ISSN 0145-8752, Moscow University Geology Bulletin, 2018, Vol. 73, No. 5, pp. 423–433. © Allerton Press, Inc., 2018.
Original Russian Text © R.R. Gabdullin, A.V. Bershov, E.N. Samarin, N.V. Badulina, M.A. Afonin, S.I. Freiman, 2018, published in Vestnik Moskovskogo Universiteta, Seriya 4: Geologiya, 2018, No. 4, pp. 30–41.

The Cyclic and Sequence Stratigraphic Characteristics of the Visean–Serpukhovian Deposits in the Southern Part of the Moscow Syneclise

R. R. Gabdullin[a], *, A. V. Bershov[a], E. N. Samarin[a], N. V. Badulina[a], M. A. Afonin[a], and S. I. Freiman[a]

[a] *Department of Geology, Moscow State University, Moscow, 119991 Russia*
**e-mail: mosgorsun@rambler.ru*

Received January 25, 2018

Abstract—The composition and origin of the Visean–Serpukhovian deposits in the southern part of the Moscow Syneclise have been characterized based upon generalizations of our own results and analysis of published and unpublished data. The levels of karst-influenced rocks correspond to the shallowest biogenic carbonate organogenic-clastic sediments of the initial and final phases of the eustatic cycle, i.e., the early transgression (transgressive system tract) and the late regression (the second half of the high-standing tract). Alluvial sands of the Oka River have been found in the karst cavities. A generalized model of the sequence has been proposed and a sequence stratigraphic interpretation of the studied section has been carried out.

Keywords: Carboniferous, Visean stage, Serpukhovian stage, stratigraphy, sequences, karst, logging, and Moscow Syneclise

DOI: 10.3103/S0145875218050071

INTRODUCTION

Sequence identification in the sections of natural outcrops or wells makes it possible to provide more accurate stratigraphic analysis and correlation of sections and also to understand the course of the geological history in the studied region. It is highly relevant to use the cyclic and sequential methods in the drilling data interpretation when drill sample recovery is insufficient and it is necessary to compare well logs.

The objective of the investigation is to perform cyclostratigraphic and sequence analysis of the Upper Visean–Lower Serpukhovian deposits in the south of the Moscow Syneclise based on the example of southern areas of the Serpukhov city (Fig. 1a, Oka right and left banks). The Serpukhovian lectostratotype section is in the Zabor'e quarry, near the studied area. The considered deposits were thoroughly studied by (Alekseev et al., 2010; Alekseeva et al., 2016; Kabanov, 2004; Kabanov et al., 2009, 2012, 2013, 2014; Makhlina et al., 1993).

MATERIALS AND RESEARCH METHODS

Performed studies: (1) macro- and microscopic petrographic description of the core in more than 50 wells; (2) micro- and macropaleontological study of well logs (more than 100 thin sections); (3) micropaleontological characterization of the studied sections; (4) identification and description of elementary bed cyclites; (5) interpretation of acoustic, radio wave, and gamma-ray logging data; and (6) sequence analysis of deposits and identification of sequence tract systems.

The exploration site as a study object is located south of the Serpukhov city on both banks of the Oka River, where many wells were drilled in the Visean–Serpukhovian deposits. A comprehensive geophysical survey was performed to correlate the studied sections; it included different logging operations.

A range of logging works were performed to estimate the geometry of the karst cavities that are abundant in the studied region, to correct field description of the core (referencing to the section), and to correlate the wells. Paleokarst and young karst were not subject to separation.

Acoustic logging (AL) makes it possible to study the fine layering of a section in detail. AL was used to identify the geometry of the karst cavities in the low-velocity zones (less than 2000 m/s). Karst is commonly confined to deposits in the second half of the high-standing tracts (HST-2) and to the transgressive system tract (TST).

G*amma logging* (GL) data were used to correct the positions of clay intervals in the well logs. Growth was observed in the GL curve at a higher clay content.

Radio wave logging (RWL): the rocks with a lower specific resistivity (ρ_{ef}) and dielectric permittivity (ε_{ef})

