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Eustatic, tectonic, and climatic signatures in the Lower Cretaceous siliciclastic succession on the Eastern Russian Platform

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ABSTRACT

A methodical approach to identifying major abiotic events in the siliciclastic succession accumulated in the shallow epicontinental basin on the Eastern Russian Platform during the Early Cretaceous is presented. On the basis of a reliable chronostratigraphic framework a comparison between global and regional sea level curves was undertaken. The intervals during which the global and regional sea level curve trends are similar correspond to a predominance of eustasy in the particular basin. Alternatively, tectonic activity dominates during intervals when there is no similarity between the trends of the global and regional sea level curves. Three intervals of non-coincidences of trends of these two curves matched with major tectonic events that took place within the Eastern Russian Platform in the Early Cretaceous: the Early Hauterivian tectonic uplift, subsequent Late Hauterivian subsidence and the Late Albian uplift. The main consequences of the tectonic activity were two large regional unconformities and hiati. The comparison of main global and regional sea level trends also reveals major climatic events. "The cold snaps" that occurred during the Early Cretaceous greenhouse world (Hu et al., 2012) coincided with simultaneous global and regional sea level lowstands, peak shallowing of the basin and the almost complete absence of sediments. "The cold snap" is identified in the Late Aptian sedimentary sequences on the Eastern Russian Platform.

1. Introduction

An extensive amount of published data on sequence stratigraphy shows that the subdivision of geological successions into sequences, together with the analysis of tectonic activity and eustatic changes, allows for a deeper understanding of basin evolution. Thus, genetic relationships between the Lower Cretaceous sediments of the Russian Platform and global sea level changes in conjunction with tectonic activity and sediment supply were defined by analyzing a voluminous amount of well data from the Central Russian Platform (Sahagian and Jones, 1993; Sahagian et al., 1996) and on the basis of reliable chronostratigraphic analyses of the particular sections and further regional-scale investigations on the Eastern Russian Platform (Zorina, 2009; Zorina et al., 2009; Zorina, 2012). The most important results of the latter were the regional sea level curve and the regional tectonic curve that have been produced for the Mid Jurassic–Lower Cretaceous of the Eastern Russian Platform (Zorina, 2012).

In this study a new methodical approach for identifying major abiotic events in the Early Cretaceous epicontinental Russian sea is presented. It is shown that tectonic subsidences–uplifts and the so-called climatic "cold snaps" can be detected by the comparison between global and regional sea level curves. Importantly, widely discussed Early Cretaceous cooling events can be identified in the geological sections without isotopic and other "high-tech" data. The causes and consequences of major Early Cretaceous abiotic events on the Eastern Russian Platform, including Oceanic Anoxic Event-1a (OAE-1a), are also discussed.

It should be noted that the results of present study, based on the basin depth estimations, strongly differ from the recent analysis attempted by Zorina and Ruban (2012) in which shoreline shifts (reflecting transgressions and regressions) were taken into account. An urgency of such a distinction was previously argued by Ruban (2007) and it was recently clarified by modeling different transgressive–regressive and shallowing–deepening situations in the sedimentary basin (Zorina, 2014).

2. Geologic setting and chronostratigraphic position of the Lower Cretaceous megasequences

Current understanding of the occurrence and distribution of the Lower Cretaceous deposits within the Eastern Russian Platform (Fig. 1) is mainly the result of voluminous stratigraphic data that have been compiled and published (e.g., Sasonova and Sasonov, 1967; Vereshchagin and Ronov, 1969; Chirva, 1993). However, this information is not used for the purposes of chronostratigraphy.

