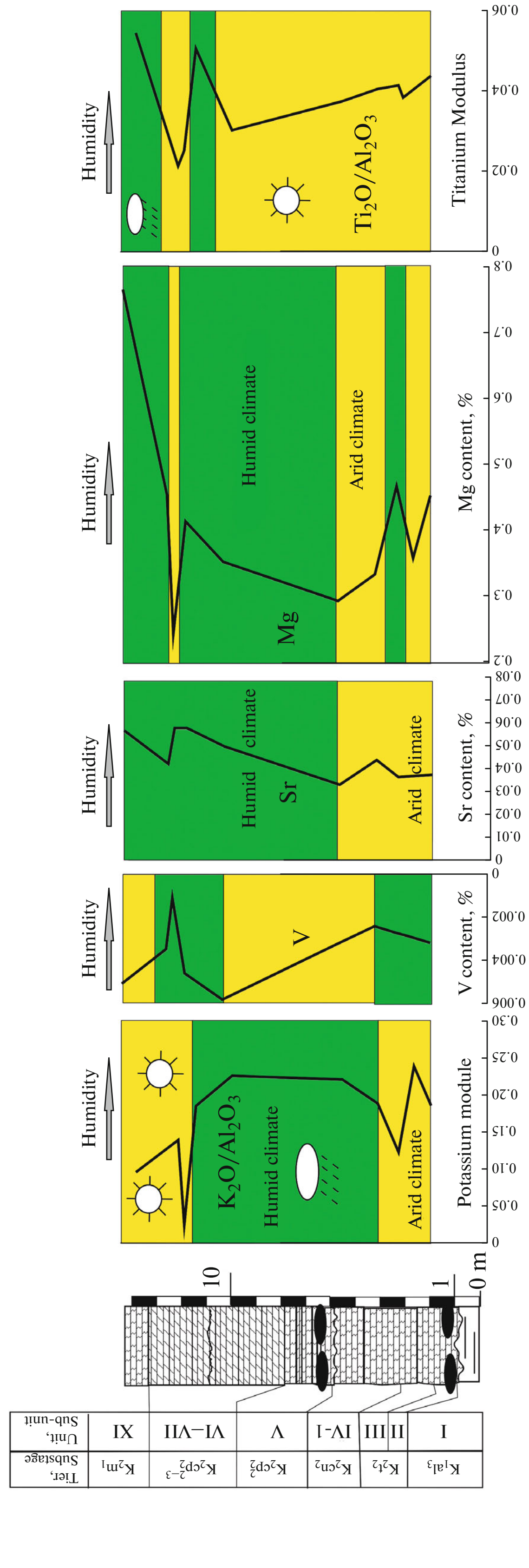

Fig. 3. Changes in the type of climate (arid/humid) in the study area in the Upper Turonian, Lower Maastrichtian.