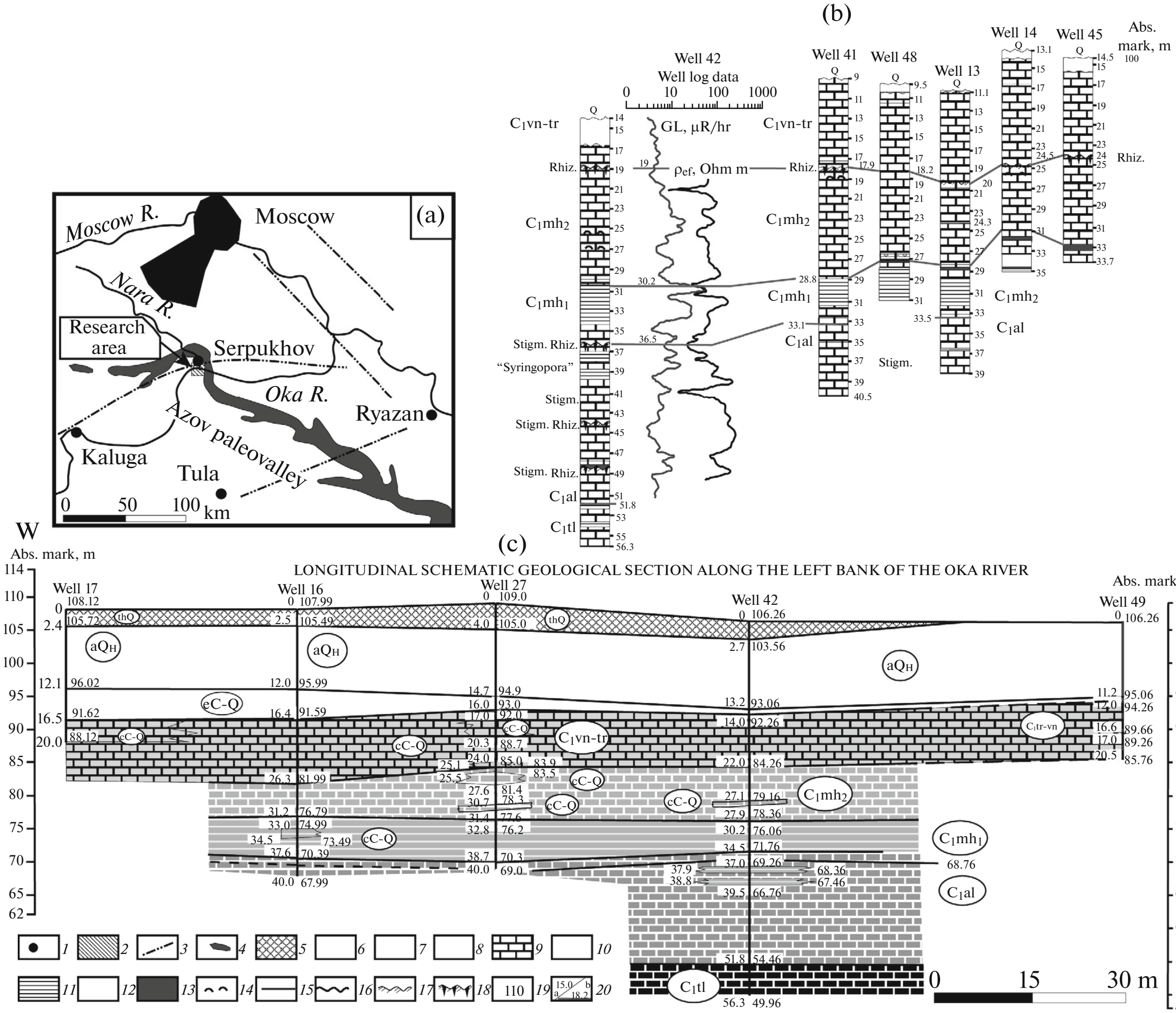

Fig. 1. The location and lithologic–stratigraphic characteristics of the Visean–Serpukhovian deposits: (a) schematic map of the south of the Moscow Syneclise with location of the research area (Azov paleovalley is indicated with grey); (b) comparison of basic wells; (c) longitudinal schematic geological section along the left bank of the Oka River: (*1–4*) in the inset (a): (*1*) settlements; (*2*) research area; (*3*) liniaments, according to (Ulomov, 2009); (*4*) contours (in the inset (a)) and filling (in the inset (b)) of the Azov paleovalley (Makhlina et al., 1993); (*5–20*) in c: (*5*) Quaternary deposits of technogenic genesis; (*6*) Quaternary sand of alluvial genesis; (*7*) sediments of eluvial genesis (crushed stone and broken rocks); (*8*) sediments of colluvial genesis (flour and crushed limestone in sandy–loamy aggregate); (*9*) limestone; (*10*) clay limestone; (*11*) clay, (*12*) aleurite; (*13*) coal (only in c); (*14*) brachiopods *Gigantoproductus*; (*15–19*) geological boundaries: (*15*) conformal, (*16*) nonconformal, (*17*) with silicified hard ground, (*18*) with rhizoids; (*19*) abs. mark (m); (*20*) well depth (a), depth of geological boundaries (m) and correlation line (b). Abbreviations: (Rhiz) rhizoids, (Stigm.) stigmaria.

are characterized by a higher radio wave absorption. The dielectric permittivity increases at higher concentrations of ferromagnetic materials in the section, and a specific electric resistivity falls at a higher porosity. Sandy rocks and sandy differences of clay and carbonate rocks commonly contain ferromagnetic minerals and are easily identified by this method.

Lithologic and Stratigraphic Description

In general, the investigated deposits (Fig. 1c) correspond to the top of the Visean stage (the Tula, Aleksin, Mikhailov, and Venev horizons) and, to a lesser extent, to the Serpukhovian stage (Tarusa horizon). The latter is heavily transformed (eluvium); its presence can most likely be reliably judged in few wells. The Tula deposits (Fig. 1c) were uncovered only by one well, while the Lower Carboniferous roof was composed of crushed stone used to make a single foraminifera determination in the Tarusa horizon. Most of the factual material covers the Aleksin, Mikhailov, and Venev horizons. The stratigraphic breakdown and description of the key wells (Fig. 1c) was carried out by A.S. Alekseev (Moscow State University). Deposits of this stratigraphic range were described in (Alekseev et al., 2015), while breakdown charts were given in (Alekseev et al., 2010, 2013; Heckel and Clayton, 2006; Kulagina, 2008).

Tula horizon. Upper (Olkhovets) subformation (C_1ol_2). Deposits at the top of the Tula horizon were drilled at a depth of 51.8 m (altitude 54.46 m) by a single well through an apparent thickness of 4.5 m; they are composed of interstratified black silty clay, carbonaceous clay with muscovite and marcasite and of grey, durable, layered, and occasionally clayey limestone. The entire core could not be lifted up from the bottom hole; uplifted sand most likely indicated a karst cavity.

Aleksin horizon. Aleksin Formation (C_1al). The horizon consists of monotonously alternating grey, dark-grey massive, thick-plate foraminifer–detritic limestone and indistinctly laminated, thin-plate, detritic limestone. The organogenic material in limestone is up to 60–90%. The deposits of this horizon in the Moscow Syneclise reach 11–36 m in thickness (Makhlina et al., 1993).

According to our investigation results, at the horizon base, the first Aleksin limestone is underlain by a 3-meter member of light grey micaceous clayey aleurolite interstratified with white fine-grained sand and thin clay interbeds.

The multi-ordinal cyclic structure of the stratum is well defined. At the horizon top, the limestone is grey, compact, strong, heavy, slightly cavernous with deep dissolution channels filled by clay with plant detritus (rhizoids). The section top in the horizon consists of an interbedded member as grey or dark-grey limestone, dark-grey detritic marl (dissolved limestone), and sea terrigenous silty clay with crushed brachiopods, lagoon carbonic black clay with detritus, as well as continental silty micaceous grey clay with alluvial sand interbeds. Gradual transitions are observed between them. The limestone member is located lower down. It is followed by a clay member and then limestone again. Grey massive durable breccia-like limestone contains fragments of carbonized tree trunks (for example, Fig. 2b, well 41, int. 36.7–37.5 m). Each member is a few meters in thickness. The limestone roof is marked by small or deep rhizoids filled by calcareous sand or highly micaceous aleurite (muscovite). An extended biostrome *Syringopora* sp. was noted (Fig. 2d). The horizon roof was drilled in the depth range of 31.0–32.0 m (wells 41 and 13, respectively) at an altitude of 68–69 m. The maximum penetrated thickness reached 9.5 m.

