*ISSN 0869-5938, Stratigraphy and Geological Correlation, 2014, Vol. 22, No. 5, pp. 518–537. © Pleiades Publishing, Ltd., 2014.*
*Original Russian Text © V.N. Beniamovskii, A.S. Alekseev, A.V. Podgaetskii, M.N. Ovechkina, V.S. Vishnevskaya, L.F. Kopaevich, V.G. Pronin, 2014, published in Stratigrafiya. Geologicheskaya Korrelyatsiya, 2014, Vol. 22, No. 5, pp. 77–96.*

# Upper Campanian–Lower Maastrichtian Sections of Northern Rostov Oblast: Article 2. Depositional Environments and Paleogeography

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Received November 26, 2012; in final form, May 29, 2013

**Abstract**—The study present the results of the integrated study on the Belgorod and Pavlovka formations (upper Campanian), Sukhodol Formation (Campanian–Maastrichtian), and Efremovo-Stepanovka Formation (Maastrichtian). Variations in lithological indicators and associated changes in the biotic assemblages were used to distinguish three stages in the basin evolution separated by hiatuses (Belgorod–Pavlovka, Sukhodol, and Efremovo-Stepanovka). This basin occupied the upland area in the north of the Paleozoic Donets Basin during late Campanian–early Maastrichtian times. Each stage was characterized by a specific depositional environment accompanied either by a decrease or by an increase in the terrigenous sediment supply from the Donets Basin and, possibly, Ukrainian Shield and sea-level and temperature fluctuations, as well as specific paleobiogeographic relations. During the Belgorod–Pavlovka stage, the basin was characterized by relatively deep-water environments, with warm waters and normal salinity, and predominantly carbonate sedimentation. The Sukhodol stage was marked by terrigenous sedimentation, a predominance of the agglutinated foraminiferal forms, and abundant radiolarians, which occurred during a marine regression and overall cooling. This stage corresponds to the global "Campanian–Maastrichtian boundary event." The first half of the Efremovo-Stepanovka stage was marked by resumed carbonate sedimentation, warming, transgression, and deepening of the basin, which were replaced by a renewed regression at the end of this time interval.

*Keywords*: upper Campanian, lower Maastrichtian, depositional environments, paleogeography, biotic and abiotic events, Rostov oblast, Russia

**DOI:** 10.1134/S0869593814050037

## INTRODUCTION

It has been more than a half-century since the publication of the paper by Lipnik and Tkachenko (1960) on upper Campanian and lower Maastrichtian deposits of the northern Donets Basin. This paper dealt with a reference section described in a borehole drilled near the village of Kruzhilovka, at the border between Lugansk oblast, Ukraine, and Rostov oblast, Russia, in the vicinity of the folded Donets Basin. This section consists of three lithologic units (Pavlovka, Sukhodol, and Efremovo-Stepanovka formations): a lower marl, containing abundant upper Campanian calcareous secreted benthic foraminifera; a middle silt, which contains, along with secreted foraminifers species, an abundant primitive agglutinated benthic foraminiferal fauna and radiolarians; and an upper marl with a lower Maastrichtian secreted benthic foraminiferal assemblage.

The middle terrigenous unit (Sukhodol Formation) is widespread at the northern margin of the Donets Basin and in Rostov oblast in Russia. The presence of lithologically similar siliceous strata of the Nalitovka Formation occurring farther north in the Saratov Volga region (Naidin et al., 2008) may indicate that these two formations, which appear to be coeval, were presumably deposited in similar marine environments within the same marine basin. Since the Nalitovka Formation is now recognized to be older, the reconstruction of depositional environments of the Sukhodol Formation is a contentious issue and is the focus of the present study. The results of lithologic and mineralogical analysis were used in this study to reconstruct the depositional environments at the Campanian–Maastrichtian boundary.

In the previous paper (Beniamovskii et al., 2012), we presented a complete description and subdivision of the studied sections (Tarasovskii 1 and 2, Rossypnoye, Efremovo-Stepanovka, and Znamenka 1A Borehole; Fig. 1), introduced a new lithostratigraphic subdivision into formations, proposed a new zonation scheme, and determined the age of the identified stratigraphic units on the basis of benthic foraminiferal assemblages, radiolarians, calcareous nannoplankton, and belemnites. The aim of this study is to interpret and reconstruct changes in the late Campanian–early Maastrichtian depositional environments and paleogeography at the northern margin of the Donets Basin induced by global and regional events.

## MATERIALS AND METHODS

Lithological and mineralogical analysis was conducted on samples collected at 0.5–1 m intervals for microfaunal determination. A total of 38 standard thin sections were prepared from samples collected from the Efremovo-Stepanovka section and examined by A.S. Alekseev under a Carl Zeiss Axiolab petrographic microscope.

The $CO_2$ content measured at the Geological Institute, Russian Academy of Sciences (Moscow), was used to determine the total carbonate mineral content ($CaCO_3$) of the rock samples collected from the Efremovo-Stepanovka section. Samples taken from Rossypnoye, Tarasovskii 1 and 2, and Borehole 1A sections were prepared using the same preparation method: samples of 10 g of rock were ground to a fine powder and dissolved with 15% acetic acid. The $CaCO_3$ content of the samples was determined as weight loss by measuring the released $CO_2$ with 2% accuracy. The calcium carbonate content was determined for more than 100 samples. Variations in the calcium carbonate content of sediments from the Rossypnoye, Efremovo-Stepanovka, and Znamenka 1A Borehole sections were shown in the previous paper (Beniamovskii et al., 2012).

The mineral compositions of 24 samples (Fig. 2, Table 1) were analyzed by powder X-ray diffraction with a DRON 3.0 diffractometer at the Institute of Comprehensive Exploitation of Mineral Resources, Russian Academy of Sciences (Moscow). The 0.063-mm grain size fraction for XRD analysis was prepared by grinding in an agate mortar and was subsequently mounted in a quartz platelet with a film of petroleum jelly. Scans were run continuously between 6° and 80° 2Θ with Cu$K_\alpha$ radiation generated at 35 kV and 20 μA, using a monochromator and a rotating sample holder, at a scanning speed of 2°/min. The resulting X-ray diffraction data were registered and processed using the X-RAY software program (Moscow State University). Clay mineral identification and analysis was performed using oriented specimens of the <0.002-mm size fraction of both air-dried and glycerol-solvated samples at a scanning speed of 1°/min. The results of XRD semiquantitative analysis are reported as percent crystallinity (i.e., not accounting for the amorphous fraction). Feldspars are reported as the total amount of microcline and plagioclase. Illite is probably a mixed-layer/illite association (X-ray amorphous phase) ($d \sim 7.0$ Å). The mineralogy of the carbonate-free fraction (clay minerals, in particular) was determined on the insoluble residue from three samples using XRD techniques (Fig. 2). Carbonates were removed by treatment with cold 3% HCl solution by G.N. Aleksandrova at the Laboratory of Paleofloristics of the Geological Institute, Russian Academy of Sciences (Moscow).

The whole-rock chemistry of three representative samples was determined by silicate analysis following a standard procedure at the Geological Institute, Russian Academy of Sciences (Moscow) (Table 2).

The chalk and marl classification used in this study for the Upper Cretaceous section of the adjacent Dnieper–Donets basin was adopted from Bushinskii (1954). Unlike many other classifications restricted to a single variety of carbonate minerals, this classification is suitable for distinguishing between different carbonate varieties in the carbonate-bearing intervals, which allowed us to identify the distinctive lithologies of the formations.

## LITHOLOGY

Thin sections of samples were used to describe the lithologies encountered in the Efremovo-Stepanovka section, where all formations are present except the Belgorod Formation.

The Pavlovka Formation (Samples ES-1–ES-3) consists of silty marls, containing numerous pockets of silt- and sand-size quartz grains (up to 10%), rounded and subangular grains (up to 0.1 mm in diameter) of light green glauconite (from isolated grains up to 5%), and occasional mica flakes. Samples ES-2 and ES-3 contain abundant fragments of siliceous sponge spicules (up to 10% of the thin section area). Benthic foraminiferal tests and thin-shelled bivalves are rare. It should be noted that Sample ES-1 contains a single oval-shaped (0.5 mm in diameter) grain of quartzite.

The Sukhodol Formation (Samples ES-6–ES-30) consists at its base (Sample ES-6) of argillaceous siltstones with intense bioturbation and abundant silt-size and larger (up to 0.1 mm across) angular quartz grains. The rock sample also contains many scattered small (up to 0.15 mm), rounded glauconite grains (3–5%) and numerous tiny mica flakes. Upward, the section consists (samples ES-11 and ES-12) of argillaceous siltstone and silty clay with minor amounts of fine-grained glauconite (1–3%) and small (up to 0.2 mm) mica flakes (1–3%). The