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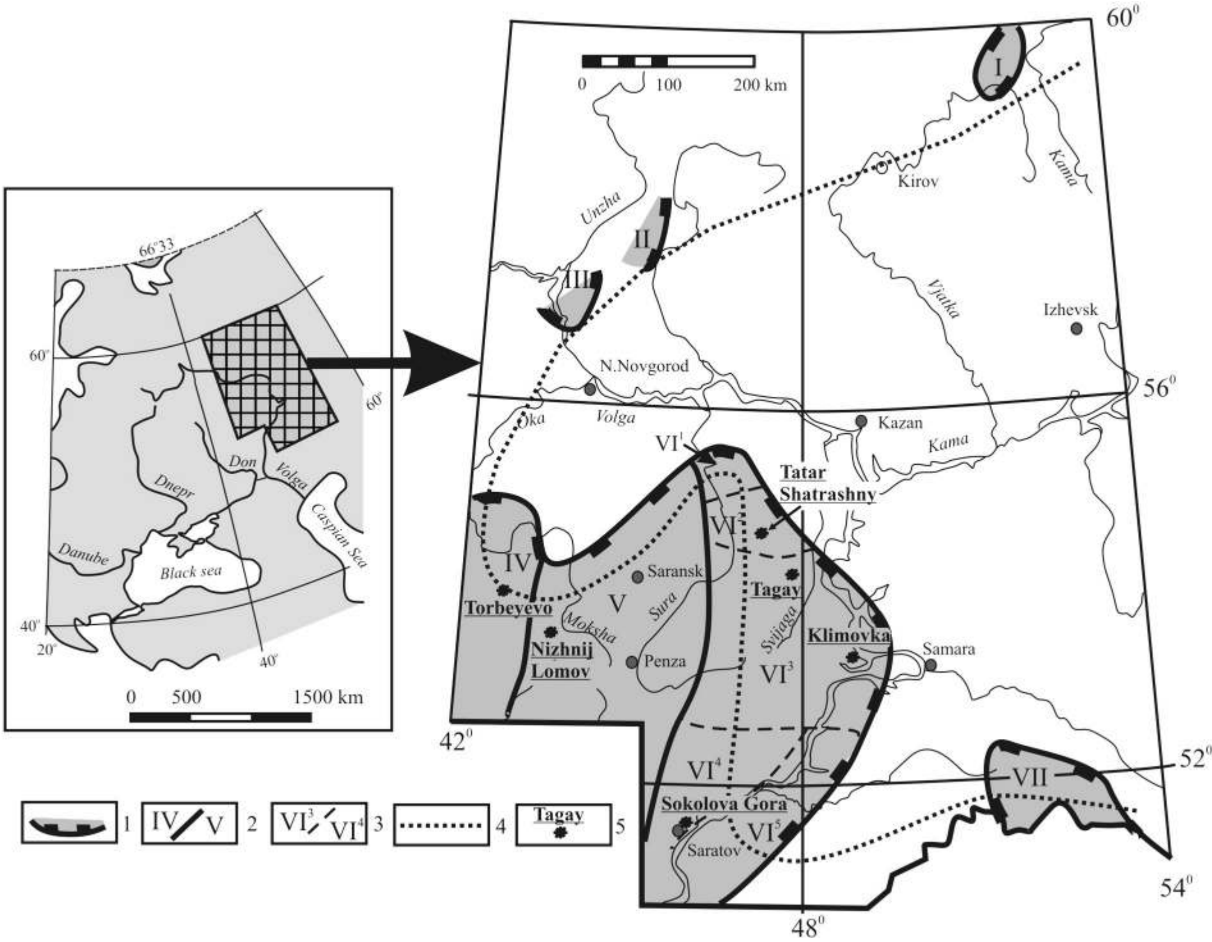

Fig. 1. Location of studied territory and structural zoning of the Lower Cretaceous deposits of the Eastern part of the Russian Platform. Legend: 1 — spread of the Lower Cretaceous; 2 — boundary of structural-geological zones; 3 — boundary of structural-geological subzones; 4 — the profile line through all the zones and subzones; and 5 — location of Boreholes. Structural-geological zones and subzones according to the Unificated Stratigraphic Scheme of the Lower Cretaceous Deposits of the Russian Plate (Chirva, 1993) with adds (Zorina, 2009). I — Vjatka–Kama Depression; II — Moscow Syneclise; III — Kovernin Depression; IV — Oka–Don Depression; V — Murom-Lomov Trough; VI — Ulyanovsk–Saratov Trough: VI^1 — Cheboksary Volga Region, VI^2 — NE part of the Ulyanovsk–Saratov Trough, VI^3 — Ulyanovsk–Samara Volga Region, VI^4 — Saratov Right Bank Region, and VI^5 — Saratov Left Bank Region; and VII — Buzuluk Depression.

The Lower Cretaceous siliciclastic sediments are represented mainly by clays and sandstones, with a maximum thickness of 450 m. They are underlain by the Upper Tithonan sandstones with pebbles, bituminous shales and clays, or by the Callovian clays in some areas. The Lower Cretaceous deposits are overlain by the Cenomanian calcareous sandstones, or by the Turonian–Coniacian marlstones or chalks.

In the Early Cretaceous the Eastern Russian Platform was an area of inner shelf sea, which was connected episodically by N–S oriented channels with the South and Boreal seas (Sasonova and Sasonov, 1967). Based on quantitative analyses of benthic foraminiferal communities, its depth is estimated at about 200 m, varying in the range from 150 m to 350 m (Zorina, 2013).

It was established (Zorina, 2009, 2012), that Lower Cretaceous strata within the Eastern Russian Platform stack to form three siliciclastic megasequences that were developed as a result of regional sea level fluctuations and climate changes.

Meanwhile, the major features of the geologic history of the studied area (Fig. 1) can only be identified using a reliable chronostratigraphic framework. A reliable and accurate basis for sequence stratigraphic and paleoenvironmental reconstructions was made as the results of the comprehensive litho- and biostratigraphic investigations of more than 200 borehole sections and outcrops (Figs. 2, 3). More than 100 of them were used in the compilation of the composite section of the northeastern Ulyanovsk–Saratov Trough (Zorina, 2009) (Fig. 4). The latter was compared with the regional stratigraphic scheme of the Lower Cretaceous deposits of the Eastern Russian Platform (Chirva, 1993) and correlated with the Geological Time Scale (Gradstein et al., 2012) (Fig. 4).