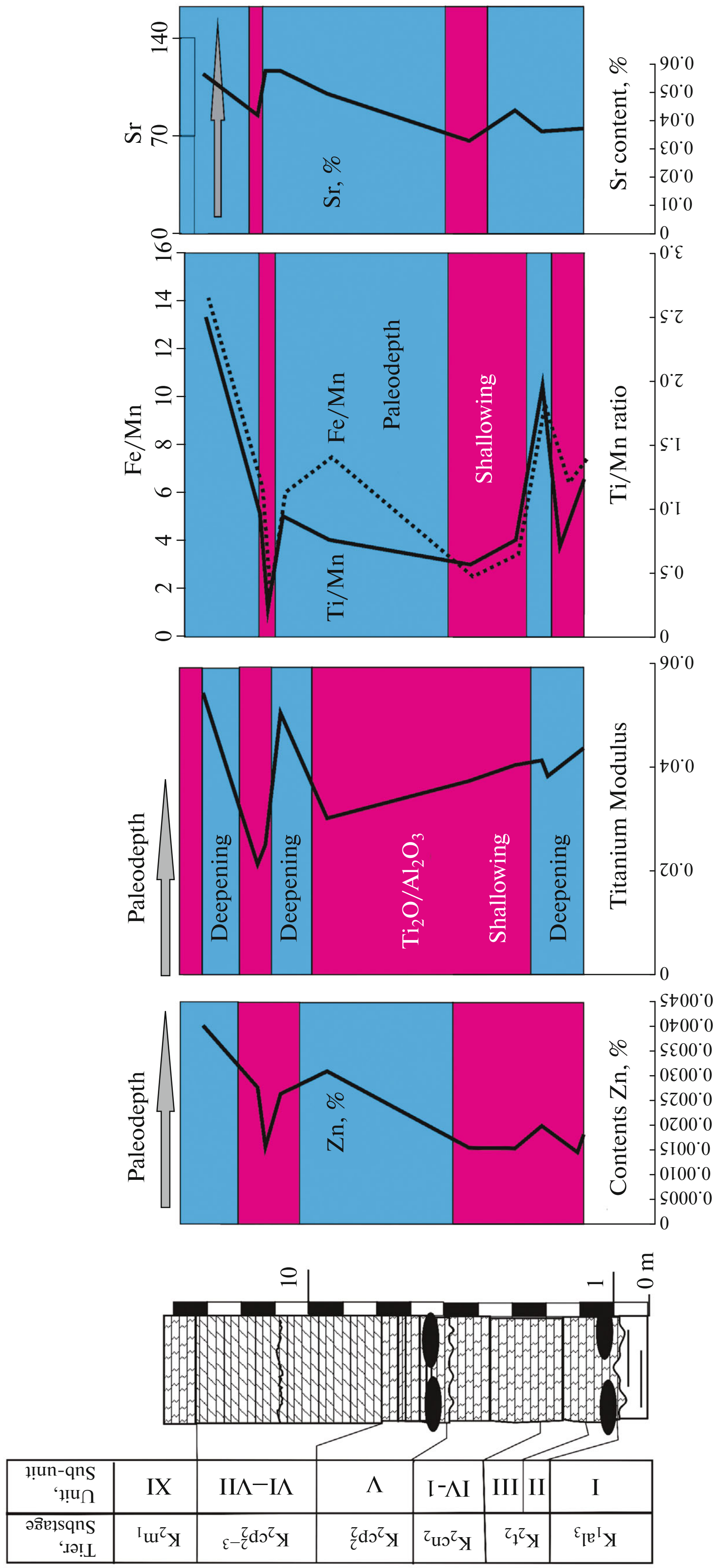

Fig. 4. The ratio of the paleobatimetry curves for the Upper Turonian–Lower Maastrichtian of the Ulyanovsk–Saratov trough, obtained from geochemical data.

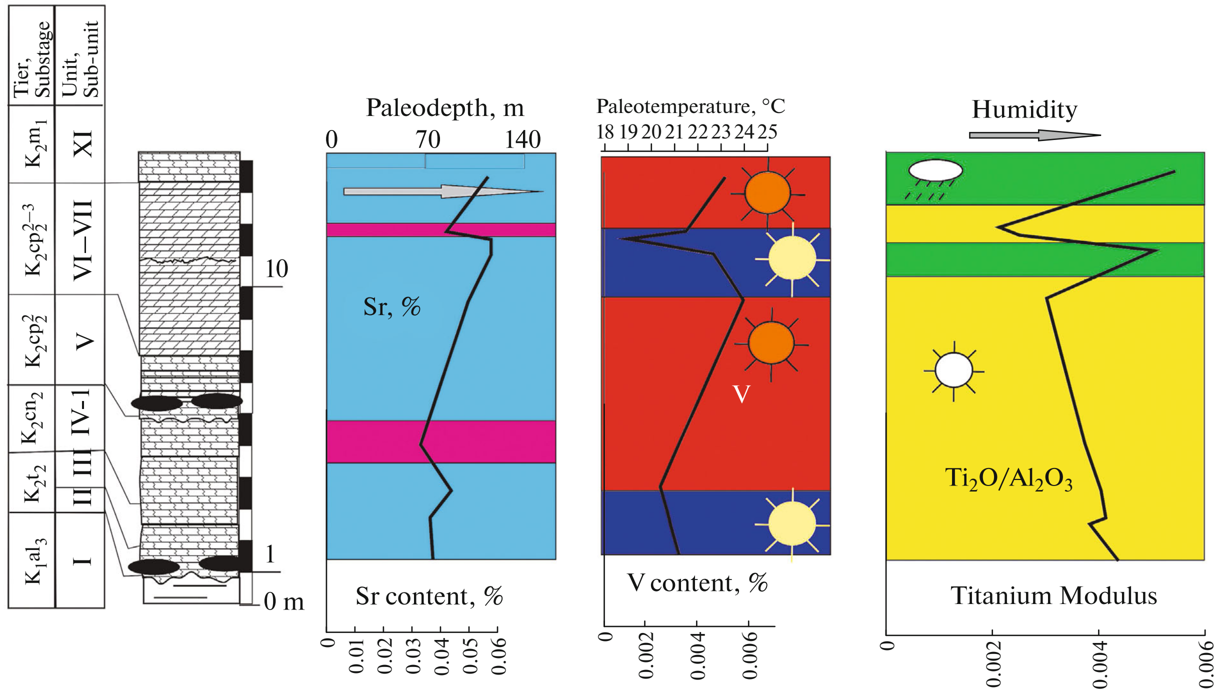

Fig. 5. Curves of changes in paleobatimetry, paleotemperature, and humidity in the sediments of the Upper Turonian–Lower Maastrichtian of the Ulyanovsk–Saratov trough, based on geochemical data.

Shatsk., *B. m. mucronata*, *B. m. senior*, as well as sea urchins *Micraster grimmensis* Nietsch. and *Coraster cubanicus* Posi. Accordingly, it belongs to the Upper Campanian and is represented by its second and third horizons (Gerasimov et al., 1962). Thus, the considered stratigraphic interval of the section is characterized by the *mucronata* and *langei* zones.