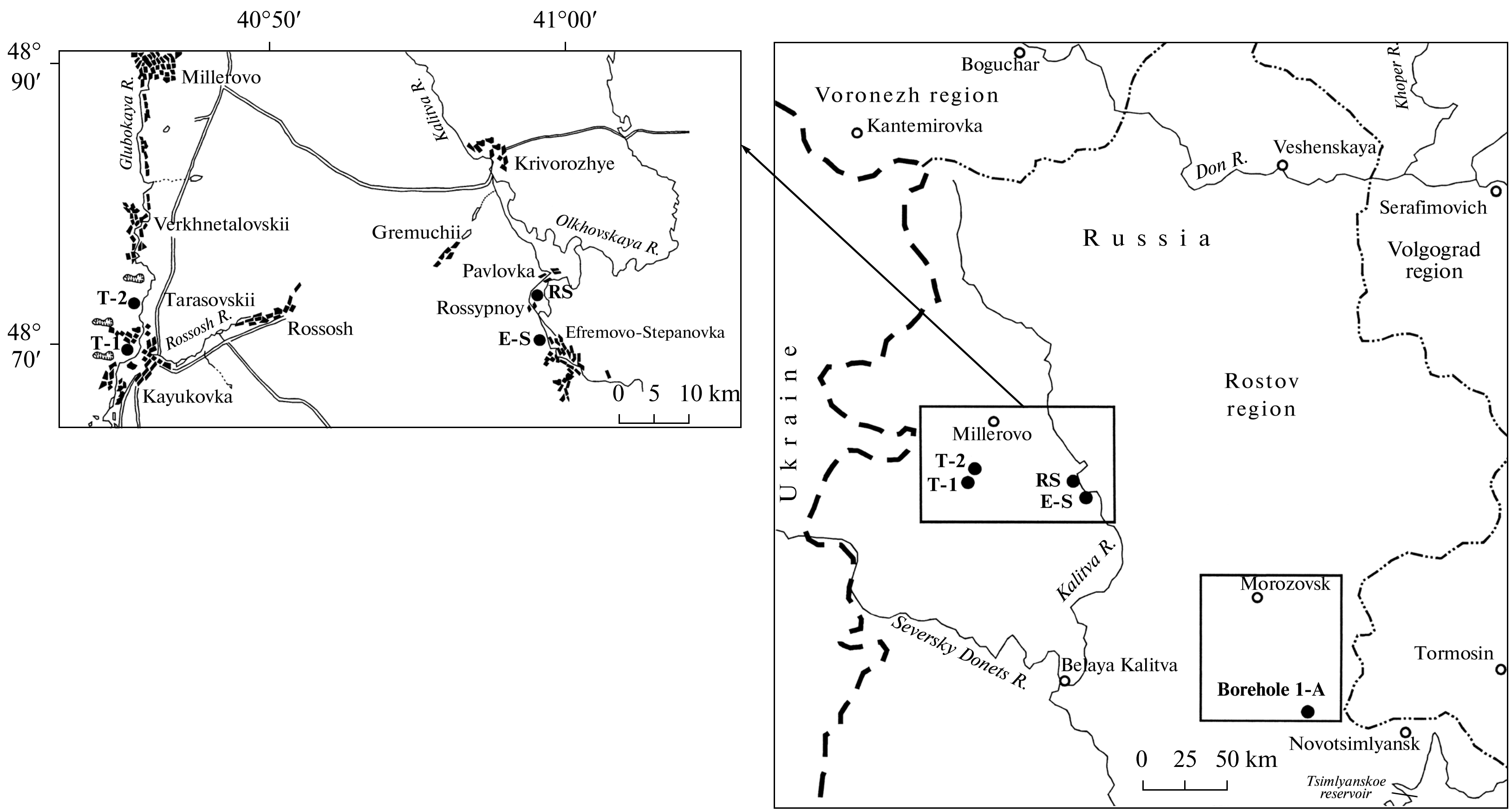



**Fig. 1.** Geographical map of northern Rostov oblast. Shown are sites of studied sections: T-1 and T-2—Tarasovskii 1 and 2; RS—Rossypnoye; E-S—Efremovo-Stepanovka; also, Znamenka 1A Borehole.

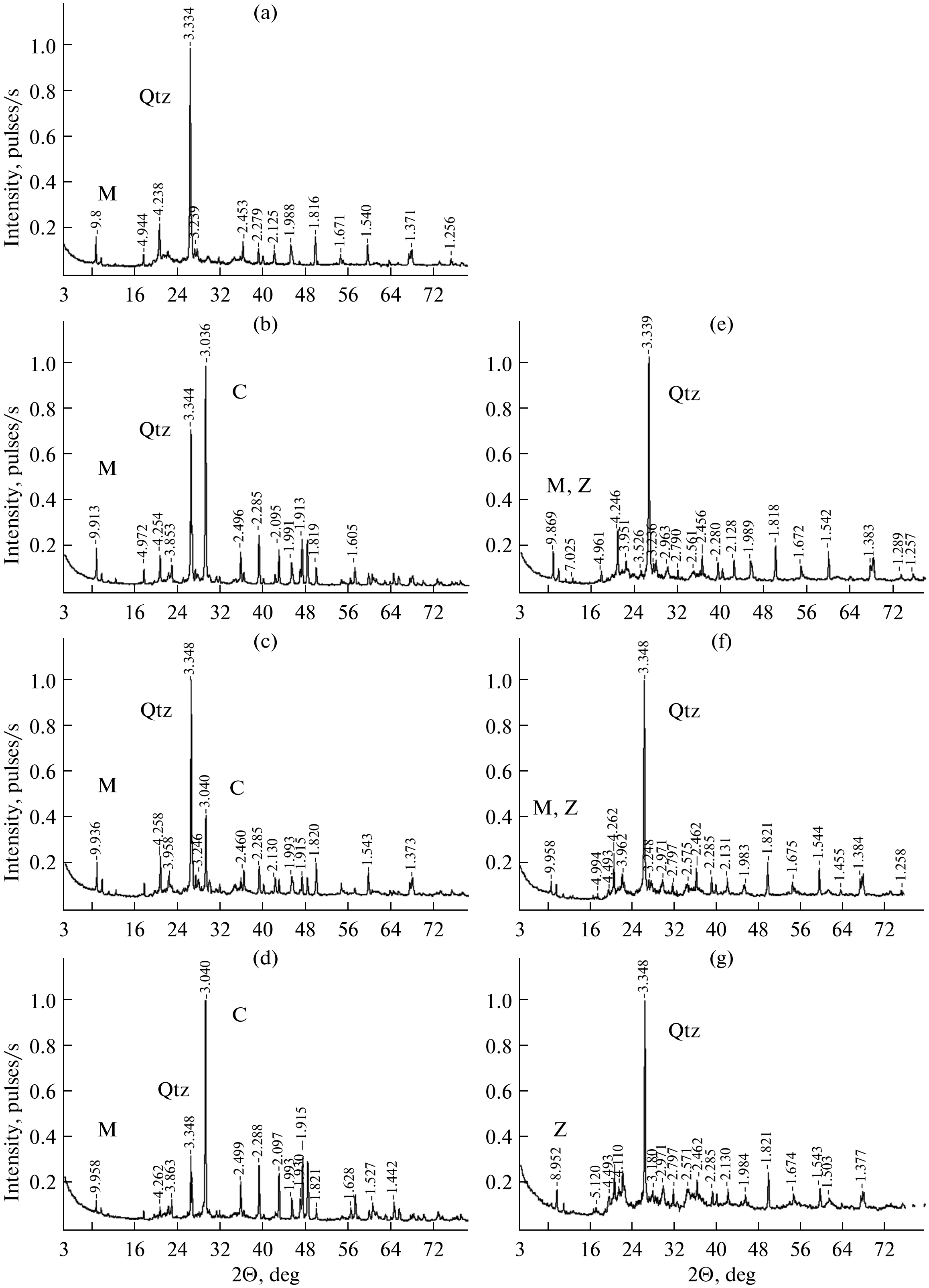


**Fig. 2.** X-ray diffraction patterns of carbonate rocks and insoluble residues from the Efremovo-Stepanovka section. (a, b) Efremovo-Stepanovka: (a) opoka-like clay (Table 2, Sample ES-50), (b) argillaceous marl (Table 2, Sample ES-40); (c) Sukhodol Formation, calcareous clay (Table 2, Sample ES-21); (d) Pavlovka Formation, argillaceous marl (Table 2, Sample ES-2), (e–g) insoluble residue of samples ES-40, ES-21, and ES-2, respectively. Mineral abbreviations: Qtz—quartz, C—calcite, M—mica, Z—zeolite.

**Table 1.** The results from XRD measurements at Rossypnoye and Efremovo-Stepanovka sites

| No. | Sample no. | Rock type | Mineral composition (rock-forming minerals in % of crystalline phase) | | | | | Formation |
|---|---|---|---|---|---|---|---|---|
| | | | calcite | quartz | feldspar | mica | zeolite | |
| **Rossypnoye** | | | | | | | | |
| 1 | RS-3 | Carbonate | 94.2 | 2.4 | n/d | 0.3 | 3.1 | Belgorod |
| 2 | RS-5 | | 94.2 | 2.6 | n/d | 0.6 | 2.7 | |
| 3 | RS-6 | | 79.1 | 12.9 | n/d | 1.6 | 6.5 | Pavlovka |
| 4 | RS-9 | | 83.7 | 11.1 | n/d | 1.0 | 4.2 | |
| 5 | RS-13 | | 83.6 | 9.1 | n/d | 1.8 | 5.6 | |
| 6 | RS-18 | | 76.2 | 15.3 | n/d | 1.7 | 6.8 | |
| 7 | RS-23 | | 75.2 | 16.3 | n/d | 2.2 | 6.3 | |
| 8 | RS-24 | Terrigenous | 12.5 | 63.9 | 10.3 | 4.8 | 8.4 | Sukhodol |
| 9 | RS-27 | | 21.5 | 44.9 | 17.1 | 6.8 | 10.2 | |
| 10 | RS-32 | | 20.3 | 40.0 | 16.7 | 6.5 | 16.6 | |
| 11 | RS-37 | | 22.2 | 52.6 | 14.8 | 2.5 | 7.9 | |
| 12 | RS-42 | | 14.0 | 63.7 | 10.6 | 4.2 | 7.5 | |
| 13 | RS-47 | | 15.2 | 56.4 | 14.0 | 5.5 | 9.0 | |
| 14 | RS-52 | Terrigenous–carbonate | 59.9 | 24.8 | 6.6 | 3.5 | 5.3 | Efremovo-Stepanovka |
| 15 | RS-57 | | 62.1 | 21.8 | 8.5 | 3.0 | 4.5 | |
| **Efremovo-Stepanovka** | | | | | | | | |
| 16 | ES-2 | Carbonate | 71.9 | 17.5 | 4.9 | 1.7 | 4.0 | Pavlovka |
| 17 | ES-6 | Terrigenous | 19.6 | 67.5 | 6.7 | 2.4 | 3.8 | Sukhodol |
| 18 | ES-7 | | 41.5 | 42.7 | 10.2 | 1.8 | 3.8 | |
| 19 | ES-15 | | 13.4 | 61.8 | 9.4 | 4.9 | 10.6 | |
| 20 | ES-21 | | 23.0 | 57.1 | 8.2 | 4.6 | 7.1 | |
| 21 | ES-30 | | 19.4 | 56.6 | 10.0 | 5.4 | 8.5 | |
| 22 | ES-31 | Terrigenous–carbonate | 47.7 | 34.3 | 10.5 | 4.5 | 3.0 | Efremovo-Stepanovka |
| 23 | ES-35 | | 57.8 | 30.2 | 5.6 | 3.9 | 2.5 | |
| 24 | ES-40 | | 54.0 | 31.0 | 7.8 | 3.9 | 3.3 | |

Samples ES-15 and ES-30 contain a detectable amount of the X-ray amorphous phase ($d \sim 7.0$ Å); n/d—not detected. Semiquantitative patterns were calculated as crystalline percentages (not accounting for the amorphous phase). The feldspar content is reported as a total amount of microcline and plagioclase.