To ensure a robust and complete chronostratigraphic description of the study deposits, a comparison of regional composite sections of the Eastern Russian Platform was undertaken. Each of the sections has the detailed ammonite zonation, with the Boreal standard ammonite zone of the Lower Cretaceous (Baraboshkin, 2004) (Fig. 4). In addition, all the sections were tied to the timescale of Gradstein et al. (2012) that provided absolute ages for eustatic, tectonic and climatic events. Thus, the proposed chronostratigraphic scheme of the Lower Cretaceous of the Eastern Russian Platform (Fig. 4) reflects the state-of-the-art stratigraphy of the study area and certainly requires a continuous updating by new stratigraphic data.

The chronostratigraphic differentiation of the Lower Cretaceous sections revealed a series of continuously accumulating sediments with large dividing stratigraphic hiati (Fig. 4). As the duration of each of these continuous lithologic series varies from 5 to 20 Myr they are distinguished as megasequences according to the hierarchy by Vail et al. (1991).

In the studied area three megasequences are clearly identified (Fig. 4): Valanginian, Upper Hauterivian–Aptian, and Albian. They are well characterized by ammonites belonging to ammonite zones (Baraboshkin, 2004), which allow the studied strata to be correlated with Geological Time Scale (Gradstein et al., 2012).

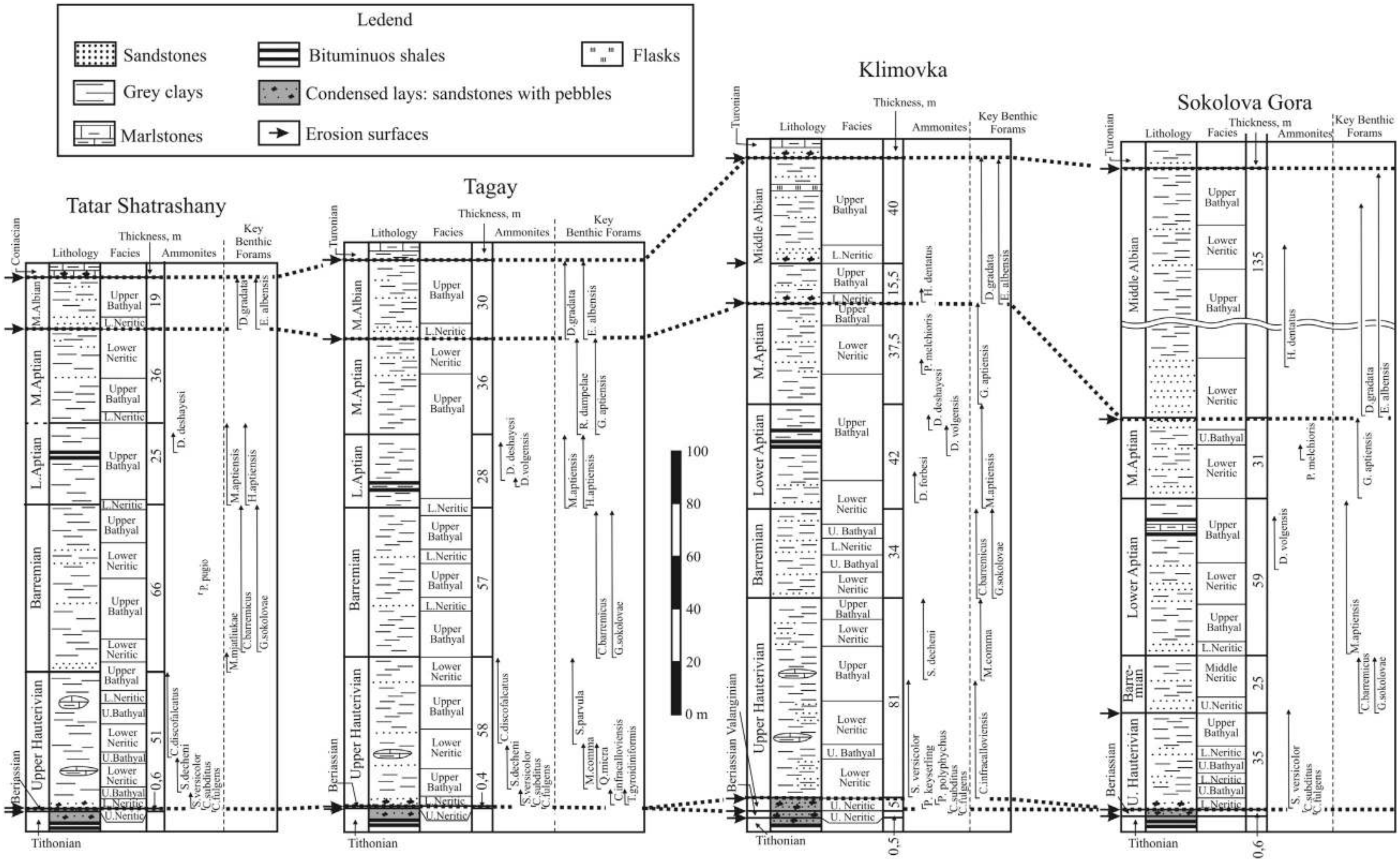

Fig. 2. N–S correlation between borehole sections from the Northern Ulyanovsk–Saratov Trough till the Right Bank of the Saratov Volga Region, based on lithology, facies, major ammonites and benthic foraminifera occurrences.