Mikhailov horizon. Mikhailov Formation (C_1mh). The horizon is dominated by gray and dark-grey foraminifer–detritic massive limestone alternating with softer unclearly platy microlayered limestone (Fig. 2). The section top in the studied horizon is mostly dominated by grey, yellowish-grey, occasionally grey–black, rarely white limestone that stains the hands (thickness approximately 10 m); it is overlain by aleurite, clay, and clayey limestone (marl) with differences of a few meters in thickness. The dominant limestone strata can contain thin subordinate clay interbeds, while dominant clays can contain limestone interbeds. At the horizon top there are rhizoid limestones and/or marls (paleosoils) with a silicified roof shell (Fig. 2f). The weathering processes occasionally transformed the stratum roof to crushed stone eluvium in a lenticular clayey filling material. The horizon roof is well-traced by abundant large brachiopods *Gigantoproductus* (Fig. 2c) (Makhlina et al., 1993).

According to our observations, the clayey bottom of the horizon is characterized by facies that gradually replace each other: (a) sea black clay (sometimes brecciated) with crushed dissolved white thin-walled monotonous and uniform brachiopod shells with marcasite concretions; (b) lagoon black sooty carbonized clay with vegetable detritus; (c) lagoon continental, marshy silty and sandy clay, sporadic clayey aleurite with coal interlayers (Fig. 2). Terrigenous rock levels enriched in muscovite are observed throughout the studied area. The horizon base contains coal interlayers with a thickness of approximately 0.3 m.

The horizon roof was drilled in the depth interval of 17.9–24.0 m (wells 41 and 45, respectively) in the altitude range of 82–84.3 m. The horizon was 12.0–13.6 m in thickness (wells 13 and 41, respectively).

Venev horizon. Venev Formation (C_1vn). The Venev horizon is dominated by light grey strong fine-detritic foraminifer limestone, which are often spotted. This horizon is characterized by widespread algae limestone with *Calcifolium*. A subordinate role is given to crinoid limestone and grey vague microlayered limestone with thin-walled fossils, which are widespread in the Tarusa horizon (Makhlina et al., 1993).

At the investigated top of these deposits, the first few meters are composed of beige, grey, biodetritic, fragile, highly porous, loose, earthy, highly fractured, and cavernous limestone that stains the hands; the core is therefore obtained as crushed stone, flour, crushed stone in flour, and clay soft plastic filling material. The stratum groundmass is then largely composed of limestone that is slightly less loose and earthy, sometimes clayey, highly clayey in the base, and also of marl, rarely, of soft plastic multicolored clay. In some intervals, limestone is nodular, unevenly cemented, breaks when taken in the hands, with leaching caverns on bioclasts, it can be fragile or extremely fragile. The stratum is highly karst-influenced, and clay–sandy filling material of cavities and caverns is rare. The horizon roof was drilled in the depth interval of 9.0–14.5 m (wells 41, 48, and 45, respectively). The thickness of the horizon varies from 8.9 to 11.4 m (wells 41 and 14, respectively). Oka alluvial sand occasionally occurs in the karst cavities.