**Table 2.** Whole-rock chemistry of rocks from the Rossypnoye section (wt %)

| Formation | Sample no. | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sukhodol | RS-21 | 61.70 | 0.47 | 8.32 | 3.03 | 0.27 | 0.01 | 1.41 | 9.57 | 0.23 | 2.52 | 0.13 | 11.98 | 99.64 |
| | RS-30 | 64.48 | 0.48 | 8.65 | 3.26 | 0.28 | 0.01 | 1.40 | 7.55 | 0.23 | 2.50 | 0.11 | 11.01 | 99.96 |
| Efremovo-Stepanovka | RS-40 | 42.09 | 0.28 | 4.00 | 2.06 | 0.21 | 0.02 | 0.69 | 25.80 | 0.15 | 1.47 | 0.18 | 22.25 | 99.20 |

Sukhodol Formation consists for the most part (samples ES-15–ES-30) of silty clay containing small (up to 0.05 mm) isolated grains of glauconite and localized irregular patches of silicification.

The Efremovo-Stepanovka Formation is divided into two parts. The base of the formation (samples ES-31–ES-42) consists of bioturbated silty marls (containing up to 30% quartz) containing rare benthic foraminiferal tests, isolated glauconite and mica grains, and occasional fragments of siliceous sponge spicules. The top of the formation (Samples ES-43–ES-51) is represented in thin sections by siltstone, usually intensely bioturbated, containing scattered mica flakes (1–3%) and subangular glauconite grains (1–3%). All thin sections exhibit intensive silicification.

The determination of the calcium carbonate content enabled a more detailed and accurate lithological description for the Upper Cretaceous unit. All rocks comprising the Efremovo-Stepanovka and Rossypnoye sections were formerly classified as marls (Ovechkina, 2007, p. 49). On the basis of the calcium carbonate content data, the Belgorod Formation rocks were reinterpreted as argillaceous chalk, and the Pavlovka Formation rocks were classified as argillaceous marls, whereas the Sukhodol Formation proved to be mostly silty and calcareous clays, carbonate-free clays in places, and siltstones. The Efremovo-Stepanovka Formation, overlying the Sukhodol Formation, comprises highly argillaceous, silty marls, grading up to a silty-siliceous-argillaceous stratum containing a minimum content of carbonate minerals. All lithological varieties contain variable amounts of fine-grained glauconite, but the coarser glauconite pellets are the most abundant in the lower part of the Sukhodol Formation.

X-ray diffraction analysis indicates that α-quartz is the most abundant silica phase in the samples from the Efremovo-Stepanovka section, whereas amorphous phases, such as opal-cristobalite, are almost absent, although two samples from the Sukhodol Formation (ES-15 and ES-30) contain substantial amounts of the X-ray amorphous silica phase, most likely biogenic opal (Fig. 2, Table 1).

The sedimentary rocks of all formations (Table 1) contain hydromica and zeolite in trace amounts, which are indicated by X-ray reflections of $d = 9.9$ and 8.9 Å, respectively. The samples taken from the Belgorod, Pavlovka, and Efremovo-Stepanovka Formation at the Rossypnoye section have low zeolite contents (averaging 2.9, 5.9, and 4.9%, respectively), which are two times higher in clays and siltstones of the Sukhodol Formation (averaging 9.9%). The Efremovo-Stepanovka section shows a similar trend, but with slightly lower zeolite contents.

Feldspars are present at average percentages of 5.6–17.1% in almost all samples of the Sukhodol and Efremovo-Stepanovka Formations, but their average content significantly increases to 13.9% in the samples from the Sukhodol Formation at the Rossypnoye section. Quartz and calcite contents show an opposite tend and vary widely in all samples from this section (20–60%). Quartz contents vary from 34.8 to 61% in rocks of the Sukhodol Formation and decrease to 21.2–25.5% in marls from the Efremovo-Stepanovka Formation.

X-ray diffraction analysis of the insoluble residue showed that carbonate-free portions of sediments from the Pavlovka Formation (Fig. 2g) consist of quartz, mica, zeolite, and a phase having a reflection of $d = 4.11$ Å in the center of a broad bulge of amorphous scattering. This is indicative of the presence of some cristobalite or opal-cristobalite, which is common in Upper Cretaceous sedimentary rocks of the East European Platform (Bardoschi et al., 1965; Sen'kovskii, 1971, 1977; Shumenko, 1971; Naidin et al., 2008). According to its basal reflections at 8.9, 7.9, 3.95, and 2.97 Å, this zeolite can be classified as heulandite or structurally similar clinoptilolite (Shumenko, 1971). Mica in the samples is illite or a hydrated variety of muscovite.

The insoluble residue of samples from the Sukhodol Formation (Fig. 2f) consists of quartz, hydromica, and zeolite, whereas insoluble residues from the Efremovo-Stepanovka Formation contain, in addition to the above minerals, trace amounts of kaolinite identified by a *d*-spacing of 7.05 and 3.52 Å (Fig. 2e).

The silicate analyses of three samples from the Rossypnoye section (Table 2) show a one-third decrease in $SiO_2$ and a one-half decrease in Al, with a threefold increase in Ca and a considerable decrease in K, which indicates the increased carbonate content in the Efremovo-Stepanovka Formation compared with the Sukhodol Formation. It is noteworthy that rocks of the Sukhodol Formation at the Rossypnoye section are chemically similar to those at Kruzhilovka site (Lipnik and Tkachenko, 1960), which suggests that they represent a single terrigenous unit.

## PALEOGEOGRAPHY, BIOTIC EVOLUTION AND ENVIRONMENTAL CHANGE

The results of mineralogical, petrographic, and paleontological studies of rocks presented in the our previous paper (Beniamovskii et al., 2012) provide new insights into the late Campanian–early Maastrichtian evolution of part of the basin located northward of the Donets Island. The reconstruction of changing environmental parameters such as water depth, temperature, and paleobiogeographic relationships was based on a data set compiled from our own data and those previously published on the adjacent areas of the Voronezh anteclise, eastern Dnieper–Donets basin, and Volga monocline (Ovechkina, 2007; Naidin et al., 2008; Veklich, 2009; Zakrevskaya, 2009).

### *Sedimentological Indicators*

Lithologies found in the studied stratigraphic intervals are typical of marine Upper Cretaceous sedimentation in the southern areas of the East European Platform.

During deposition of the Belgorod and Pavlovka formations, carbonate sedimentation prevailed (Beniamovskii et al., 2012, Fig. 4), although the calcium carbonate content of sediments decreased gradually from 60 to 50% in Pavlovka times.

During Sukhodol times, carbonate sedimentation was replaced by carbonate–siliceous–terrigenous sequences, as indicated by a decrease in the calcium carbonate content to 25% and to 3% at individual levels and by a considerable increase in the quartz and feldspar contents to 60 and 17%, respectively. This may have resulted from a sharp increase in clastic sediment supply.

The depositional environments during Efremovo-Stepanovka times clearly reflects increased accumulation of biogenic carbonates (marls).

It should be noted that multiple hiatuses of different duration were identified between the Belgorod and Sukhodol formations in the west of the study area (settlement of Tarasovskii) and between the Pavlovka, Sukhodol, and Efremovo-Stepanovka formations in the east (Kalitva River basin), which indicate interruptions of the marine conditions at that time (Fig. 3), but no direct evidence to support a nonmarine depositional setting has yet been found.

It is noteworthy that all of the studied samples are characterized by a consistent occurrence of zeolites and the zeolitic content is twice as high in samples from the Sukhodol Formation. Authigenic zeolites in marine sediments were formed by low-temperature alteration of volcanic glass, resulting in the release of dissolved silica during reaction with carbonate minerals (Petzing and Chester, 1979). However, dissolution of siliceous skeletons of various microorganisms (biogenic opal produced by diatoms and radiolarians, and sponge spicules) may be another important source of dissolved silica to the marine environment (Gingele, and Schulz, 1993). This scenario seems more realistic, although the aeolian supply of volcanic ash from Transcaucasia and Turkey, the sites of active volcanism at that time (Dzotsenidze, 1964; Bektaş et al., 1999; Eyüboğlu, 2010), cannot be ruled out.

All of the studied rocks do not contain any significant amount of biogenic opal, but a small fraction of the amorphous phase (mostly likely, silica) was detected in two samples from the Sukhodol Formation and in only one insoluble residue sample from the Pavlovka Formation. At the same time, siliceous skeletons of sponge spicules and radiolarians are present in most samples but account for less than 1 wt %. This value is supported by the fact that the >0.05 mm fraction with low siliceous microfossil content constitutes 2–5% and, rarely, more than 15% of the rock samples collected from the Sukhodol Formation.

### *Biotic Indicators*

Among all fossil groups found in the studied sections, radiolarians and foraminifera have the greatest potential for reconstruction of depositional environments. Calcareous nannoplankton may be less reliable indicators because of being susceptible to strong dissolution during diagenesis. The macrofaunal elements found in the sediments are some belemnite species typical of the South European province of the Boreal Realm (Naidin et al., 1984, 1988).