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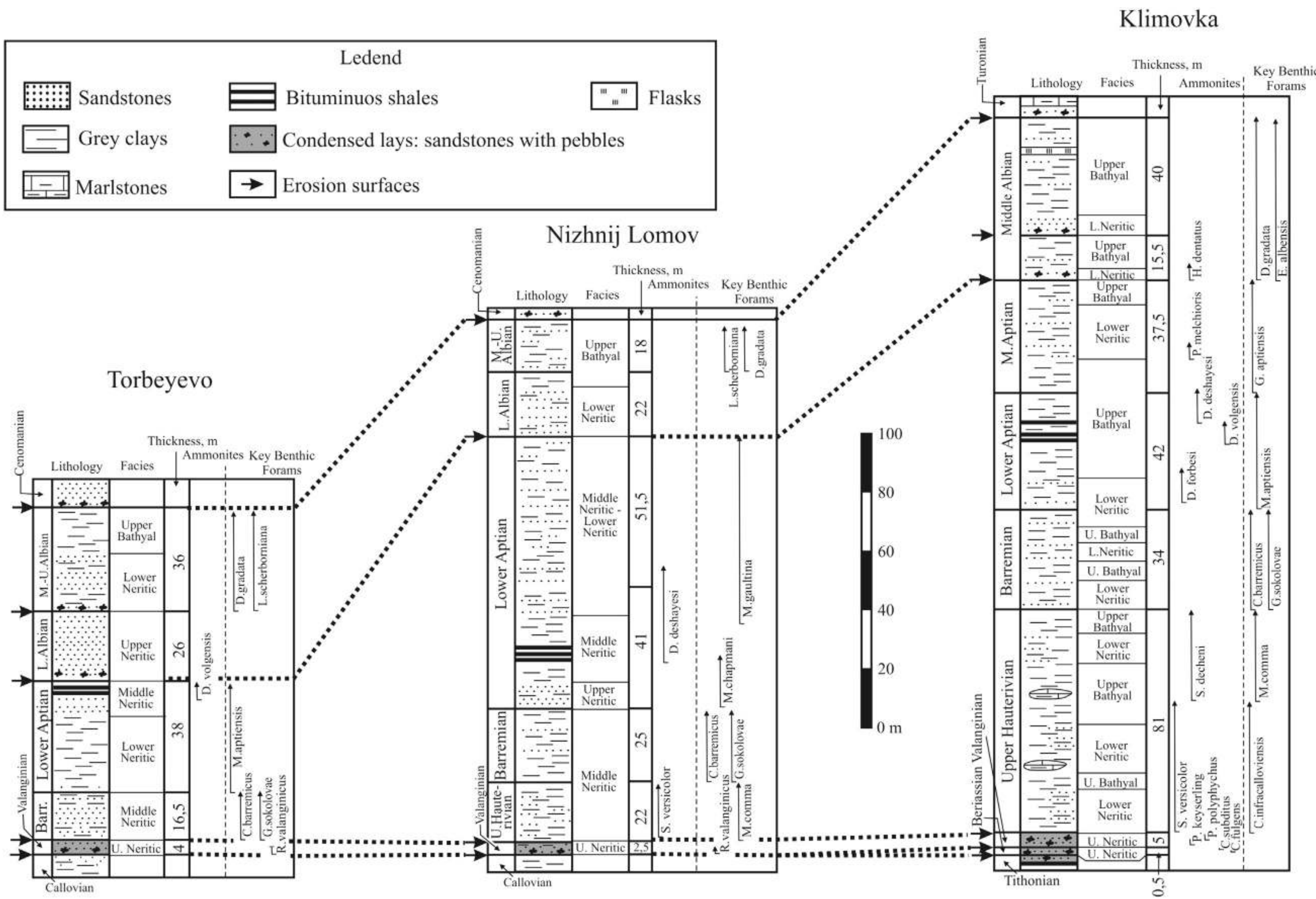

Fig. 3. W–E correlation between borehole sections from the Oka–Don Depression till the Ulyanovsk–Samara Volga Region, based on lithology, facies, major ammonites and benthic foraminifera occurrences.

The underlying deposits are represented by the terminal strata of the Oxfordian–Berriasian megasequence, including the lowermost Cretaceous (Berriasian) strata. The Berriasian eroded and condensed sediments, with a total thickness about 1 m, are not distributed ubiquitously (Zorina et al., 2009) (Figs. 2–4). They consist mostly of green, glauconite-bearing, fine-grained sandstones, and phosphorite-bearing conglomerates. Ammonites *Kachpurites fulgens* (Trautschold, 1861), and *Craspedites* cf. *okensis* (d'Orbigny, 1845) are quite abundant there, allowing for the strata to be correlated with Lower Berriasian *Kachpurites fulgens*, *Craspedites subditus* and *Craspedites nodiger* Zones (Baraboshkin, 2004).