Finds of cephalopods (*Bostrychoceras*), bivalves (*Spondylus*) and scaphopods (*Dentalium*), brachiopods and solitary corals (*Parasmilia*) were also described in the Vol'sk region Campanian deposits. This interval of the section was named the Microrastrovo cemetery because of the abundance of the sea urchin shells finds (Matesova, 1930). In addition, traces of *Thallassinoides*, *Teichichnus*, and *Planolites* were found in the Vol'sk section.

Cyclicity in the thickness of the banded chalk is represented by ten type 1 cyclites: chalk (0.4–0.1 m) – clay marl (0.02–0.05 m). At the top of the more carbonate rhythm elements (MCRE), chalk layers, erosional surfaces are observed. The rhythm in the brecciated chalk is an interlayer of massive (2.5–0.6 m) and clay marls (0.03–0.05 m). Three cyclites were classified as type 2.

The lower substage of the Maastrichtian Stage. The thickness of the sediments of this interval in the Vol'sk region is up to 30–50 m. We note that there are deposits of the very first subzone ($K_2m_1^1$) – *Belemnella licharewi* in the section of the quarry of the Kommunar cement plant located nearby (Vol'sk), which are not found in the studied section. These rocks are represented by grayish-white sandy chalk with thin clay interlayers (0.3–4 m).

Unit VIII consists of white writing chalk with interlayers of greenish-gray marl (10–15 m). The Early Maastrichtian age of the deposits is confirmed by the finds of *Bel. lanceolata*, *Baculites anceps leopoldensis*, *Acanthoscaphites tridens*, *Hoploscaphites constrictus* (Gerasimov et al., 1962). This community of forms characterizes the middle subzone of the Lower Maastrichtian ($K_2m_1^2$).

The unit contains eight cyclites of type 1: writing chalk (2.5–0.2 m) – clay marl (0.03–0.17 m). The cyclites are emphasized by the weathering section and are not uniform in thickness (0.35–2.6 m).

The lower–upper substage of the Maastrichtian stage. Unit IX. Writing chalk with interlayers of clays and marls, alternating at the top with glauconite sandy marls, 30–57 m thick.

The unit is represented by white writing chalk (>30 m). The third subzone of the Lower Maastrichtian ($K_2m_1^3$) is established in the studied section based on *Bel. lanceolata sumensis*, *Bac. anceps leopoldensis*, *Asc. tridens*, *H. consitrictus*, *In. balticus* Boehm. Upper Maastrichtian deposits (K_2m_2) compose the upper 10 m of the section. The unit is represented by type 1 cyclites: writing chalk (1.1–2 m) – clay marl, clay (0.03–0.05 m). X-ray phase analysis showed that most of the clay interlayers are clay writing chalk. Cyclites