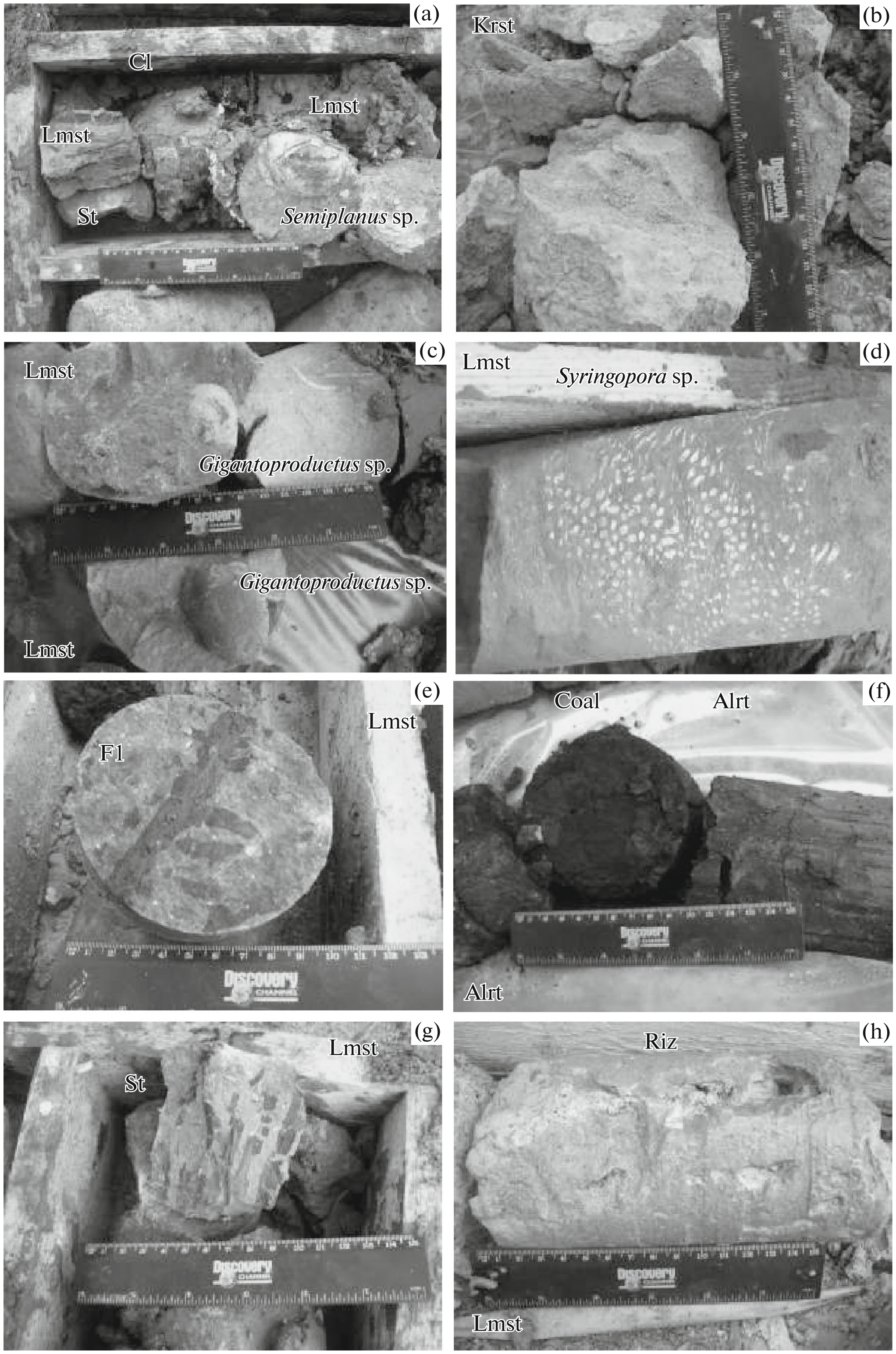

Fig. 2. Photo image of the well core: (a) thin bed cyclicity in the Mikhailov horizon, represented by alternating limestone containing stigmaria or shells of brachiopods *Semiplanus* sp. and clay; (b) wood fragments in paralic limestone of the Aleksin horizon; (c) shells *Gigantoproductus* sp. in the Mikhailov roof; (d) corals *Syringopora* sp. in the Aleksin horizon; (e) stigmaria in Mikhailov limestone; (f) rhizoid limestone in the Mikhailov roof. (Lmst) limestone, (Cl) clay, (St) stigmaria, (Riz) rhizoid limestone.

Table 1. A description of the studied fractures

Well no.	Interval, m	Horizon	Number of fractures, pcs	Description of fractures
20	27.5–28.0	C_1mh_2	1	Large vertical fracture is healed by clay
7	33.7–35.3	C_1al_2	1	Vertical, with a length of approximately 10 cm
7	35.5–38.0	C_1al_1	1	The same
12	20.0–22.0	C_1mh_2	1	
12	25.0–28.0		1	
36	24.7–28.0		1	
38	25.8–28.8		Up to 2 per 1 m of core	Subvertical and inclined (at an angle of 60–90°)

(C_1mh_2) The upper largely carbonate part of the Mikhailov horizon, (C_1al_2) the top of the Mikhailov horizon, above the clay interbed; (C_1al_1) the bottom of the Mikhailov horizon, below the clay interbed.

Paleontological Description

Some macrofauna included brachiopods of the genera *Semiplanus* (Fig. 2a), *Gigantoproductus* (Fig. 2c) and corals (tabulates) of the genus *Syringopora* (Fig. 2d). It was used in subdivision and correlation of the sections. As an example, the roof of the Mikhailov horizon is characterized by numerous *Gigantoproductus* brachiopods. The biostrome *Syringopora* sp. in Aleksin limestone extends from the right to the left bank perpendicular to the Oka River channel for a distance of more than 500 m at a depth of 37–38.0 m (altitude approximately 69–70 m).

In *terms of tectonics*, the exploration site with wells is located in the southern wing of the Moscow Syneclise. Along the Oka River valley, the traced range of faults forms a linear zone separating the second-order tectonic structures: the northern structure as the Serpukhov structural stage and the southern structure as the Aleksin protrusion (Ulomov, 2009). The OSR-97S seismic zoning map of the Russian Federation shows a tectonic lineament extended along the Oka River, near Serpukhov, south of Moscow. This fact explains its straight channel in the investigation site.

Vertical and subvertical cracks that accelerated the karst process and deeply crosscut the core were noted in a number of wells in the Aleksin and Mikhailov limestone strata (Table 1). Alluvial sand likely spilled through them into the karst cavities.

Cyclostratigraphic Description

The Carboniferous deposits of the Moscow Syneclise are characterized by a cyclic structure. The cyclicity of the elementary stratum (with a few centimeters or decimeters in thickness) is grouped into larger cyclites, in the two–four-order sequences. The tectonic factor was negligible or moderate in the Visean–Serpukhovian period, while the glacioeustatic changes in the ocean level related to glaciation and subsequent melting of the Gondwana glacier played a more important role. A cyclic structure of the Visean–Serpukhovian section was noted. In the course of the lithological genetic classification, the deposits were subdivided into fifteen limestone lithotypes corresponding to shallow sea and lagoon (fresh and salty) settings (Makhlina et al., 1993).

The constructed rhythmograms for a number of wells in the sections of the Venev, Mikhailov, and Aleksin horizons made it possible to conduct their layer-by-layer correlation.

The logging records and well core demonstrate well-defined multi-ordinal cyclicity, while the basic trends, for example, the compared gamma-ray logs of stratotype regions, correlate well with the data of previous studies (Makhlina et al., 1993). According to the Golovkinsky–Walther law, the facies are replaced in both vertical and horizontal directions from one well to another. The settings cyclically replace one another from continental settings through lagoon to a sea type. Eustatic variations are reflected in changes in the lithological composition of the rocks, i.e., in changes of their physical properties, leading to variations in the logs. The typical trends of these diagrams and their interpretation from the standpoint of sequence stratigraphy were described in (Gabdullin et al., 2010). The log curves demonstrate progradation, retrogradation, and aggradation strata types corresponding to three paleogeographic settings such as regression, transgression, and stabilization of the shoreline (sea level), respectively.

According to the chronostratigraphic scheme (Heckel and Clayton, 2006), the Venevian and Mikhailovian ages were 3 Ma in duration. This makes it possible to partially associate formation cyclites with cycles of eccentricity with a duration of 1000 ka. Hence, multi-ordinal cycles of the Earth's orbit eccentricity (cycles of 100, 400, 1000 and 2000 ka in duration) are one of the factors that contributed to the formation of the cyclically structured strata.