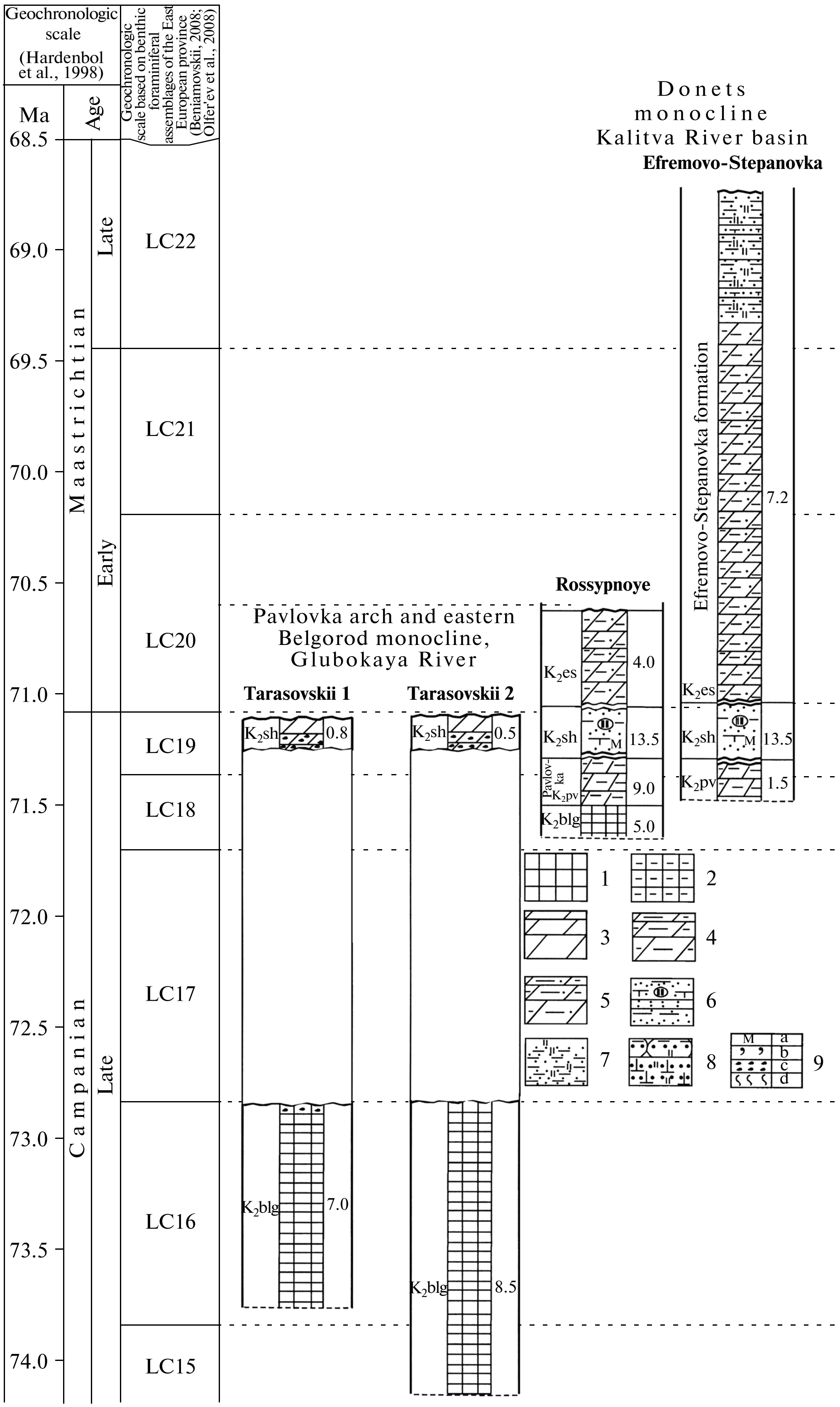
### *Radiolarians*

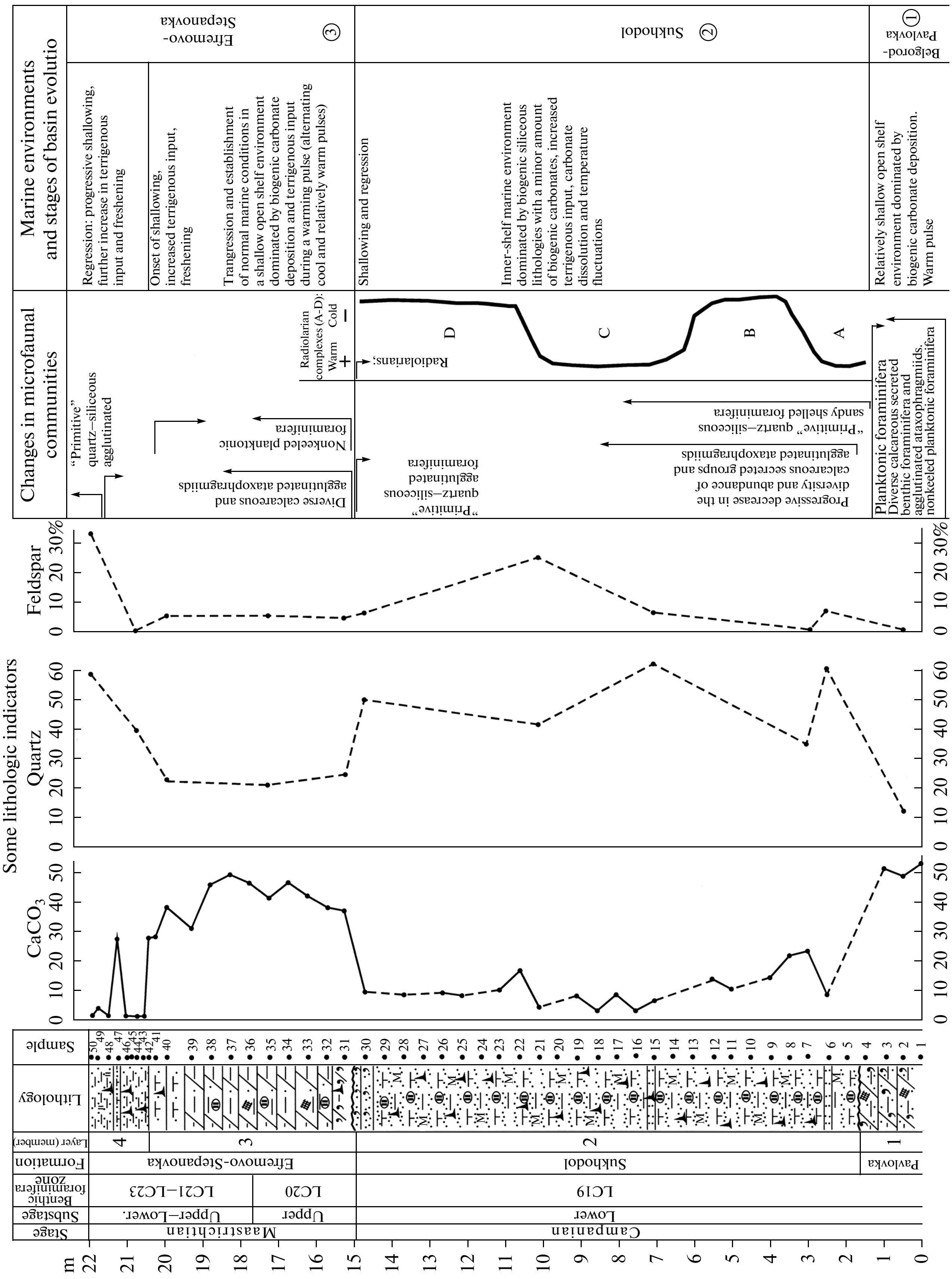
Changes in radiolarian assemblages at the Efremovo-Stepanovka section (Beniamovskii et al., 2012, pp. 52–53, fig. 8) may record temperature changes and thus provide the basis for reconstructing the intervals of relatively warm and cold conditions in the history of the basin.

**Assemblage A.** The Pavlovka stage and the earliest Sukhodol stage are characterized as relatively warm intervals (Fig. 4). About half the radiolarians at that time were represented by subtropical species first described from California: *Theocapsomma comys* Foreman, *Crucella espartoensis* Pessagno, *Phaseliforma carinata* Pessagno, *P. subcarinata* Pessagno, *Orbiculiforma* ex gr. *sempiterna* Pessagno, *Amphipyndax stocki* (Campbell et Clark), *Dictyomitra densicostata* Pessagno, etc.

**Assemblage B.** The upper interval (above Sample ES-8) is marked by blooms of spongy thick-walled spumellarian forms of the genus *Prunobrachium*, with vertically elongated skeletons, and simple discoidal forms of the genus *Orbiculiforma*, which together accounted for more than 70% of the assemblage. Analysis of the paleobiogeography of the radiolarian genus *Prunobrachium* shows (Amon, 2000) that the species of this genus display a bipolar distribution pattern and consist of mid- and high-latitude taxa. This genus inhabited the area of latitudes 35°–69° N of the Northern Hemisphere and 50°–52° S of the Southern Hemisphere. In upper Campanian sediments of Russia,

**Fig. 3.** Duration of hiatuses in the studied sections defined from benthic foraminiferal zonation. $K_2$es—Efremovo-Stepanovka Formation, $K_2$sh—Sukhodol Formation, $K_2$pv—Pavlovka Formation, $K_2$blg—Belgorod Formation. Thicknesses (m) are given in the column to the right of the lithology. Here and in Figs. 4 and 5: (1) chalk; (2) argillaceous chalk; (3) marl; (4) highly argillaceous marl; (5) highly argillaceous sandy marl; (6) calcareous, carbonate-free clay (silicified in places), with various sand contents (sometimes high), grading in places to sand and silt; (7) carbonate-free and opoka-like, sandy clay; (8) sandstone and silicified and carbonate silt; (9a) mica, (9b) glauconite, (9c) phosphorite nodules, (9d) bioturbation.


Geochronologic scale (Hardenbol et al., 1998)
Ma
Age
Geochronologic scale based on benthic foraminiferal assemblages of the East European province (Beniamovskii, 2008; Olfer'ev et al., 2008)
68.5
69.0
69.5
70.0
70.5
71.0
71.5
72.0
72.5
73.0
73.5
74.0
Maastrichtian
Campanian
Late
Early
Late
LC22
LC21
LC20
LC19
LC18
LC17
LC16
LC15
Pavlovka arch and eastern Belgorod monocline, Glubokaya River
Tarasovskii 1
Tarasovskii 2
K2sh
0.8
0.5
K2blg
7.0
8.5
Rossypnoye
K2es
4.0
13.5
Pavlovka K2pv
9.0
5.0
Donets monocline Kalitva River basin
Efremovo-Stepanovka
Efremovo-Stepanovka formation
7.2
1.5
1
2
3
4
5
6
7
8
9
M
a
b
c
d



Marine environments and stages of basin evolutio
Belgorod-Pavlovka ①
Sukhodol ②
Efremovo-Stepanovka ③
Relatively shallow open shelf environment dominated by biogenic carbonate deposition. Warm pulse
Inner-shelf marine environment dominated by biogenic siliceous lithologies with a minor amount of biogenic carbonates, increased terrigenous input, carbonate dissolution and temperature fluctuations
Shallowing and regression
Trangression and establishment of normal marine conditions in a shallow open shelf environment dominated by biogenic carbonate deposition and terrigenous input during a warming pulse (alternating cool and relatively warm pulses)
Onset of shallowing, increased terrigenous input, freshening
Regression: progressive shallowing, further increase in terrigenous input and freshening
Changes in microfaunal communities
Radiolarian complexes (A-D): Warm + Cold −
Radiolarians;
Planktonic foraminifera
Diverse calcareous secreted benthic foraminifera and agglutinated ataxophragmiids, nonkeeled planktonic foraminifera
Progressive decrease in the diversity and abundance of calcareous secreted groups and agglutinated ataxophragmiids
"Primitive" quartz–siliceous sandy shelled foraminifera
"Primitive" quartz–siliceous agglutinated foraminifera
Diverse calcareous and agglutinated ataxophragmiids
Nonkeeled planktonic foraminifera
"Primitive" quartz–siliceous agglutinated
Some lithologic indicators
Feldspar
Quartz
CaCO3
Sample
Lithology
Layer (member)
Formation
Benthic foraminifera zone
Substage
Stage
Pavlovka
Sukhodol
Efremovo-Stepanovka
LC19
LC20
LC21–LC23
Lower
Upper
Upper–Lower.
Campanian
Maastrichtian
m

including its northeastern part, the representatives of this genus are reported mostly from the Boreal Realm (Vishnevskaya, 2008, 2011). Radiolarians of the genus *Prunobrachium* probably inhabited relatively cold (or cool), shallow coastal waters (Amon, 2000). Radiolarian assemblages dominated by genera *Prunobrachium* and *Orbiculiforma* are indicative of the climatic pessimum. At the same time, the representatives of the California assemblages, such as *Spongurus occidentalis* Campbell et Clark, *Orbiculiforma renillaeformis* (Campbell et Clark), *O. sacramentoensis* Pessagno, *Stylotrochuus polygonatus* (Campbell et Clark), and *Tholodiscus fresnoensis* (Foreman), indicate mixed affinities.