The Valanginian megasequence is also fragmentary. It is presented predominantly by greenish-gray, glauconite-bearing, and phosphorite-bearing conglomerates with interlayers of glauconite-bearing sandstones and carbonate-free clays. These strata also show evidence of strong erosion and condensation. The total thickness varies from 0 to 5 m. The strata contain ammonites *Polyptychites michalskii* (Bogoslowsky, 1902), *Polyptychites* cf. *keyserlingi* (Neumayr & Uhlig, 1881), *Polyptychites polyptychus* (Keyserling, 1846), and *Temnoptychites mokschensis* (Bogoslowsky, 1902) which are widely distributed within *Polyptychites michalskii* and *Polyptychites polyptychus* Lower Valanginian Zones.

The Upper Hauterivian–Aptian and Albian megasequences cover the whole territory of the Eastern Russian Platform. They both consist of dark gray, carbonate-free clays, with rare interlayers of quartz sandstones. The total thickness of the Upper Hauterivian–Aptian megasequence is about 290 m, and the Albian megasequence is 130 m in thickness. Importantly, the Upper Hauterivian–Aptian megasequence includes bituminous clayey strata of low thickness (3–5 m) related to Early Aptian OAE-1a (Gavrilov et al., 2002) (Figs. 2–4).

Ammonites are abundant in the Upper Hauterivian–Aptian strata: *Speetoniceras versicolor* (Trautschold, 1865), *Simbirskites coronatiformis* (M. Pavlow, 1886), *Speetoniceras inversum* (M. Pavlow, 1886), *Simbirskites pavlovae* (Tschernova, 1951) from the Upper Hauterivian *Speetoniceras versicolor* Zone, *Craspedodiscus discofalcatus* (Lahusen, 1874) from the Upper Hauterivian *Craspedodiscus discofalcatus* Zone, *Praeoxyteuthis hibolitiformis* (Stolley, 1925) from the Lower Barremian *Praeoxyteuthis hibolitiformis* Zone, *Praeoxyteuthis jasikofiana* (Lahusen, 1874) from the Lower Barremian *Praeoxyteuthis jasikofiana* Zone, *Praeoxyteuthis pugio* (Stolley, 1906) from the Lower Barremian *Praeoxyteuthis pugio* Zone, *Aulacoteuthis speetonensis* (Pavlow et Lamplugh, 1892) from the Lower Barremian *Aulacoteuthis descendens* Zone, *Oxyteuthis brunsvicensis* (Strombeck, 1861) from the Upper Barremian *Oxyteuthis brunsvicensis* Zone, *Oxyteuthis germanica* (StoHey, 1925) from the Upper Barremian *Oxyteuthis germanica* Zone, *Oxyteuthis lahuseni* (Pavlow, 1901) from the Upper Barremian *Oxyteuthis lahuseni* Zone, *Deshayesites tenuicostatus* (von Koenen, 1902) from the Lower Aptian *Deshayesites tenuicostatus* Zone, *Deshayesites volgensis* (Sasonova, 1958) from the Lower Aptian *Deshayesites volgensis* Zone, *Deshayesites deshayesi* (Leymerie in d'Orbigny, 1841) from the Lower Aptian *Deshayesites deshayesi* Zone, and *Tropaeum* (*T.*) *bowerbanki* (J. de C. Sowerby, 1837) from the Lower Aptian *Tropaeum* (*T.*) *bowerbanki* Zone (Fig. 4).

Albian strata are poor in ammonites. They are usually correlated with a chronostratigraphic chart using forams Zones (Figs. 2, 3).

The abovementioned biostratigraphical data enabled the Lower Cretaceous megasequences to be correlated with the Geological Time Scale (Gradstein et al., 2012) and the chronostratigraphic scheme of the Eastern Russian Platform to be presented (Fig. 4).

3. Methods

According to previous studies (Sasonova and Sasonov, 1967; Vereshchagin and Ronov, 1969) and recent paleobasin and paleobathymentic investigations (Zorina, 2009, 2012, 2013), two facies within Lower Cretaceous sediments on the Eastern Russian Platform were distinguished: (a) coast-marine sandstones and conglomerates; and (b) shallow shelf mudstones (Fig. 4).

The analysis of facies changes of sediments in time and in the lateral direction allowed for the assessment of the dynamics of the basin depth and for the construction of a regional sea level curve (Zorina, 2009) (Fig. 4). This curve is accompanied with generalized trends of shallowing and deepening of the basin. The paleobathymetric curve, drawing upon the basis of the quantitative analyses of the Lower Cretaceous benthic foraminifera in conjunction with the investigations of the habitat characteristics of the calcareous and agglutinated forms, is presented to improve the depth variations in the Early Cretaceous (Zorina, 2013).

The obtained framework was supplemented by the Early Cretaceous global sea level curve (Haq, 2014) and the stages of eustatic fluctuations which proved to be very informative in further comparisons.