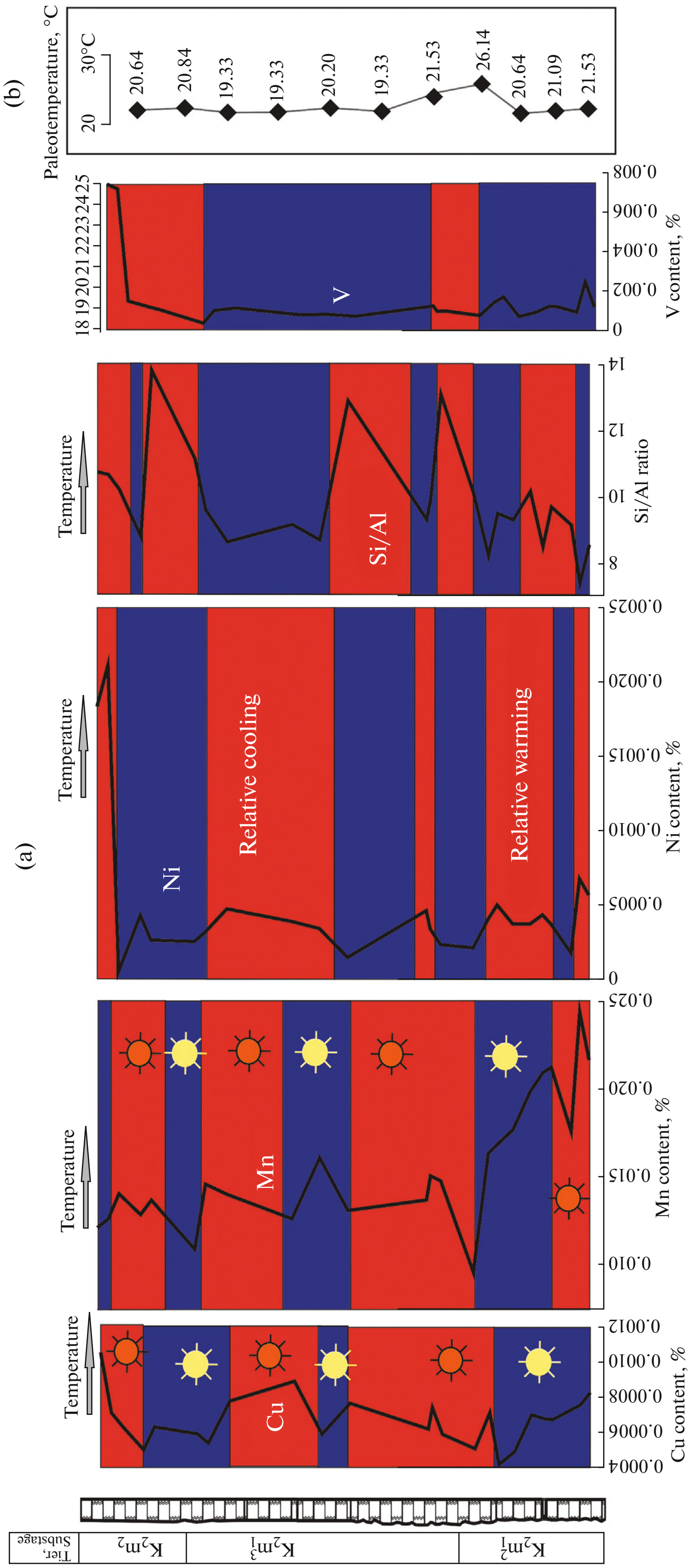

Fig. 6. Variations in paleotemperature values: (a) in areas of denudation (obtained by us from geochemical data); (b) paleotemperature curve according to isotopic paleothermometry data.

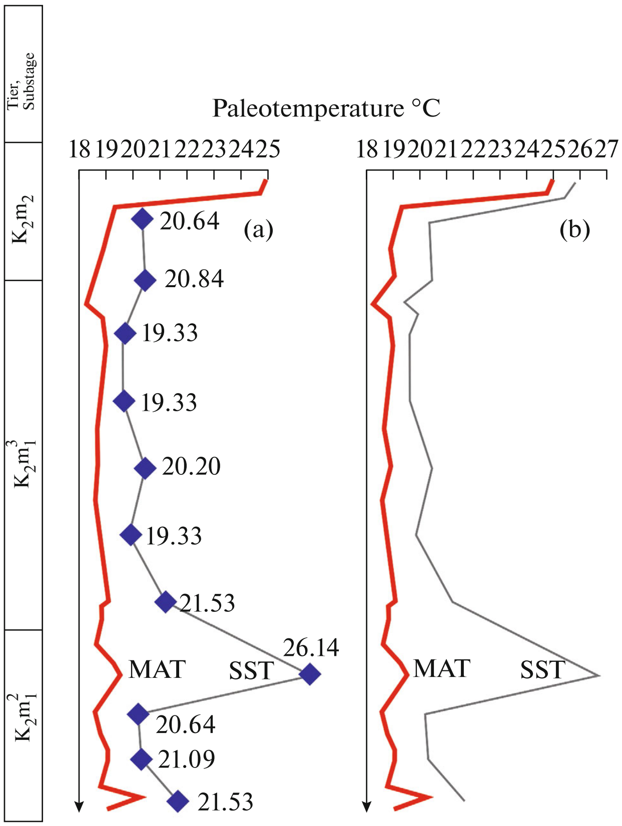

Fig. 7. Paleotemperature curves for Maastrichtian (MAT, average annual, SWT, surface water): (a) those we received via the weathering index according to geochemical data (left) and according to isotope paleothermometry (Badulina et al., 2016) (right); (b) corrected versions of the same paleotemperature curves.

are well manifested in the weathering section and are well sustained in thickness (1.15–2.05 m). Moreover, it is possible to isolate higher order cyclites by grouping them into pairs. In other words, 1-m-thick cyclites regularly alternate with 2-m-thick cyclites. Thus, it is possible to distinguish eight cyclites of the third order and four cyclites of the second order in the interval of 12 m from the base of the unit. The stratum is then acyclic for 11 m, and then two chalk–clay cyclites of the third order (thickness of rhythms 1–2.5 m) or 1 cycle of the third order are observed. Then, over 10 m, the thickness is also acyclic. Acyclic intervals that are 10—12-m thick are possibly elements of the first-order cyclite, alternating with cyclical intervals.

The Maastrichtian rocks in the Vol'sk region also contain cidaroids (*Cidaris*, *Salenia*), spatangoids (*Echinocorys*), oysters (*Pycnodonte*, *Hyotissa*, *Ostrea*), pectenids (*Spondylus*, *Chlamys*, *Cyosira*), sponges and corals (*Ventricul*); brachiopods and gastropods (*Pleurotomaria*?) are rare (Matesova, 1930, 1935). They contain ichnofossils *Thallassinoides*, *Teichichnus*, and *Planolites*.