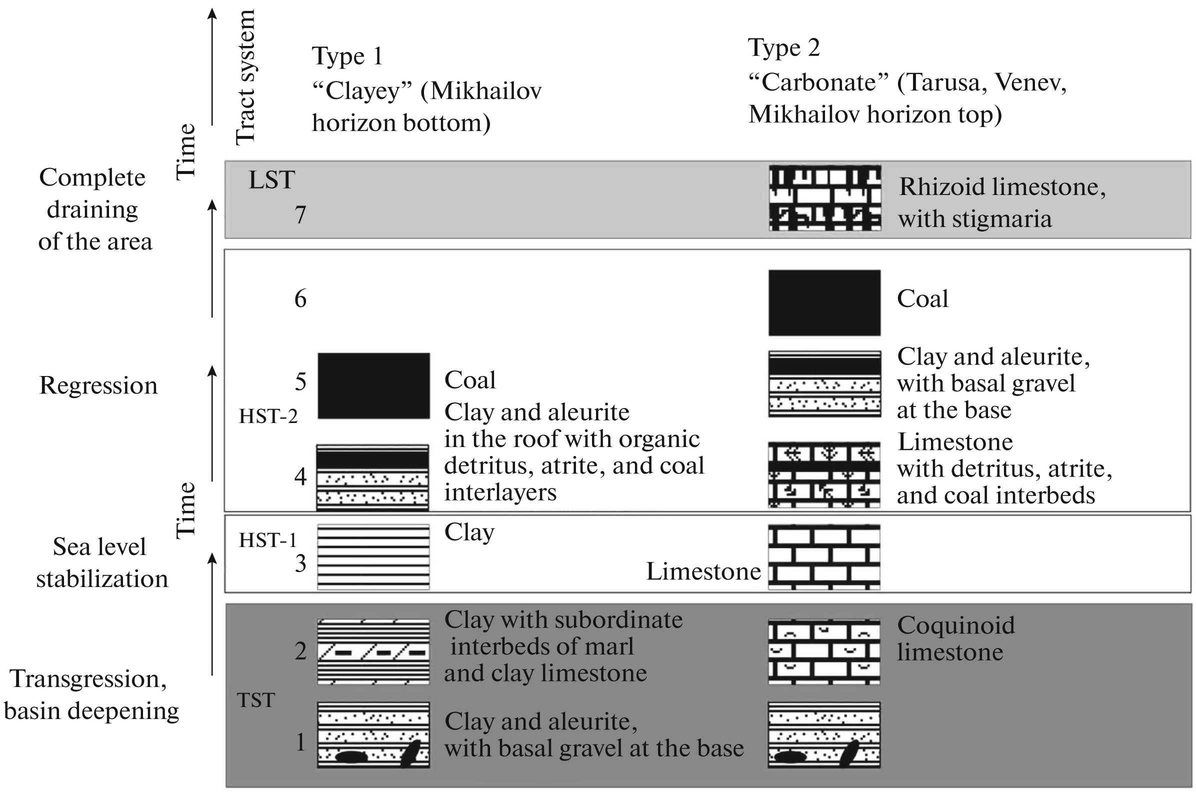

Fig. 3. The summary sections of the sequences.

A Sequence Stratigraphic Description of the Lower Carboniferous Deposits

The epeiric seas of the East European Platform are characterized by the following tract systems: low-standing tracts (LST), transgressive system tracts (TST), and high-standing tracts (HST). These have been considered in a number of works based on the example of the Middle and Upper Carboniferous sections of the Moscow Syneclise and the Upper Cretaceous sections of the Voronezh Anteclise and Ulyanovsk–Saratov trough (Gabdullin, 2010; Gabdullin et al., 2008; 2010; Kabanov et al., 2012; Makhlina et al., 1993, 2001). The LST time is related to incised valleys, in particular, one such valley embedded into the pre-Vereiskian paleorelief is almost 500 km in length; it is filled by sand–clay deposits of the Azov Formation of the Bashkirian stage. It is located somewhat to the north of the studied area. Its incision is 100 m in depth, 2–3 km in width, rarely, 6 km. The Formation is subdivided into lower and upper subformations. The bottom is composed of channel sand or sand–aleurite sediments followed by silty–clayey and clayey deposits of floodplain and liman facies (Makhlina et al., 2001). Paleolandslides over the Lower Carboniferous deposits were noted in its steep southwestern slope near the Serpukhov city.

The investigated area is located in the region with actively changing paleogeographic conditions, often at the facies boundaries. The terrigenous section components such as sea (with small brachiopods), lagoon, coastal plain (with rare brachiopods and carbonized vegetation) clay and aleurite and continental components (muscovite type with carbonized vegetation) correspond to high-standing tract, transgressive system tract or the second half of the high-standing tract (HST-2) and the low-standing tract (LST), respectively (Fig. 3). Clays with coal (a limnic setting) correspond to the transgressive system tract (TST) and the regressive part of the second half of a high-standing tract (HST-2), as well as presumably to a low-standing tract (LST) (Fig. 3). Limestones with coal (paralic setting) mark the transgressive system tract (TST) and regressive part of the second half of a high-standing tract (HST-2) (Fig. 3). Limestone characterizes the first half of a high-standing tract (HST-1) (Fig. 3). Clay limestone corresponds to the end of a transgressive tract (TST) and the start of a high-standing tract (HST).

Limestones with stigmaria mark continental breaks, boundaries of tectonic eustatic cycles and their components, boundaries of sequences, and systemic tracts. They represent a temporary analog of the LST (Fig. 3).

The sequences and their components (the LST, TST, and HST) are clearly identified in the well sections and logs. The logs show a two- and three-membered structure of the formations and subformations (prototype of LST, TST, and HST).

The nature of the cavernous porosity in the limestone massif makes it possible to correlate certain levels of the section with the corresponding sequential tracts. As a rule, the initial transgressive and final regressive limestones (section components) are the most karst influenced. The karst process is confined to the shallowest porous biogenic limestone of the second half of high-standing tracts (HST-2) and the transgressive system tracts (TSTs); it can serve indirectly as an indicator of paleogeographic conditions. The diverse filling material of the karst cavities includes sand, crushed limestone, limestone flour, breccias, and clay (Fig. 4).