Differentiation in the influence of eustasy and tectonic activity was provided by comparing the global sea level curve with the constructed regional sea level curve. The intervals where a similarity between trends of curves is observed correspond to the predominance of eustasy; whereas tectonic activity dominates at the stages of noncoincidence in the sedimentation process. This was a key approach to draw up a relative tectonic curve and identify major tectonic events expressed in subsidence or uplift (Fig. 4).

Additionally the comparison of main global and regional sea level trends reveals major climatic events. "The cold snaps" (Hu et al., 2012; Maurer et al., 2013) coincided with simultaneous eustatic lowstands, peak shallowing of the basin and the almost complete absence of sediments.

4. Results and discussions

4.1. Stages of eustasy and regional sea level changes

The evolution of the general trend of the global sea level curve in the Early Cretaceous (Haq, 2014) is represented by several major stages (Fig. 4). The time span from the beginning of the Early Cretaceous through the Berriasian is marked by a continued sea level fall. This time interval completes a large global cycle that is accepted to have begun in the late Bajocian (Middle Jurassic) with a sea level rise (Haq, 2014). Following a sea level peak in the Middle Kimmeridgian, the Late Tithonian–Early Berriasian mark a stable eustatic fall. The Late Berriasian marks a sea level rise, the beginning of a new eustatic cycle with maximum highstand during the Late Hauterivian–Early Barremian. A subsequent gradual fall in sea level continued to the second half of the Late Aptian. At the turn of the Aptian–Albian, a steady sea level rise opened a new large global cycle. The peak of the latter occurred during the Late Cretaceous. Thus, four stages of global sea level fluctuations are recorded in the Early Cretaceous.

It should be noted that regional sea level fluctuations were not only a result of global sea level changes but also appears to have been influenced very much by increase of the tectonic activity, which largely concealed global eustasy. The tectonic activity is recorded by a relative tectonic curve (Fig. 4), which was derived from the analysis of the variations in areal extent of the lithostratigraphic units through time, changes of sedimentary facies, heterochrony and synchrony of the hiati.

4.2. Comparison of global and regional sea level curves: noncoincidences. Major tectonic events

Three intervals of noncoincidences of trends of global and regional sea level curves matched to major tectonic events that took place within the Eastern Russian Platform in the Early Cretaceous (Fig. 4): the Hauterivian tectonic cycle (uplift–subsidence) and the Late Albian uplift. A short-term regional cycle of the tectonic uplift in the Early Hauterivian and subsequent subsidence in the Late Hauterivian was manifested as a large diachronous hiatus spanning until the Late Early Hauterivian, which is being associated with almost synchronous inundation of the entire studied area. The Late Albian uplift phase is marked