RESULTS AND DISCUSSION

The geochemical characteristics of the section. The geochemical data allowed us to calculate the concentrations (ppm) of 29 elements and compounds, as well as six of their ratios (moduli) required to clarify the conditions of sedimentation and the genesis of cyclicity. Many works have been devoted to the description of this technique (Engalychev, Panova, 2011; Climate ..., 2004; Sklyarov, 2001). The data we obtained in the context of their paleogeographic interpretation are

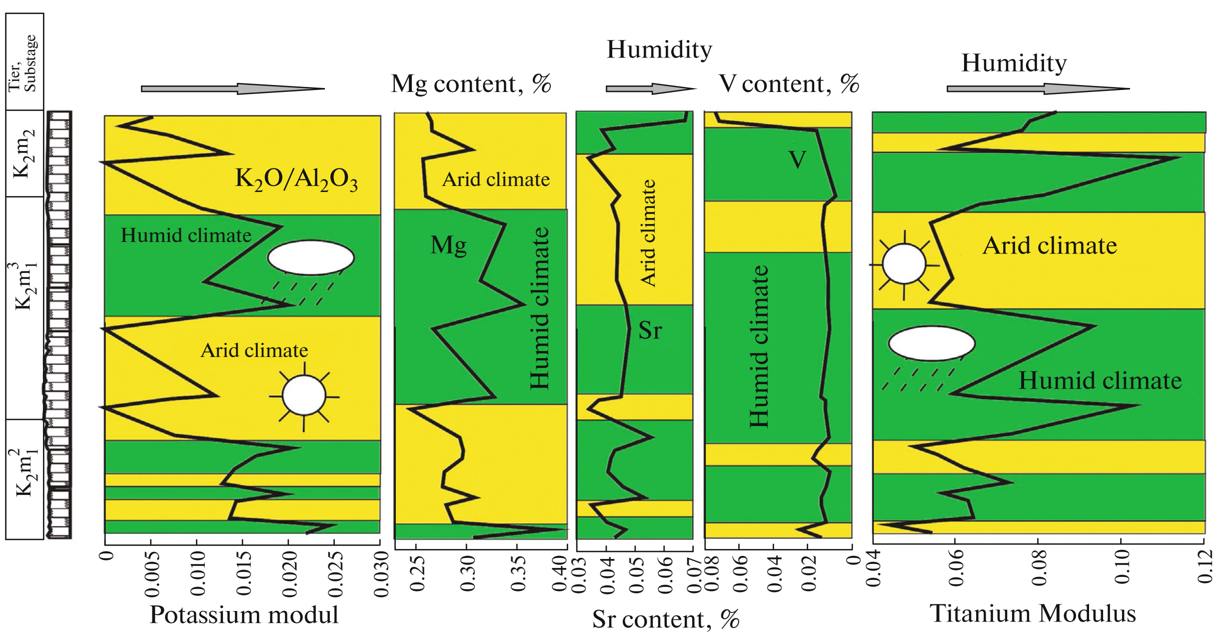

Fig. 8. The changes in the type of climate (arid/humid) in the study area in the Maastrichtian.