**Assemblage C.** A warming pulse (above Sample ES-13) is indicated by the composition of radiolarian assemblages from the middle part of the Sukhodol Formation. In the assemblages from this interval, about half of the species percentage is represented by subtropical forms, including discoids *Pseudoaulophacus riedeli* Pessagno, *Spongostaurus hokkaidoensis* Taketani, *Patulibracchium delvallensis* Pessagno; prunoids *Archaeospongoprunum andersoni* Pessagno, *A. hueyi* Pessagno; and numerous cytroids *Archaeodictyomitra regina* (Campbell et Clark), *Amphipyndax stocki* (Campbell et Clark), *A. enesseffi* Foreman, *A. tylotus* Foreman, *Lithostrobus natlandi* Campbell et Clark, *Dictyomitra andersoni* Campbell et Clark, as well as some representatives of the California assemblage such as *Orbiculiforma insignis* (Campbell et Clark), *Eucyrtis carnegiense* (Campbell et Clark), and *Stichomitra manifesta* Foreman.

**Assemblage D.** The Sukhodol stage (above Sample ES-23 to the top of the formation) is terminated by a cooling pulse. This assemblage is mostly composed of cold-water species (over 75%), which include the dominant spongy forms of the genera *Spongurus*, *Phaseliforma*, and *Amphymenium* (*A. concentricum* Lipman, *A. sibiricum* Lipman, *A. splendiarmatum* Clark et Campbell, *A. vishnevskayae* Amon) and abundant West Siberian species *Theocampe animula* Gorbovetz.

Radiolarians may serve as indicators of changes in water temperature in the Sukhodol basin, which are reflected in the alternating warming and cooling pulses. A pronounced cooling is evident at the end of Sukhodol times, which is consistent with changes in sea-surface temperature reconstructed on the basis of nannoplankton assemblages from the Maastrichtian section in the Saratov oblast (Ovechkina and Alekseev, 2004; Ovechkina, 2007).

### *Foraminifera*

The Belgorod–Pavlovka stage is characterized by a diverse group of secreted benthic foraminifera with calcareous walls (Fig. 4). Agglutinated benthic taxa are represented by trochoid ataxophragmiid forms with complex shell structure and abundant calcareous wall material. In addition to benthic foraminifera, co-occurring planktonic taxa are represented by the genera *Globotruncana*, *Rugoglobigerina*, *Globigerinelloides*, and *Archaeoglobigerina*. The more westerly section (Tarasovskii 1) contains relatively abundant and well-preserved *Globotruncana* species (Fig. 5). The composition of the foraminiferal assemblages described above indicates normal salinity conditions and depths favorable to planktonic species. The co-occurrence of benthic foraminifera and typical late Campanian European Province species points to the existence of open connections between the basin and other areas.

The Sukhodol stage marks significant changes in the foraminiferal assemblage, which resulted in first a complete disappearance of planktonic foraminifera and second an abrupt decrease in the number and diversity of secreted calcareous benthic foraminifera. Euribiontic discorbids are found abundantly preserved in sediments. Third, this was accompanied by changes in the agglutinated foraminifera fauna: the trochoidal ataxophragmiids with complex shell structure and fine-grained sandy walls were replaced by “primitive” agglutinants, which have tubular, straight or spiral and globular-curved tests with a siliceous–quartz coarse sand texture of the test walls, loosely cemented with a calcareous cement with inequigranular sand grains. This may indicate a shallower water depth and changes in bottom sediment facies.

The “primitive” agglutinated benthic foraminifera are represented by three groups of species, with different regional and stratigraphic ranges. Group 1 (six species) includes cosmopolitan forms with a wide stratigraphic range embracing the whole Meso-Cenozoic: *Psammosphaera fusca* (Schulz), *Ammodiscus* cf. *incertus* (d’Orb.), *Glomospira gaultina* Berth., *G. charoides* (Jones et Parker), *Hyperammina friabilis* Brady, *Rhabdammina cylindrica* Glaes. Group 2 (five species) is represented by forms which are common in Upper Cretaceous sediments of Southern Trans-Urals and West Siberia (Subbotina, 1964): *Hyperammina camelliformis* Bulat., *Reophax angusticolis* Kipr., *Haplophragmoides sibiricus* Zasp., *Adercotrima glomeratoformis* (Zasp.), *Spiroplectammina kelleri* Dain. The last species was also reported from the terminal Campanian and lower Maastrichtian in the southeastern part of the Russian Plate (Baryshnikova, 1967). Group 3 (two species) consists of endemic forms described from the upper Campanian section of the Sukhodol Formation in the eastern part of the

**Fig. 4.** Abiotic and biotic components and stages of the basin evolution in the north of Rostov oblast during the late Campanian–Maastrichtian on the basis of data from the Efremovo-Stepanovka section.
For legend see Fig. 3.

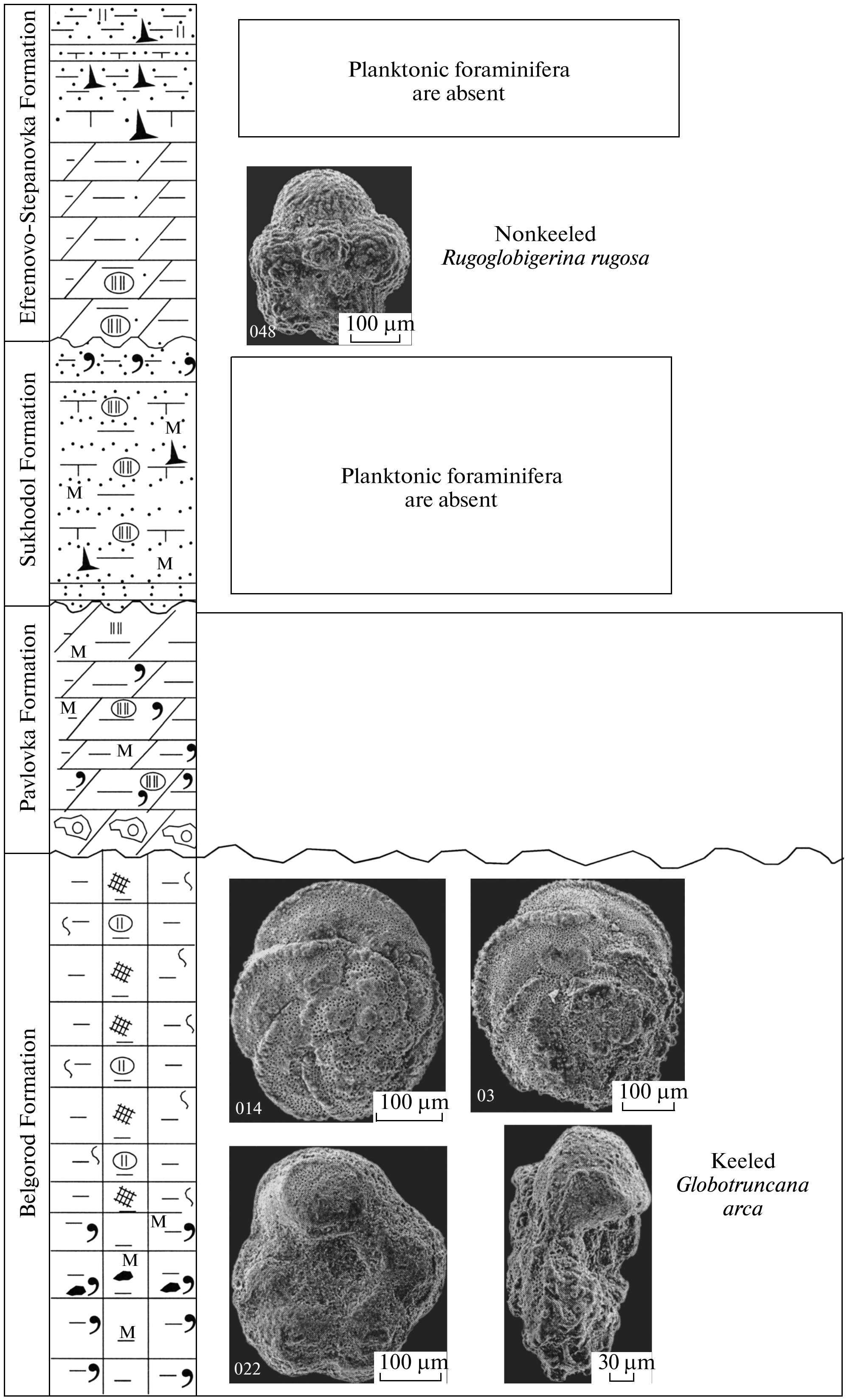



**Fig. 5.** Upper Campanian–lower Maastrichtian planktonic foraminifera from northern Rostov region. For legend see Fig. 3.

Donets Basin (Lipnik, 1978): *Reophax incompletus* Lipnik and *Pseudoreophax*? *ambigens* Lipnik.

The Efremovo-Stepanovka stage is marked by the disappearance of the agglutinated foraminiferal assemblage typical of the Sukhodol Formation and the appearance of diverse secreted forms with a minor proportion of ataxophragmiids.