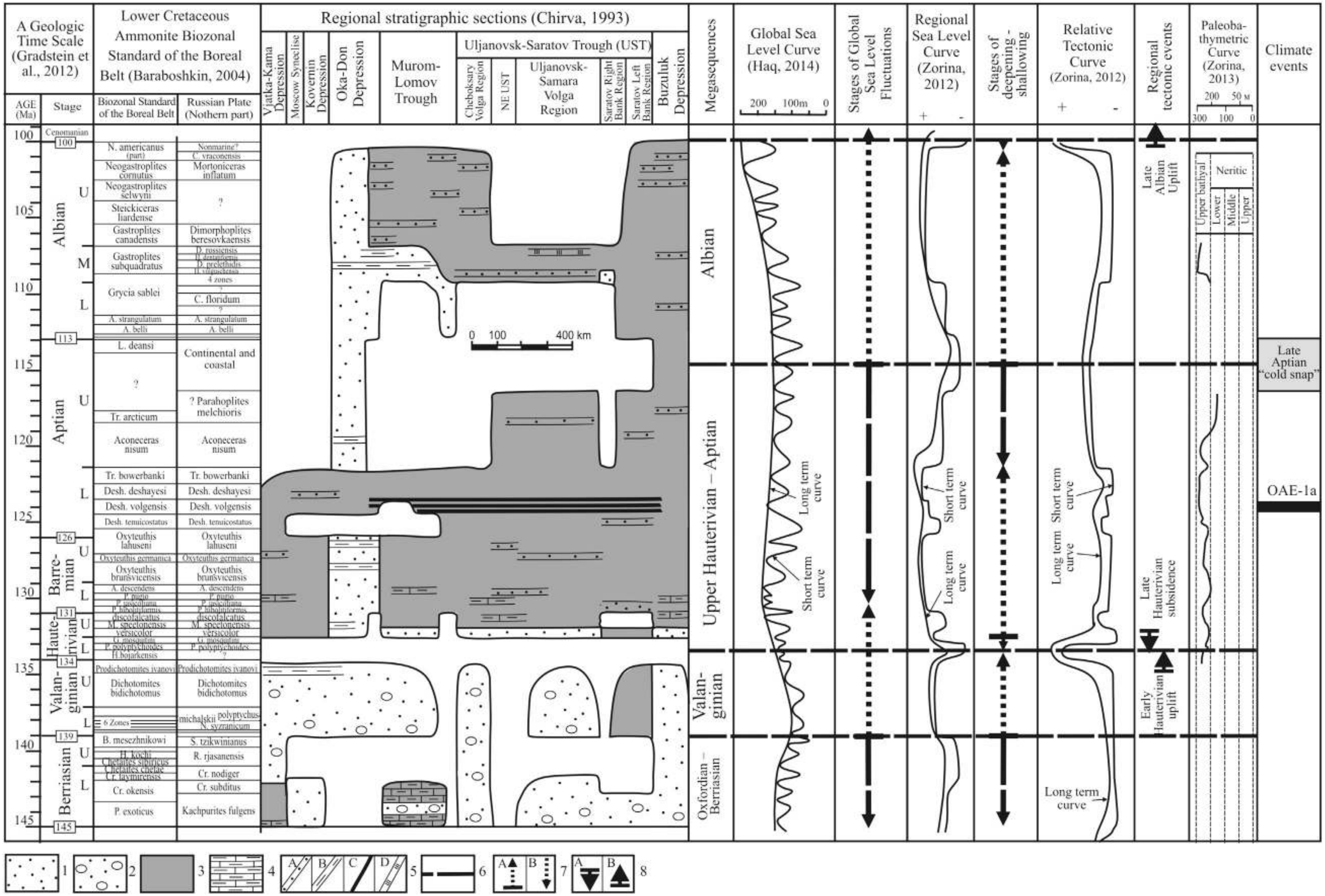

Fig. 4. Chronostratigraphic scheme of the Lower Cretaceous deposits of the Eastern Russian Platform. Legend: 1 — sandstones; 2 — conglomerates; 3 — mudstones; 4 — marls; 5 — interlayers: A — sandstones, B — clays, C — bituminous shales, and D — flasks; 6 — megasequences boundaries; 7A — sea level rise, 7B — sea level fall; and 8 — tectonic events: A — subsidence, and B — uplift.

by a synchronous hiatus that spanned from the Late Albian through the Late Cretaceous during a rapid and stable sea level rise with a global highstand.

In addition to the abovementioned tectonic activity that influenced the entire area of the Eastern Russian Platform, the effects of vertical tectonic movements were also significant in the Late Hauterivian. Thus, the hiati formed in four regions during an overall rise in global sea level (Fig. 4). This situation is in contrast to the Early Aptian. Two consecutive deepening phases have been recognized here during a time of sea level fall, which have formed as a result of two-stage subsidence of the Ulyanovsk–Saratov Trough that appears to have promoted isolation of the basin with anoxic conditions and continuous deposition until Middle-Late Aptian. In the Late Aptian, over half of the Eastern Russian Platform experienced a pronounced fall in sea level, which caused a substantial hiatus.

The consequences of identified tectonic events were the hiati between the Valanginian and the Upper Hauterivian–Aptian megasequences, and between Albian and the lowest Upper Cretaceous megasequences.

On the whole, during the Early Cretaceous the study areas were tectonically unstable, consisting of troughs, depressions, anteclises and uplifts (Sasonova and Sasonov, 1967; Baraboshkin, 2004). Such a heterogeneous structure was typical for the Platform since the Precambrian phase, when the Archean–Proterozoic Craton was initially broken by deep aulacogenes (Shatsky, 1946; Muratov et al., 1975; Khain et al., 2010). The tectonic instability of the Platform is confirmed by differentiation of the structural plan during the Phanerozoic development of the Platform, for instance by appearance of inversion Ulyanovsk–Saratov Trough on the base of Volga–Ural Anteclise (Muratov et al., 1975).

Concerning the possible causes of activation of the tectonic activity, they may be associated with convection processes on the top layer of the mantle (Turcotte and Oxburgh, 1967, 1969; Turcotte et al., 1973; Peltier, 1989). Subsidence of the sea floor away from mid-ocean ridges is caused by the thickening and cooling of the thermal boundary layer at the Earth's surface (Turcotte and Oxburgh, 1967; Müller et al., 2008).

As it was revealed, the present tectonic activity of the Russian Platform links to spreading processes in the North Atlantic and Arctic Areas (Kopp, 2004; Sim, 2008).

4.3. Comparison of global and regional sea level curves: coincidences. Major "cold snaps"

The comparison between global and regional sea level curves revealed two main lowstands; during the late Berriasian and Late Aptian (Fig. 4). These periods are accompanied by hiati in most structural-geological zones on the Eastern Russian Platform except few depressions. Presumably, these lowstands could be caused by the so-called "cold snaps" in the Cretaceous greenhouse world, which are widely discussed and have been confirmed by various methods (Frakes et al., 1995; Miller et al., 2005; Bornemann et al., 2008; Hu et al., 2012; Maurer et al., 2013).

The Late Aptian lowstand interval detected in numerous sections of the Arabian Plate, Australia, Russian Platform and many other places is most likely connected to the global climate cooling. It should be noted that in addition to the previously used methods, this event was identified' by the comparison of global and regional sea level curves that was made possible by using reliable chronostratigraphic framework.