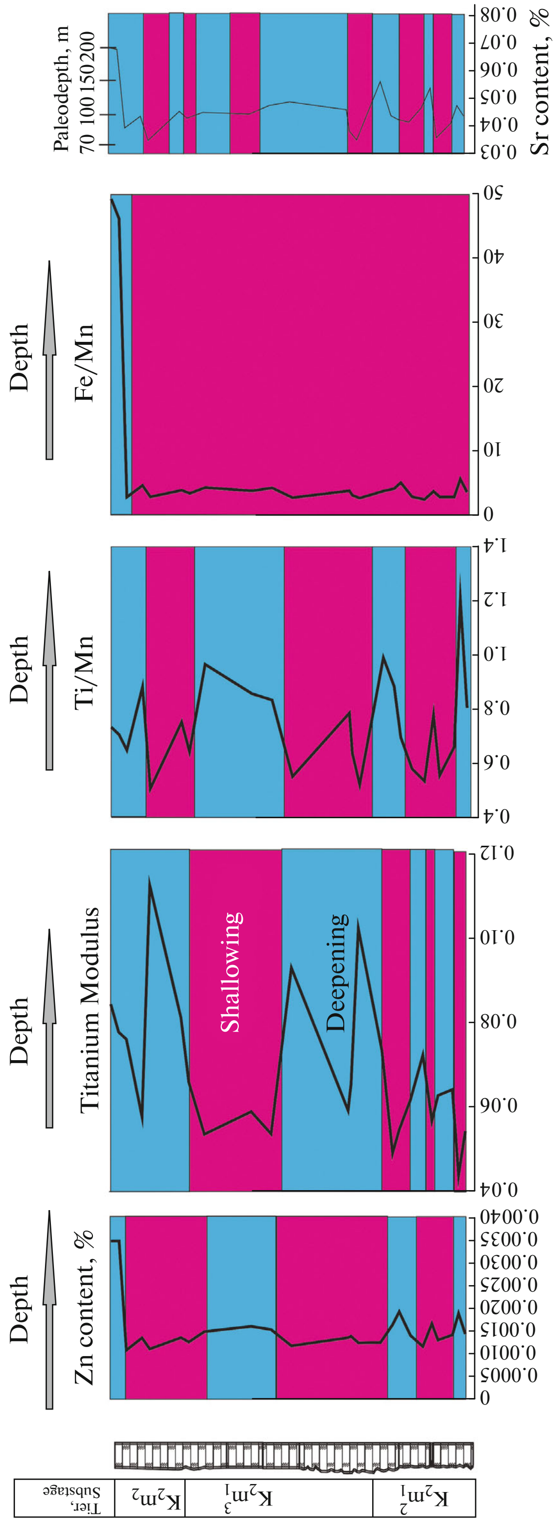

Fig. 9. The ratio of the paleobatimetry curves for the Maastrichtian part of the section, obtained from geochemical data.

often contradictory, which requires their comparison with the results of other studies. Let us briefly and selectively characterize the concentrations of elements, compounds, and their relationships.

Variations in the paleotemperature were established by the titanium modulus, the content of vanadium, copper, manganese, nickel, and the Si/Al ratio (Fig. 2, 6). A high degree of correlation is characteristic of vanadium and copper and TM. The concentrations of manganese and nickel and the Si/Al ratio are correlated. One can distinguish phases of warming and cooling of the climate on the basis of these correlations. The established phases of relative climate warming correspond to an increase in the concentration of organic carbon (C_{org}) and calcium carbonate ($CaCO_3$) in the Turonian–Campanian interval of the section. They were determined in (Gabdullin et al., 2014). At the same time, in the Campanian–Maastrichtian interval of the section no relationship between an increase in paleotemperature and an increase in the content of calcium carbonate has been revealed. The relationships between variations in the area (volume) of bioturbated rocks, the number of ichnotaxons, and the diameter of their burrows with temperature changes have not been established. The curve of changes in the V content was taken as the temperature variation curve.

It became possible to move from a qualitative graph to quantitative values based on the results of determining the values of paleotemperature by the weathering index (Table 1). The resulting paleotemperature range at the Earth's surface on paleo-uplifts (in areas of denudation), 19–25°C, is close to the range of values previously obtained by isotope paleothermometry (Teis, Naidin, 1973) (Fig. 2, B; 6, B; 7) for comparatively deep-sea epicontinental basins of the Russian Plate in the second half of the Turonian (14–15°C), the second half of Coniacian (13-15°C), and the second half of the Campanian (13–14°C). The established range of paleotemperature values according to the weathering index (19–25°C) is in good agreement with the values (19–26°C) obtained earlier by isotope analysis of the stable oxygen isotopes composition using a Delta V Advantage instrument for the Maastrichtian interval of the section (Badulina et al., 2016), as well as organisms–indicators of paleotemperature. In particular, the Maastrichtian interval of the section is characterized by corals (*Cylicosmilia* sp.) that live in water with temperatures above 20°C and bivalve pectenids (*Janira* sp.) that live in waters with a temperature of at least 23.5°C (Gabdullin, Ivanov, 2002). The relatively cool waters of the Turonian time gradually warmed by the Coniacian time (as indicated by the content and ratio of Ca and Mg) (Gabdullin et al., 2014).

In the Turonian–Campanian interval, a climatic cyclicity can be distinguished, including periods of relative cooling (Turonian–Cognac) with a paleotem-