A small number of nonkeeled planktonic rugoglobigerins are present. The final phase of the Efremovo-Stepanovka basin is marked by a lithologic change (marls were replaced by siltstones) and a subsequent change in the taxomonic composition of foraminiferal assemblages (Fig. 4). These changes consist in the disappearance of the planktonic forms (Sample ES-43) and the decreasing percentage (above Sample ES-47) of calcareous foraminifera and ataxophragmiids. The end of this stage (samples ES-48–ES-50) is marked by the dominance of "primitive" agglutinants. The above successions of events indicate progressively shallower conditions and regression at the end of the Efremovo-Stepanovka stage.

### *Calcareous Nannoplankton*

The recorded assemblages are composed of taxa typical of the Boreal Realm (Burnett, 1998). Unfortunately, because of poor to moderate preservation and dissolution of nannofossils, the sediments contain only the solution-resistant forms (especially, *Micula decussata* Vekshina and *Watznaueria barnesae* (Black et Barnes) Perch-Neilsen; see, Thierstein, 1980; Henriksson and Malmgren, 1999), which prevents the assessment of the species diversity and the proportion of forms different in their ecology. Nevertheless, the available data allow us to draw the following observations.

Belgorod Formation. The number of species varies in the samples from 24 to 39 (Sample RS-5), averaging 28.4 specimens. Common species include *Micula decussata* Vekshina, *Microrhabdulus decoratus* Deflandre, *Kamptnerius magnificus* Deflandre, and *Eiffellithus turriseiffeli* (Deflandre in Deflandre et Fert) Reinhardt. Rare warm-water species, such as *Uniplanarius gothicus* (Deflandre) Hattner et Wise, are present only in Sample RS-5.

Pavlovka Formation. In this interval, the diversity shows minor changes (27.2), with *Micula decussata* Vekshina, *Microrhabdulus decoratus* Deflandre, *Eiffellithus turriseiffeli* (Deflandre in Deflandre et Fert) Reinhardt, *Reinhardtites levis* Prins et Sissingh, *Prediscosphaera grandis* Perch-Nielsen, and *Pr. cretacea* (Arkhangelsky) Gartner identified as common. The taxon *Thoracosphaera saxea* Stradner is rare. Similar to the Belgorod Formation, warm-water taxa like *Uniplanarius gothicus* (Deflandre) Hattner et Wise are rare and were found only in a few samples.

Sukhodol Formation. The abundance and diversity of nannoplankton species decrease at this level, which is readily correlated with terrigenous lithologies of the section. Taxonomic diversity decreases to 23.2 species (minimum 17 species per sample). Common forms include *Micula concava* (Stradner in Martini et Stradner) Verbeek, *Prediscosphaera grandis* Perch-Nielsen, *Pr. cretacea* (Arkhangelsky) Gartner, *Watznaueria barnesae* (Black in Black et Barnes) Perch-Nielsen, and *Reinhardtites levis* Prins et Sissingh. The warm-water *U. trifidus* (Stradner in Stradner et Papp) Hattner et Wise and *U. gothicus* (Deflandre) Hattner et Wise are rare and were found only in five samples.

Efremovo-Stepanovka Formation. In marls, the taxonomic diversity of nannofossils increases to 28.4 species (a maximum of 37 species in Sample RS-53). *M. concava* (Stradner in Martini et Stradner) Verbeek, *M. decussata* Vekshina, *Prediscospahera cretacea* (Arkhangelsky) Gartner, and *Watznaueria barnesae* (Black in Black et Barnes) Perch-Nielsen remain common. As in the down-section intervals, the warmer-water taxa of the genus *Uniplanarius* are few to rare and were found only in samples RS-53 and RS-58.

Therefore, unlike the overlying and underlying formations, the low-carbonate Sukhodol Formation contains appreciably less diverse nannofossil assemblages. This may indicate both shallower water and cooler conditions, as well as increased dissolution of nannofossils in low-carbonate sediments.

### *Other Groups*

The micropaleontological samples from the Efremovo-Stepanovka section were analyzed for bioclast composition. The results confirm low bioclast diversity, which is indicated by common radiolarians and foraminifera, siliceous sponge spicules, and fish remains, as well as fragments of bivalves, isolated prisms of broken *Inoceramus* shells, and ostracods found in the Pavlovka Formation sediments. The lower part of the Sukhodol Formation (samples ES-12–ES-16) contains rare echinoid spines, which temporarily disappear above this interval but appear again in the basal marls of the Efremovo-Stepanovka section, where they were detected as isolated specimens in almost half of the samples. The absence of echinoid spines from a thicker interval of the Sukhodol Formation can be interpreted as freshwater influence or it can be associated with deposition of unfavorable muddy and silty substrates.

The rocks of the Sukhodol Formation at the Rossypnoye site (samples RS-22 and RS-23) exhibit numerous empty casts of siliceous spicules, which are very abundant in the upper part of the Pavlovka Formation at the Efremovo-Stepanovka section, rare to few in the Sukhodol Formation, and almost absent in the Efremovo-Stepanovka Formation. Therefore, this group of fossils provides incomplete information for paleoenvironmental reconstruction; however, it may indicate the presence of large amounts of free silica in seawater.

### *Paleogeographic Interpretation*

There are three stages in the basin evolution that can be designated by the names of the corresponding formations: (1) Belgorod–Pavlovka stage (late Campanian), (2) Sukhodol stage (transitional from Campanian to Maastrichtian), and (3) Efremovo-Stepanovka stage (Maastrichtian). Two short-lived hiatuses separate the Sukhodol stage from the other two.

During the Belgorod–Pavlovka stage, relatively warm, deep-water marine conditions were established in the basin dominated by carbonate sedimentation. The environments were dominated by abundant subtropical radiolarian species (up to 50%), while planktonic foraminifera were another major component. In Pavlovka times, a gradual decrease in the calcium carbonate content may indicate the onset of the next stage.

The Sukhodol stage began with an abrupt decline in the calcium carbonate content accompanied by a major influx of fine-grained terrigenous material and increased zeolite abundances in sediments. The biotic indicators suggest a remarkable drop in seawater temperature, although the middle of the Sukhodol stage was marked by a minor warming pulse (the sudden appearance of subtropical radiolarians), which was replaced by another cold-water pulse with the predominance of the Arctic–Boreal and West Siberian radiolarian taxa. It is clear that these events were accompanied by marine regression, which led to a shallowing of the marine environment to depths where radiolarian abundance remained optimal.

The change from carbonate deposition to mixed carbonate–siliceous–terrigenous deposition with abundant siliceous fossils (radiolarians, sponges, "primitive" agglutinated benthic foraminifera such as astrorhizids and ammodiscids) in late Campanian–early Maastrichtian times was observed along the northern and eastern margins of the Donets Basin: in the interfluve areas between the Don and Seversky Donets rivers and Don and Volga rivers, in northern Rostov oblast, and on the right bank of the Volga River (Baryshnikova, 1958, 1967, 1978; Morozov, 1958, 1962; Lipnik and Tkachenko, 1960; Shvemberger, 1962; Blank and Gorbenko, 1968; Lipnik, 1974, 1978).

Thin-section and mineralogical analyses of rock samples collected from the Efremovo-Stepanovka section show a sharp increase in the silica-quartz component, which confirms an increase in clastic sediment supply from upland source areas in the Donets Basin, as previously suggested for the Maastrichtian of the study area (Morozov and Orekhova, 1970, p. 332, fig. 53; Grossgeim, 1972). In the study area, the folded Donets Basin is composed of intensely folded and faulted Middle–Upper Carboniferous sequences mainly consisting of sands (Pogrebnov, 1975), which may have been eroded and redeposited. The possible source of feldspar remains unclear, because it may have been supplied from the Rostov basement high in the south or Azov massif in the west. The Donets Island at that time was some 30–40 km in width and more than 200 km in length.

We suggest that terrigenous material was supplied to the basin by small rivers. Increased river discharge may have caused freshening of seawaters in the adjacent Sukhodol basin. In addition, the fluvial freshwater discharge is one of the main sources of dissolved silica (Conley, 1997) taken up by diatoms and radiolarians to build their skeletons, which could explain at least in part an increased silica content of the Sukhodol clays and siltstones. However, the problem of freshening of the basin seawater remains unresolved because of the presence of a stenohaline fauna (radiolarians) and the absence of other indicator groups of faunas (except for echinoids) throughout the section of the Sukhodol Formation.

The Efremovo-Stepanovka stage was found to share similarity with the Pavlovka stage, although slight differences do exist.

The dominantly carbonate sedimentation resumed during Efremovo-Stepanovka (Maastrichtian) times. Lithological and mineralogical changes were concurrent with biotic changes. (Figs. 2, 4), as indicated by a complete disappearance of siliceous groups of fossils (radiolarians and "primitive" agglutinated foraminifera with a coarse-grained sandy texture of quartz–siliceous walls). Benthic foraminifera were represented by a diverse fauna of secreted calcareous and fine-grained sandy shelled ataxophragmiids. The representatives of the nonkeeled planktonic genus *Rugoglobigerina* were rarely present. The basal part of the section contains well-preserved rostra of the belemnites *Belemnella lanceolata*.

Therefore, it can be assumed that, during the Efremovo-Stepanovka stage, much of the sediment source area within the Donets Island became flooded owing to a rise in sea level and subsequent marine transgression, which significantly decreased the amount of clastic sediment supplied to the basin. The climatic pessimum in late Sukhodol times was followed by a relatively warm pulse, and deepening of the basin promoted the migration of nonkeeled plaktonic forms of *Rugoglobigerina* and the appearance of calcareous secreted and agglutinated benthic foraminifera with complex shell structure.

It is important to note the appearance of *Anomalinoides pinguis* (Jennings) and *A. gankinoensis* (Neckaya), indicating the establishment of open-water connections to the West Siberian Sea, from which these species migrated into the East European province and where they became widely dispersed at the end of the early Maastrichtian and in the late Maastrichtian.