Regarding the Late Berriasian lowstand, there are not so many examples of its manifestation in geological sections globally. Although the lowstand, and associated hiatus, is identified in many sections on the Eastern Russian Platform (Zorina et al., 2008) and in North America (Sloss, 1963). The Late Berriasian deposits need further investigation by detailed paleoecological investigations and isotope analyses in various sedimentary basins.

The main consequence of "the cold snaps" during the early Cretaceous greenhouse world was rapid sea level fall. This is also reflected in the sea level record of the inner basin on the Russian Platform with almost total termination of sedimentation here.

4.4. Oceanic Anoxic Event-1a

As previously mentioned, an anoxic basin was isolated on the Eastern Russian Platform during the early Aptian *volgensis* phase (Baraboshkin and Mikhailova, 2002; Gavrilov et al., 2002; Bushnev, 2005; Zorina, 2009; Zakharov et al., 2013). The Lower Aptian bituminous sediments formed in the upper bathyal zone with estimated depth of about 250 m (Zorina, 2013). Bituminous shales and sheeted calcite concretions ("Aptian Slab") that accumulated in the Ulyanovsk–Saratov and Murom–Lomov troughs and Oka–Don Depression (Fig. 4) are widely interpreted as being a regional manifestation of the global geological episode defined as OAE-la.

It was proposed that the enrichment in organic matter (6–8% C_{org} on average) in the Lower Aptian bituminous sediments was caused by a bloom of bioproductivity of marine plankton including bacterioplankton and phytoplankton (Gavrilov et al., 2002). It has been suggested that the horizon of bituminous shale accumulation was deposited as a result of erosion of nearshore facies during rapid marine transgression after termination of a regressive episode (Gavrilov et al., 2002).

Recently, major isotope investigations of the aragonitic bivalve shells and heteromorph ammonites from the bituminous shales of the lower Aptian deposits of the Ulyanovsk area were undertaken by a group of specialists (Zakharov et al., 2013). Paleotemperatures calculated from oxygen and carbon isotopic analyses showed extremely warm conditions: 24–33.2 °C ($\delta^{18}O$ values fluctuate from −3.6 to −2.2‰; and $\delta^{13}C$ values fluctuate from −3.8 to +1.88‰). It was established that the onset of OAE-1a coincides with a negative carbon isotope excursion (the value of $\delta^{13}C$ fluctuates between −2 and 0‰). This inference agrees well with the isotope analyses obtained from the black shale facies of Italy, Germany, France, Spain, and England where the negative C isotopic anomaly was also recorded at the onset of mid early Aptian OAE-1a (Weissert and Erba, 2004; Zakharov et al., 2013).

According to undertaken constructions, the onset of the bituminous shales is interpreted to reflect the maximum of the Early Aptian global sea level cycle, which in combination with regional sea level highstand and the subsidence in some parts of the Platform may have triggered acceleration of marine transgression in the Volga region at a more modest rate than assumed by the proponents of the short-lived global cycle.

The obtained materials of recent years confirmed that the major forcing mechanisms behind OAEs are an abrupt rise in temperature (Read, 1995, 1998), a decrease in dissolved oxygen in the water (Schlanger and Jenkyns, 1976), a significant increase in the oceanic productivity (Leckie et al., 2002; Erba and Tremolada, 2004), and a decrease of the global ocean circulation probably caused by large-scale Pacific volcanism during the formation of the Ontong Java Plateau, the Manihiki Plateau and the Nova-Canton Trough (Larson and Erba, 1999; Erba and Tremolada, 2004; Tejada et al., 2009; Jenkyns, 2010). This large-scale volcanism is associated with the formation of sediments enriched C_{org} during OAE-1a not only on the Pacific volcanic hills, but also worldwide.

5. Conclusions

Major abiotic events in the epicontinental sea can be identified by the comparison between global and regional sea level curves. Tectonic activity dominated during the intervals where the trends of both curves did not coincide. Alternatively, during the intervals of coincidences eustasy was the predominant process. Three intervals of noncoincidences of trends of global and regional sea level curves matched with major tectonic events that took place within the Eastern Russian Platform in the Early Cretaceous: the Early Hauterivian tectonic uplift, subsequent Late Hauterivian subsidence and the Late Albian uplift. The consequences of identified tectonic events were the hiati between Valanginian and Upper Hauterivian–Aptian megasequences and between the Albian and the lowest Upper Cretaceous megasequences. The comparison of the main global and regional sea level trends revealed major climatic events. "The cold snaps" during the Early Cretaceous greenhouse world (Hu et al., 2012) coincided with simultaneous global and regional sea level lowstands, peak shallowing of the basin and the almost complete absence of sediments. "The cold snap" was identified in the Late Aptian on the Russian Platform. The Lower Aptian bituminous shales and sheeted calcite concretions accumulated on the Eastern Russian Platform are interpreted as being a regional manifestation of the OAE-1a. It has been probably confirmed that the forcing mechanism behind OAE was an abrupt rise in temperature (Jenkyns, 2010).

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