Deposits of the Tarusa horizon are local in occurrence, often deeply eluviated, and occasionally hardly distinguishable from the underlying Venev sediments. As follows from well correlation by acoustic logging (without GL and RWL), the karst cavities are confined to the Tarusa–Venev (rare but large), Upper Makhailov (long and extensive) and Lower Mikhailov (extremely rare and small) deposits. Their maximum number tends to the top of the Mikhailov horizon. In addition, according to the data of acoustic and radio wave logging and cross-hole test, the karst cavities are located at the same altimetric level (Figs. 1c, 4).

Hence, the karst rock levels can be correlated with the shallowest and carbonate organogenic clastic sediments of initial and final phases of the sedimentological or eustatic cycle, i.e., with the early transgression and the later regression (Fig. 4a). This approach makes it possible to interpret the karst levels as TST and HST-2 and move from field description of the wells to their sequential eustatic (stratigraphic) interpretation (Fig. 4b).

The replacement of the tract system is reflected in fluctuations of the well-logging records. The eustatic variations in the Mikhailovian and Venevian periods are considered below.

Six variations were established in the Mikhailovian age and three were established in the Venevian (Kabanov et al., 2014). The Mikhailovian eustatic cycles are indicated with the numerals M1–M6, the Venevian is B1–B3, and the Tarussian is T. Fluctuations in the geological section are identical to variations in the log curves (gamma and radio wave logging), which makes it possible to consider variations in the log diagram themselves and their number as a prototype of eustatic or sequential cycles. Thus, in the area under consideration, we established eustatic (or sequential) cycles according to the previous studies [ibid.]. The tract system replacement is also reflected in microscopy of thin sections (Fig. 5). Transgressive system tracts (aleurite, clay, clayey and organogenic limestones such as mudstone, packstone, and grainstone), high-standing tracts (clay, clay limestone, organogenic limestone (packstone), and low-standing tracts (paleosoils and rhizoid limestone with stigmaria) were identified by petrographic analysis.

The log of well 39 (Fig. 5), which has logging results and lithologic descriptions (the core and thin sections), is considered below. The HST is characterized by coarser grains up the section with finer grains for the LST and TST. The system tract boundaries are easily identified by peaks on both or at least one log curve.

The identified sequences are considered in terms of stratigraphy from the top down (Figs. 4, 5) at the bottom of the Tarusa horizon (sequence T), the Venev horizon (sequences B3–B1), and the Mikhailov horizon (M6–M1). It should be noted that the "summary section" of sequences was compiled from the sum of all of the studied wells and all of the available material. It is evident that it is impossible to see sediments of all sequence components, i.e., a complete stratigraphic section, in each well due to a number of issues (for example, a different core recovery).

The sequence T (Tarusa horizon bottom) is represented by detritic limestone, according to microscopy, by bioclastic and also nonlaminated limestone with foraminifers and echinoderms. This sequence is characterized by the presence of the TST and HST. The TST tracts are represented by strong cavernous spotted limestone; according to microscopy; this is bioclastic limestone as packstone. The TST is characterized by a retrogradation trend and the HST shows a progradation trend (Fig. 4) with fine-grained detritic limestone, according to microscopy, with bioclastic limestone as the grainstone. The sequence (tract) boundary was established by changes in the log curve trend. The sequence is 1.8 m in thickness; the TST is 1.2 m and the HST is 0.6 m.

The sequence B3 (the top of the Venev horizon) is composed of organogenic highly fractured limestone with a large number of leaching caverns and consists of the same TST and HST components. The TST is represented by organogenic cavernous limestone: according to microscopy it is bioclastic nonlaminated limestone as packstone and grainstone and is characterized by a retrogradation trend. The HST is characterized by a progradation trend and is represented by organogenic highly fractured limestone, and, according to microscopy, by bioclastic limestone as grainstone. The sequence is 3 m in thickness, the TST is 1.1 m, and the HST is 0.4 m (Fig. 4).

Sequence B2 (the middle part of the Venev horizon) is represented by alternating interlayers of stronger and looser detritic limestone, and, according to microscopy, by bioclastic nonlaminated limestone as grainstone and packstone. This sequence is characterized by an aggradation trend in HST-2. The sequence is 2.7 m in thickness (Fig. 4).

Sequence B1 (the bottom of the Venuev horizon) is represented by cavernous and rhizoid limestone, and, according to microscopy, by bioclastic nonlaminated