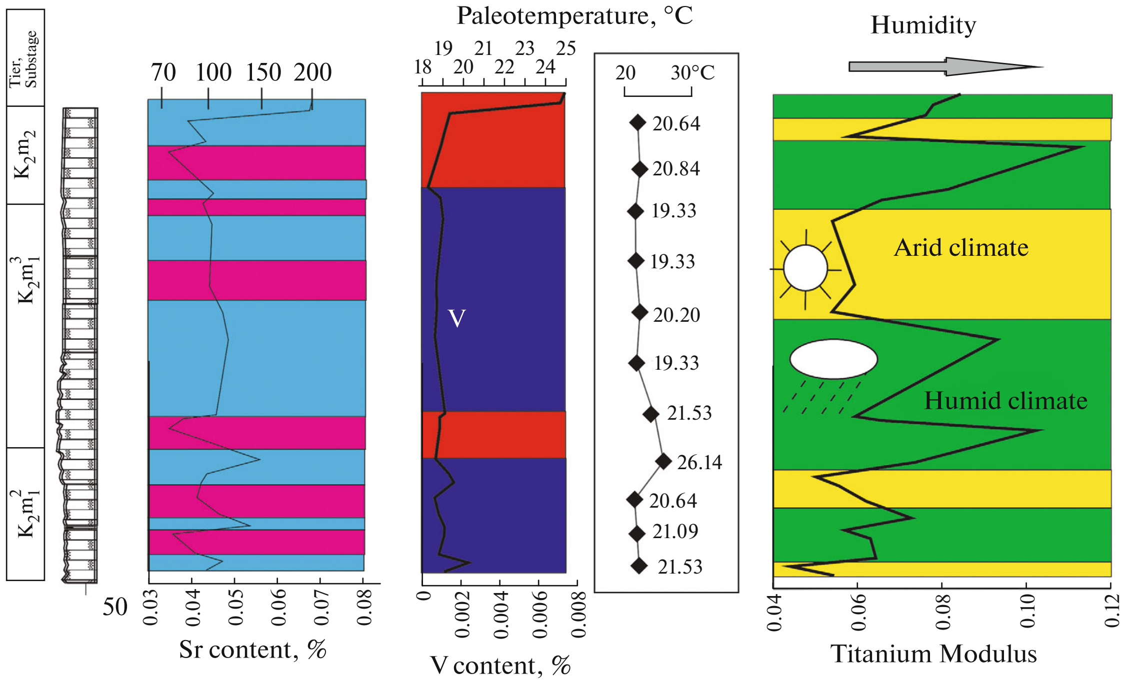

Fig. 10. Curves of changes in paleobatimetry, paleotemperature, and humidity in the Maastrichtian sediments of the Ul'yanovsk-Saratov trough, constructed from geochemical data.

perature of approximately 20°C, an epoch of relative warming in the middle of the late Campanian (20–24°C), an epoch of cooling at the end of the late Campanian (19–21°C) and a warming era at the Campanian–Maastrichtian boundary and in the early Maastrichtian. In the Maastrichtian, two climatic cycles have been identified, beginning with a time of relative cooling (approximately 19°C) and ending with a time of relative warming (approximately 20°C, at the end of the Maastrichtian up to 25°C). The calculated values of paleotemperature according to the weathering index can be identified with the average annual temperature (AAT), while the surface water temperature (SWT) can be estimated to have had values 1–2°C higher than AAT.

Humidity variations are seen on the curves of TM, PM, vanadium, strontium, and magnesium contents (Fig. 3, 8). These graphs are weakly correlated with each other (only in certain intervals). SM was chosen as a parameter for assessing the humidity of the climate, which has a high degree of correlation with the contents of $C_{org.}$ and $CaCO_3$ and was determined earlier in (Gabdullin et al., 2014). In the era of humidization of the climate in the Campanian period, the contents of $C_{org.}$ and $CaCO_3$ increased, while in the era of aridization, these indicators decreased. In the Turonian–Coniacian time, the maximum $C_{org.}$ content corresponded to the minimum of $CaCO_3$ under conditions of aridization of the climate. In the Maastrichtian time, variations in the content of $C_{org.}$ and $CaCO_3$ were minimal. The humid type of climate in the Turonian was replaced by arid conditions for the Coniacian (TM and Mg content) (Gabdullin et al., 2014). Based on the variations in the TM curve, two cycles of climate humidity change in the Campanian time and three cycles in the early Maastrichtian time, and one cycle in the late Maastrichtian time were identified. The boundary between the Early and Late Maastrich-

Table 1. Paleotemperature values calculated from the weathering index

Number	Laboratory sample number	Sample	CIA	*T*, °C
1	X10833	Vol'sk10	83	21
2	X10834	Vol'sk11	79	19
3	X10835	Vol'sk13	88	24
4	X10836	Vol'sk15	83	21
5	X10837	Vol'sk18	81	19
6	X10838	Vol'sk28	80	19
7	X10839	Vol'sk33	83	21
8	X10841	Vol'sk35	87	23
9	X10842	Vol'sk43	91	25
10	X10844	Vol'sk46	79	19

In the studied sediments, to calculate the CIA and paleotemperature values, we used the samples with the highest amount of terrigenous admixture. The content of SiO_2 >5% and Al_2O_3>1% was taken as a criterion.

tian corresponds to a change from arid conditions to humid ones. According to TM, the Turonian–Coniacian time is interpreted as arid. According to the graphs of other parameters, two cycles of humidity changes in the Turonian–Coniacian interval (magnesium content) or one (strontium and vanadium concentration) can be distinguished.

Paleosalinity variations are manifested on the curves of the Sr/Ba ratio (due to the lithological specificity of the deposits and the associated low content of the terrigenous admixture, with which Ba is associated; the curves can be plotted only for fragments of the section). The presence of echinoderms and brachiopods in the Turonian, crustaceans (traces of *Thallassinoides*) and rare pelecypods in the Coniacian deposits, as well as the Ti/Mn ratio for the Turonian Coniacian interval, confirm the normal salinity of the basin in the indicated time range (Fig. 4, 9). At the end of the Turonian, a decrease in salinity (Sr/Ba ratio) was noted, which is associated with a decrease in the depth of the paleobasin in combination with a possible increase in river runoff, which caused desalination. The finds of stenohaline corals, echinoderms, and crustaceans (traces of *Thallassinoides*) indicate the normal paleosalinity in the Campanian. For the Maastrichtian part, stenohaline pleurotomaria, corals and oysters of the genus *Pycnodonte* (12–30‰) are important indicators of normal salinity conditions. At the end of the Maastrichtian an increase in salinity is manifested on the curves of indicator elements (Sr and Zn).