By the end of the Efremovo-Stepanovka stage, the area was characterized by abrupt changes in lithology: the $CaCO_3$ content of sediments decreased to zero and siltstone became the dominant lithology. The uppermost layers (Sample ES-50) tend to have high quartz and feldspar contents. The composition of foraminiferal communities displays significant changes (Fig. 4), such as the disappearance of the planktonic forms (Sample ES-43) and abrupt decreases (above Sample ES-47) in the abundance of calcareous secreted and agglutinated ataxophragmiids. Finally, the "primitive" agglutinants became again a significant component of the assemblages in the topmost layers (at the level of samples ES-48–ES-50). These changes point to a shallowing of the basin, the onset of a marine regression, and proximity to sediment sources. However, this part of the section is severely disturbed and such changes can in part be explained by secondary silicification of Cretaceous rocks during a Cretaceous–Paleogene hiatus.

## DISCUSSION

Biostratigraphic analysis showed (Beniamovskii et al., 2012) that the Sukhodol event reflects periods of cooling, sea-level regression (benthic foraminiferal Zone LC19), and siliceous–terrigenous deposition, and it appears to be somewhat younger than a similar Nalitovka event identified in the Saratov Volga region (zones LC17 and 18). Therefore, these two events cannot be associated with the same cause, although both occurred shortly before the late Campanian.

The Sukhodol event occurred in proximity to the margins of the Donets Island. The data from the northern half of Rostov oblast (Table 3) suggest that predominantly terrigenous deposition during Sukhodol times took place north of the land area that emerged from the former Donets Basin and occupied a zone with a width of 70–80 km, extending farther west to the latitudes of present-day Lugansk and Lisichansk (Fig. 6). The eastern termination of this land area comprises a narrow belt of coarser grained sands. Unfortunately, to the north, sediments of this age are missing owing to Cenozoic erosion, so it is not possible to establish the limits of terrigenous deposition with any certainty. Farther west, where the Donets Basin extends beneath the Dnieper–Donets Depression, in Kharkov oblast and in the south of neighboring Belgorod and Kursk oblasts, the Campanian–Maastrichtian section is composed entirely of carbonate rocks (chalk), although details of this transition remain unclear.

We cannot, however, rule out any influence of the supposedly vast delta front of the proto-Don River system on the studied area of the basin, as suggested on the early Campanian lithofacies map for the East European Platform (Alekseev et al., 2005). This river system began functioning well before that time and a significant proportion of terrigenous sediments was discharged to the east, in the southern part of the present-day Volgograd region (Aleksandrova et al., 2012).

It was suggested (Naidin, 1962; Naidin et al., 2008) that the wide but temporary distribution of the siliceous organisms in a Late Cretaceous basin of the Volga region could be associated with incursions of cool and freshened waters of the Arctic–Boreal seas. Similarity in the composition of the "primitive" agglutinated foraminifera and radiolarian species in assemblages from the Sukhodol Formation and Arctic–Boreal assemblages from the Polar Urals and West Siberia (Subbotina, 1964; *Prakticheskoe*..., 1991; Amon, 2000) can provide additional support for this reconstruction. However, only in the case of freshening can the cold to Arctic waters from the northern Timan-Pechora province or Trans-Urals be expected to exert influence far beyond the boundaries of the Saratov Volga region and in the more northern areas of the Donets Basin. This is not the case as we cannot identify indicators of a reduced salinity in the composition of the biota from the Sukhodol basin, although the identification of this parameter for ancient basins represents the most difficult problem.

The above results reveals convincing evidence that the Sukhodol event occurred during a time in Late Cretaceous history, which was marked by changes in global sea level due to the alternation of cooling and warming pulses in the late Campanian–early Maastrichtian (Miller et al., 1999). This interval covering a time span of 1–2.5 m.y. was identified (Voigt et al., 2010, 2012) as the "Campanian–Maastrichtian boundary event" (CMB or CMBE). It is marked by pronounced water cooling, a negative carbon isotope excursion, and sea-level fall (Fig. 7).

At Shatsky Rise and in the equatorial Pacific, this interval was defined in the calcareous nannoplankton zone (the uppermost part of Zone UC16, Zone UC17, and the basal part of Zone UC18) with peak values of carbon isotope excursion (Jung et al., 2012). The interval starts slightly below the last occurrence of *Uniplanarius trifidus* (Stradner) Hattner et Wise and *Broinsonia parca constricta* Hattner et al. and ends above the last occurrence of *Tranolithus orionatus* (Reinhardt) Reinhardt. The age model (after GTS 2004) brackets the duration of this event from 72.1 to 70.5 Ma.

In the Kronsmoor section (northern Germany), a reference point for the upper Campanian and the Maastrichtian in the European paleobiogeographic province, the negative shift in $\delta^{13}C$ is very noticeable and correlates with the first occurrence of the ammonite *Pachydiscus neubergicus* (Hauer), the index taxon of this stage boundary, and is situated in the upper part of UC15 (Niebuhr et al., 2011). In this case, the FO of the belemnite *Belemnella lanceolata* (von Schlotheim), the traditional marker species of the lower Maastrichtian boundary in this area, should be about 450 k.y. earlier.

In the deeper water cores from the Rordal (northern Denmark) and Stevns (eastern Denmark) sites, this isotope excursion lying within calcareous nannofossil Zone UC16 (subzone UC16d$^{BP}$) was divided into three phases (Thibault et al., 2012a). The Campa-

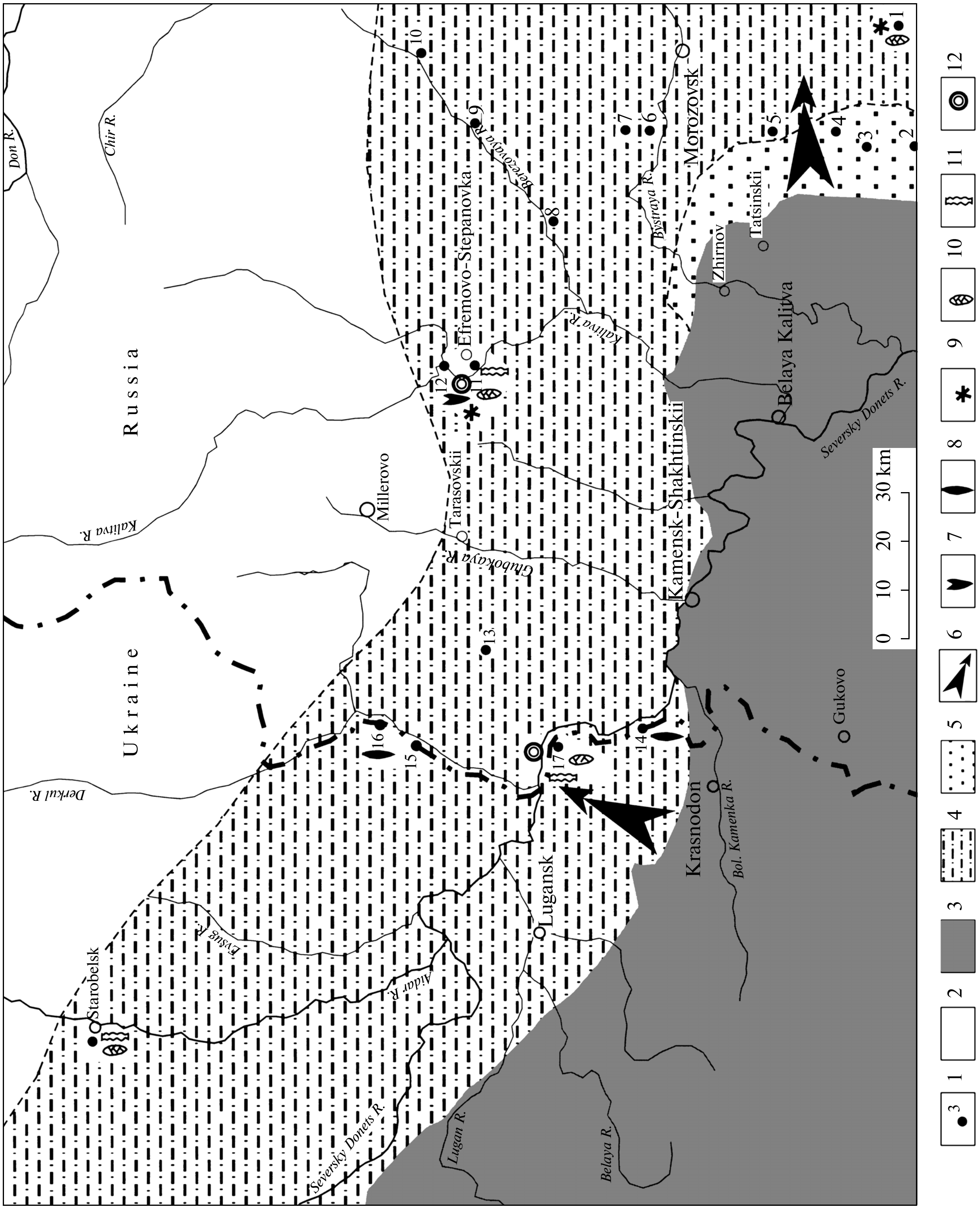



**Fig. 6.** Extent of the Sukhodol Formation (upper Campanian–lower Maastrichtian). (1) Proven occurrences of the Sukhodol Formation (Table 3); (2) areas where the Sukhodol rocks are missing; (3) Paleozoic rocks within the Donets Island; (4, 5) Sukhodol Formation: (4) calcareous and low-calcareous clay, silt, with rare fine-grained sandstone; (5) calcareous sandstone and siliceous clay; (6) sediment transport; (7–12) faunal occurrences: (7) *Belemnitella langei*, (8) *Belemnella licharewi*, (9) calcareous nannoplankton, (10) secreted benthic foraminifera, (11) coarse-sandy shelled agglutinated foraminifera, (12) radiolarians.