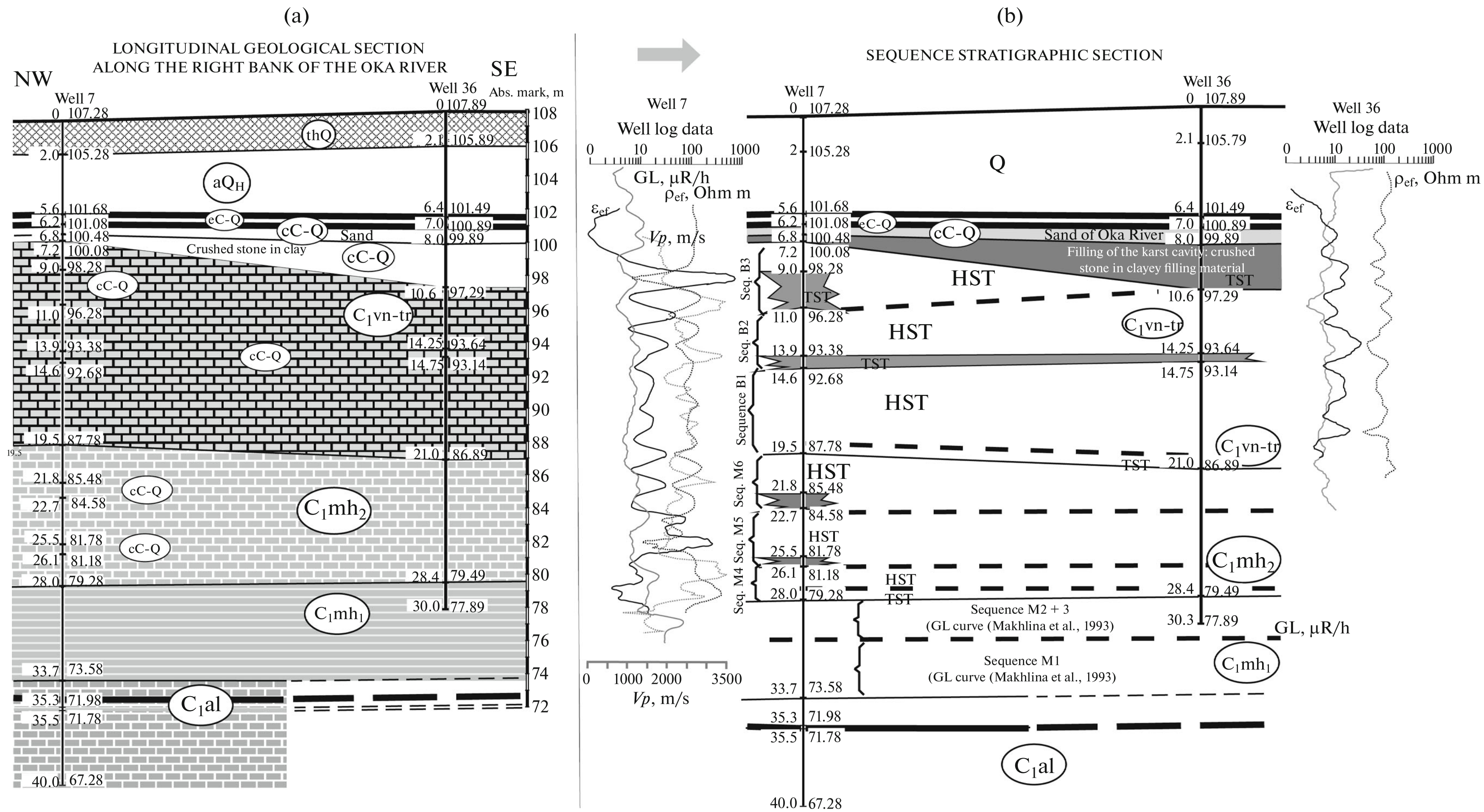

Fig. 4. The sequence stratigraphy description of the Visean–Serpukhovian deposits. (a) Longitudinal geological section along the right bank of the Oka River; (b) a sequence structure model and results of geological survey of the wells (well logging: gamma-ray logging, μR/hr (GL), acoustic logging (AL: longitudinal wave velocity (*Vp*), m/s), and radio wave logging (RWL: specific resistivity (ρ_{ef}) and dielectric permittivity (ε_{ef})). Legend is given in Fig. 1.