Variations in the paleo-depth are visible on the curves of changes in the contents of Zn, Sr, and the titanium modulus (TM), as well as on the curves of the Ti/Mn and Fe/Mn ratios (Figs. 4, 9). The values of the Ti/Mn and Fe/Mn ratios demonstrate good agreement and allow one to identify general trends. Intervals of relative deepening and shallowing of the epicontinental basin have been identified. A correlation has been established between the increase in paleodepth (under conditions of transgression) using several parameters determined earlier (Gabdullin et al., 2014), in particular, by the concentration of $C_{org.}$ and $CaCO_3$. As well, with the deepening of the basin, an increase in the area (volume) of bioturbated rocks, the number of ichnotaxa, and the diameter of their burrows was noted. In general, the conditions in the second half of the Turonian were relatively shallow (less than 100 m), while in the Coniacian, Campanian, and Maastrichtian they were relatively deep-water, corresponding to the pelagic zone with a depth of more than 100 m according to (Gabdullin, 2002) or 130–200 m according to (Bondarenko, 1990). The graphs of the Ti/Mn and Fe/Mn ratios show a decrease in the basin depth in the Coniacian time and at least three eustatic cycles in the Maastrichtian time.

The epochs of shallowing and deepening of the basin are clearly distinguished on the graphs of the Zn and Sr contents and variations of TM. All three graphs show regressive epochs at the end of the Coniacian, at the end of the Campanian, at the end of the early, and again at the end of the late Maastrichtian.

The changes in the Sr concentration were used to assess the changes in paleobatimetry,. On the corresponding curve, transgressive–regressive cycles are distinguished: in the Late Turonian–Coniacian time one cycle occurred, in the Late Campanian time it was two cycles, in the Early Maastrichtian time, five cycles, and in the Late Maastrichtian time, one cycle. We estimated the depth variations in the studied section in the range of 75–200 m. The paleodepth of the basin is estimated to have been 70–80 m in the Turonian–Coniacian time.

In the Turonian age, the accumulation of mainly carbonate silts and terrigenous phosphorite-bearing sediments occurred in relatively shallow-marine conditions (Gerasimov et al., 1962). The basin was relatively shallow, as shown by the Ti/Mn and TM ratios. In the Coniacian time, the depth of the basin increased slightly (as shown by the Ti/Mn ratio and TM), while eustatic fluctuations occurred in the Turonian and in the Coniacian (TM, SM, PM, and S concentrations) (Gabdullin et al., 2014).

In the Campanian–Maastrichtian time, the paleodepth consistently increased and varied from 100 to 200 m (on average, approximately 150 m). This is indicated by the low biodiversity of the paleocenosis represented by two species of inoceram in the Campanian period. The fauna complex is represented by echinoderms, which could feed on sponges (this indicates the possibility of the existence of sponges in this part of the paleo basin, despite the absence of their remains). All these forms lived at a depth of at least 100 m (lower sublittoral–bathyal), and relatively shallow-water forms: oysters, bivalves–pectenids, very few in number, as a rule, oppressed and, possibly, allochthonous.

CONCLUSIONS

As a result of the interpretation of geochemical data, qualitative and quantitative characteristics of changes in the main paleogeographic parameters of the paleo–basin in the region of the Ulyanovsk–Saratov trough and adjacent denudation areas were obtained (Fig. 5, 10). The paleotemperatures of the earth's surface in the areas of denudation have been calculated and the corresponding cycles have been identified. Thus, in the Turon Campanian interval, a climatic cyclicity has been identified, including epochs of relative cooling (Turonian–Coniacian) with a paleotemperature of approximately 20°C, an epoch of relative warming in the middle of the late Campanian (20–24°C), and an epoch of cooling at the end of the late Campanian (19–21°C) and a warming era at the Campanian–Maastrichtian boundary and at the beginning of the Maastrichtian.

In the Maastrichtian, two climatic cycles have been identified, beginning with a time of relative cooling (approximately 19°C) and ending with a time of relative warming (approximately 20°C, at the end of the Maastrichtian up to 25°C). Cycles of humidity changes in the climate were also revealed: two cycles in the Campanian time, three cycles in the early Maastrichtian, and one cycle in the late Maastrichtian. The boundary between the Early and Late Maastrichtian corresponds to a change from arid conditions to humid ones. Transgressive–regressive cycles are distinguished on the curves of paleobathymetry: one in the late Turonian–Coniacian time, two in the late Campanian time, five in the early Maastrichtian time, and one in the late Maastrichtian time. The depth variations were estimated: in the Turonian–Coniacian time they occurred in the range of 70–80 m, while in the Campanian–Maastrichtian time the paleodepth varied from 100 to 200 m, on average approximately 150 m.

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