**Table 3.** Site with the confirmed presence of the Sukhodol Formation

| No. on map (Fig. 6) | Borehole and section names | Location | Lithology | Thick-ness, m | Source |
|---|---|---|---|---|---|
| 1 | Znamenka 1A Borehole | Znamenka village, Morozovsk district, Rostov oblast, Russia | Calcareous, silty, micaceous, siliceous clay | 29 | This study |
| 2 | Borehole 31 | 55 km SSE of Morozovsk, Rostov oblast, Russia | Calcareous sandstone | 12 | Morozov, 1962, chart 7 |
| 3 | Borehole 40 | 44 km SSE of Morozovsk, Rostov oblast, Russia | Calcareous sandstone | 22 | Morozov, 1962, chart 7 |
| 4 | Borehole 42 | 37 km SSE of Morozovsk, Rostov oblast, Russia | Calcareous sandstone | 26 | Morozov, 1962, chart 7 |
| 5 | Borehole 61 | 25 km SSE of Morozovsk, Rostov oblast, Russia | Siliceous clay | 19 | Morozov, 1962, chart 7 |
| 6 | Borehole 66 | 17 km WNW of Morozovsk, Rostov oblast, Russia | Sandy marl | 13 | Morozov, 1962, chart 7 |
| 7 | Borehole 26 | 37 km SSE of Morozovsk, Rostov oblast, Russia | Calcareous sandstone | 9 | Morozov, 1962, chart 7 |
| 8 | Borehole 11 | 20 km upstream of the mouth of the Berezovaya River, Rostov oblast, Russia | Siltstone and clay | 48 | Morozov, 1962, chart 4 |
| 9 | Borehole 7 | 47 km upstream of the mouth of the Berezovaya River, Rostov oblast, Russia | Marl, clay, and siltstone | 35 | Morozov, 1962, chart 4 |
| 10 | Borehole 4 | In the vicinity of Selivanosvkaya stanitsa, Rostov oblast, Russia | Siltstone | 22 | Morozov, 1962, chart 4 |
| 11 | Efremovo-Stepanovka | Efremovo-Stepanovka village, right bank of the Kalitva River, Rostov oblast, Russia | Silty, calcareous, silica-rich, micaceous clay interbedded with argillaceous siltstone | 13.5 | This study |
| 12 | Rossypnoye | 2.5 km upstream of Efremovo-Stepanovka village, Rostov oblast, Russia | Calcareous and silty clay with a different degree of silicification | 13.5 | This study |
| 13 | Nizhnemityakinskii | Nizhnemityakinskii village, 23 km WSW of Tarasovskii settlement, Rostov oblast, Russia | Micaceous marl, fine-grained and sandy | 17.5 | Naidin's field book, 1954 |
| 14 | Bol. Sukhodol | Bolshoi Sukhodol (Velikii Sukhodo) village, right bank of the Severskii Donets River, Lugansk oblast, Ukraine | Sandy marl and yellowish gray sand | – | Naidin's field book, 1957 |
| 15 | Nizhne-Gerasimovskii | Nizhne-Gerasimovskii village, right bank of the Derkul River, 25 km from the mouth, Lugansk oblast, Ukraine | Dense marly clay | 6–7 | Naidin's field book, 1957 |
| 16 | Krasnyi Derkul | Right bank of the Derkul River, 4 km south of Krasnyi Dertkul village, 30 km from the mouth, Lugansk oblast, Ukraine | Marly clay | 7–8 | Naidin's field book, 1957 |
| 17 | Kruzhilovka Borehole | Borehole in the vicinity of Kruzhilovka stanitsa on the right bank of the S. Donets River, Lugansk oblast, Ukraine | Carbonaceous and micaceous siltstone | 49 | Lipnik and Tkachenko, 1960 |
| 18 | Borehole 106 Starobelsk | Borehole 106, vicinities of Starobelsk, Lugansk oblast, Ukraine | Calcareous, micaceous, silty clay | 12 | Ivannikov and Lipnik, 1971 |

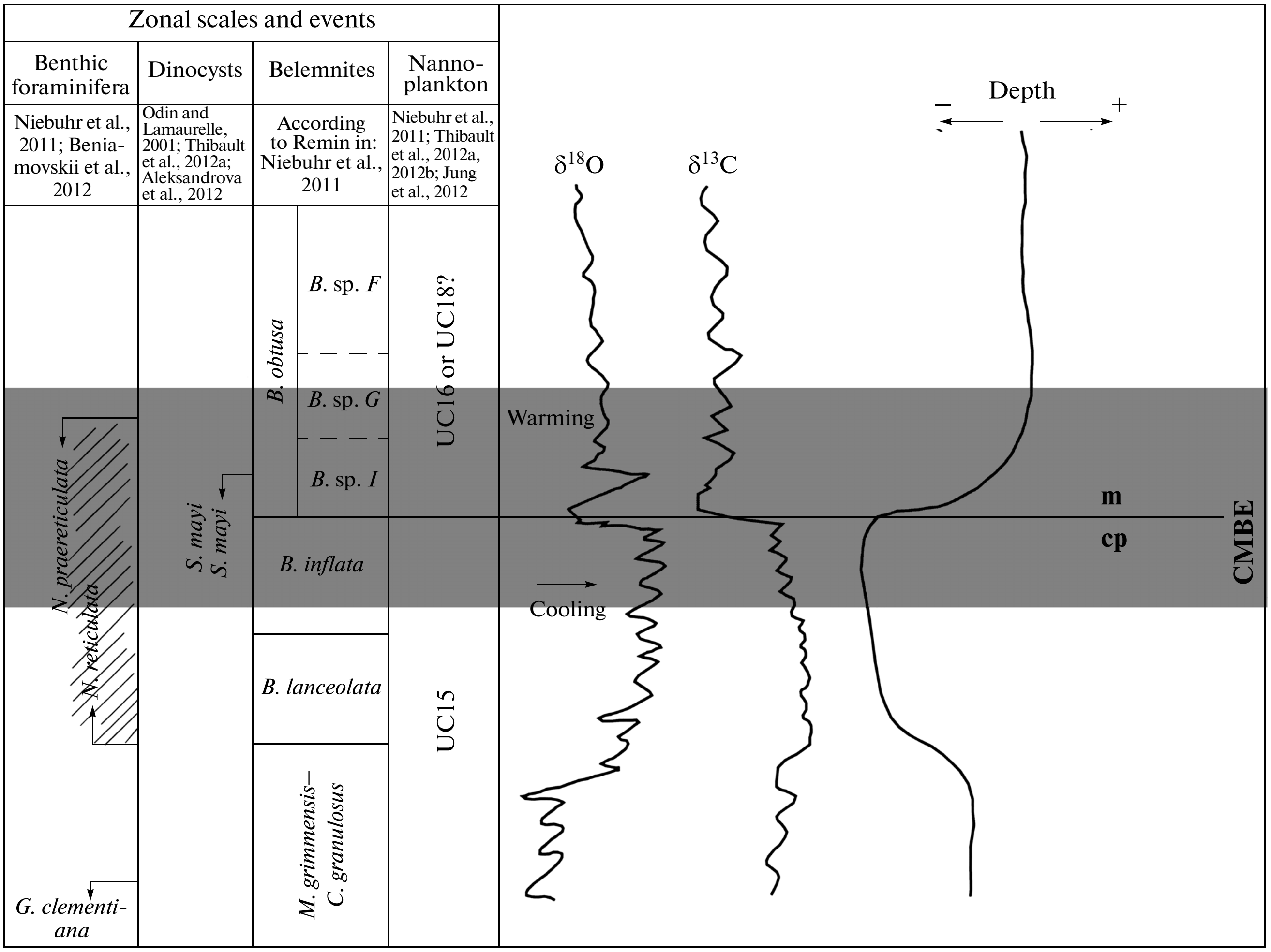



**Fig. 7.** Position of the Campanian–Maastrichtian boundary event (CMBE) in different zonal scales and generalized changes in the carbon and oxygen isotope compositions of carbonates and relative sea-level changes after Jung et al. (2012), Niebuhr et al. (2011), and Thibault et al. (2012a). m—Maastrichtian, cp—Campanian.

nian–Maastrichtian boundary was found to coincide with the CMBc phase. Fifteen $\delta^{13}C$ events were defined in the upper Campanian–lower Maastrichtian. Their correlation with the deep-water cores from the Exmouth Plateau in the tropical Indian Ocean and sections from northern Europe showed that the internationally accepted base of the Maastrichtian, defined at the base of the Belemnella obtuse Zone, corresponds to the CMBa phase in the Boreal Realm; i.e., it is approximately 800 k.y. younger than the GSSP at Tercis les Bains, France (Thibault et al., 2012b).

In northern Rostov oblast, the deposition of the Sukhodol Formation was accompanied by cooling and associated relative sea-level fall, which resulted in increased input of terrigenous material. The Sukhodol event can be interpreted to reflect one of a series of global-scale episodes of the "Campanian–Maastrichtian boundary event," which can be defined differently in different basins of the world.

## CONCLUSIONS

(1) Integrated lithological, mineralogical, and chemical studies of upper Campanian–lower Maastrichtian rocks collected at the Efremovo-Stepanovka and Rossypnoye reference sections included determination of the calcium carbonate content of rocks and X-ray diffraction, silicate, and insoluble residue analyses. The results of the analyses will help elucidate the origin of these rocks. Furthermore, we analyzed the turnover and changes in the composition of biotic assemblages.

(2) Coupling of abiotic and biotic parameters allowed the reconstruction of the evolution of the northern Rostov part of the late Campanian–early Maastrichtian basin, which was located around the Donets Island in the southern part of the Russian Plate. Three stages were identified: (a) Belgorod–Pavlovka (late Campanian), (b) Sukhodol (late Campanian–early Maastrichtian), and (c) Efremovo-

Stepanovka (Maastrichtian). Each stage was characterized by a specific environment and composition of the biotic assemblages.

(3) The results of the study confirm that the upland area within the folded Donets Basin was a main terrigenous sediment source. The input of terrigenous material was the highest at the Sukhodol stage, when a marine regression and sea-level fall caused a huge flux of sand–silty material to "splash out" from the Donets Basin and be deposited as a terrigenous tongue along the northern margin of the Donets Island. This event caused major changes in sedimentation (decrease in the carbonate content and increase in the terrigenous–siliceous component, increase in the zeolite content) and biotic composition (the appearance of "primitive" agglutinated quartz–siliceous benthic foraminifera and abundant radiolarians).

(4) Radiolarian biostratigraphic data show the alternation of cool and warm pulses during the Sukhodol stage. A distinctive cooling pulse was reconstructed for the terminal phase of the Sukhodol stage (likely, early Maastrichtian), probably, corresponding to a global cooling event, which was previously correlated with the accumulation of polar ice caps (Miller et al., 1999). Because the Sukhodol stage spanned approximately 0.3 m.y., the duration of four episodes of sea-surface temperature fluctuations was estimated to be very short (about 70–90 k.y.).

## ACKNOWLEDGMENTS

The authors thank M.S. Boiko and M.N. Ovechkina for field description of sections and sample collection, E.M. Spiridonov for providing a pure heulandite sample, and G.N. Aleksandrova for assistance with sample preparation for analysis.

This study was supported by the Russian Federation for Basic Research (projects nos. 10-05-00308, 12-05-00196, and 12-05-00690).

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*Translated by N. Kravets*