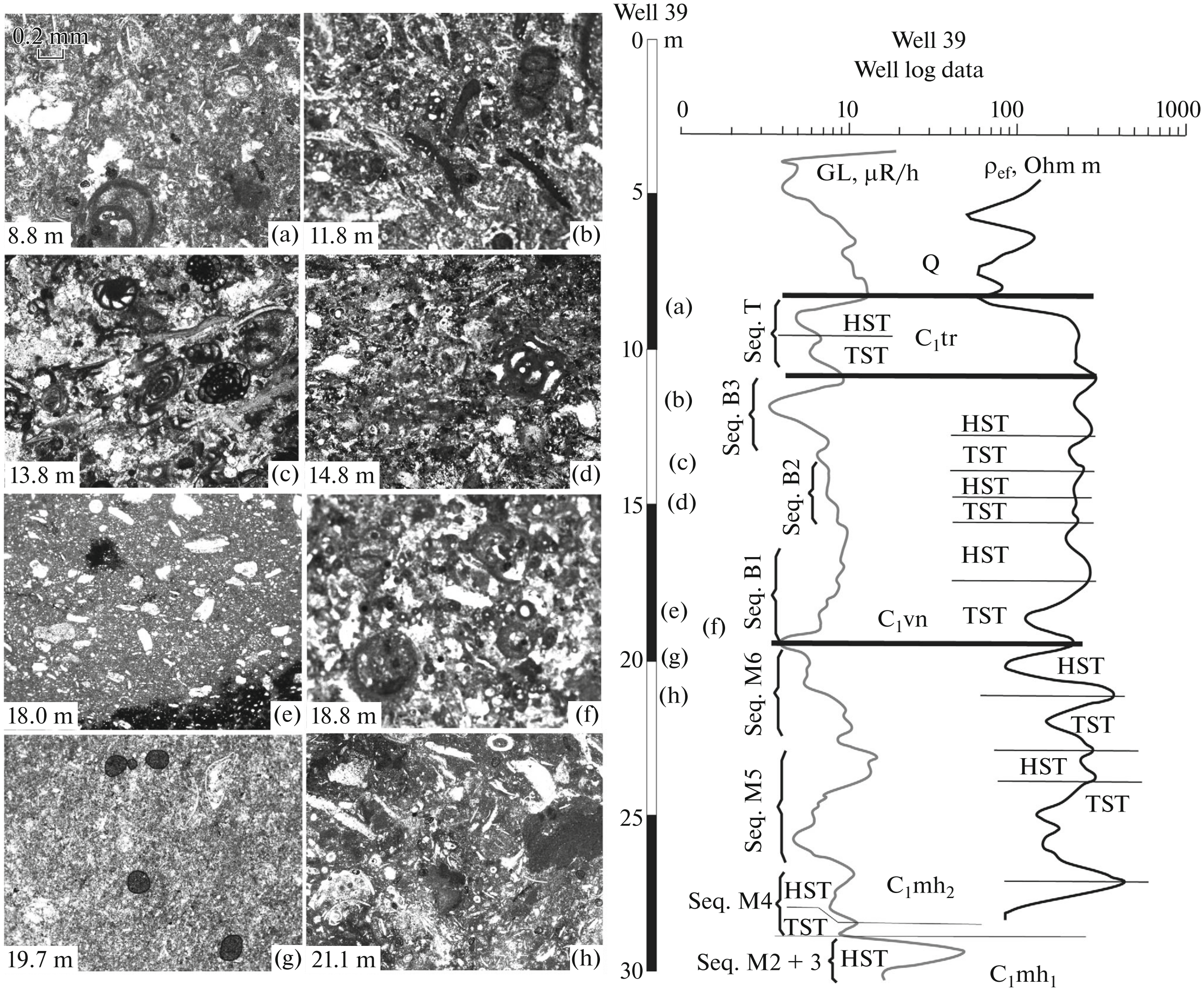

Fig. 5. A petrographic and geophysical description of the Visean–Serpukhovian deposit section in well 39. Left: photo images of thin section in transmitted light: interval 8.30–12.40 m, Tarusa horizon: (a) sample (sam.) 39/8.8 m, packstone, biomorphic limestone; (b) sam. 39/11.8 m, packstone, biomorphic limestone; (c–f) interval 12.40–20.0 m, Venev horizon: (c) sam. 39/13.8 m, grainstone, limestone with bioclasts; (d) sam. 39/14.2 m, grainstone, biomorphic limestone; (e) sam. 39/18.0 m, wackestone, limestone with bioclasts; (f) sam. 39/18,8 м, grainstone, biomorphic limestone; (g–h) interval 20.40–29.50 m, Mikhailov horizon; (g) sam. 39/19.7 m, mudstone, limestone with bioclasts; (h) sam. 39/21.1 m, packstone, biomorphic limestone, interval 33.2–40.0 m. Right: Well log data (gamma-ray logging, μR/hr and specific resistivity (Ohm m)). The position of a sample in the well log is shown with letters.

limestone as grainstone, packstone, and wackestone. This sequence is characterized by LST "traces" (rhizoid limestone) and is 3.3 m in thickness (Fig. 4).

Sequence M6 (Mihailov horizon top) is represented by very strong rhizoid limestone with stigmaria (Figs. 2E, 2F): aerial exposition of HST sediments during the break, this is an analog of the LST. According to microscopy it is bioclastic nonlaminated limestone, largely packstone. The sequence is 1.7 m in thickness, the HST is 0.7 m, and the LST is 1.0 m (Fig. 4).

Sequence M5 (the top of the Mihailov horizon) is represented by limestone with abundant *Gigantoproductus* shells (Fig. 2C), and, according to microscopy, by bioclastic nonlaminated limestone as packstone. The sequence bottom is characterized by the TST (transgression, basin deepening) represented by a retrogradation trend; while the sequence top is characterized by the HST (a progradation trend). The sequence is 18 m in thickness, the TST is 0.8 m, and the HST is 1.0 m (Fig. 4).

Sequence M4 (the middle part of the Mikhailov horizon) is represented by organogenic limestone with leached mollusk bioclasts, and, according to microscopy, by bioclastic nonlaminated limestone as packstone. The sequence is characterized by the TST and

HST. The sequence is 2.4 m in thickness, the TST is 1.3 m, and the HST is 1.1 m (Fig. 4).

The united (Kabanov et. al., 2014) sequence M2 + 3 (the bottom of the Mihailov horizon) is represented by limestone with a large number of black charred plant remains (the limnic strata HST-2 and LST), mainly underground shoots of stigmaria (Fig. 2A). Two system tracts (TST and HST-2) are relatively well defined in the gamma-ray curve (Makhlina et al., 1993). The sequence is at least 1.4 m in thickness, the HST-2 is 1.0 m, and the LST + TST is 0.4 m (Fig. 4).

Sequence M1 (The bottom of the Mihailov horizon) is represented by clay, interbeds of marl and limestone, as well as aleurite. This sequence is characterized by the HST (a progradation trend) and the TST (a retrogradation trend). The sequence is 2.3 m in thickness, the TST is 1.0 m, and the HST is 1.3 m (Fig. 4).

As a result, at least five sequences were identified in the Mikhailov horizon, and three sequences were identified in the Venev horizon. The Tarusa horizon is partially exposed and altered by eluvial processes (one sequence was identified). Only one well was drilled in the Tula horizon.

CONCLUSIONS

(1) The cyclic structure of the Upper Visean–Lower Serpukhovian terrigenous–carbonate deposits in the south of the Moscow Syneclise was established from the well core (field description and petrographic investigation in thin sections) and logging data. Our data are consistent with the previously obtained information.

(2) The cyclic structure of the section is explained by cyclic changes in the paleogeographic sedimentation conditions from continental conditions through lagoon and to shallow sea conditions. The transgressive system tracts (aleurite, clay, clayey and organogenic limestone as mudstone, packstone, and grainstone), high-standing tracts (clay, clayey limestone, organogenic limestone (packstone), and low-standing tracts (paleosoils and rhizoid limestone with stigmaria) were identified.

(3) At least two sequences were identified in the Aleksin horizon, at least five in the Mikhailov horizon, two in Venev horizon, and at least one in the Tarusa horizon (the horizon is partially exposed and altered by alluvial processes). Only one well was drilled in the Tula horizon; it is impossible to identify any sequences.

(4) The tectonic lineament that extend to the south of Serpukhov along the Oka River explains its straight channel at the investigation site. The confinement of the research area to the fault zone is confirmed by slight deformations of the sedimentary cover due to the newest tectonic dislocations, in particular, due to vertical cracks from the surface of the Carboniferous deposits and up to the Aleksin and Mikhailov limestone strata. Alluvial sand of the Oka River likely spilled through these fractures into the karst cavities.

(5) The karst rock levels can be correlated with the shallowest and biogenic carbonate organogenic clastic sediments of the initial and final phases of the sedimentological or eustatic cycle, i.e., with the early transgression and late regression. This makes it possible to interpret the karst levels as a transgressive system tract (TST) and the second half of a high-standing tract (HST-2). A generalized sequence structure model (Fig. 3) has been proposed and a sequential stratigraphic interpretation of the studied section has been carried out (Figs. 4, 5).

ACKNOWLEDGMENTS

This work was supported by PetroModeling Group of Companies and Russian Foundation for Basic Research (project no. 18-05-00495).

REFERENCES

Alekseev, A.S. and Goreva, N.V., Field Meeting of the International Subcommission on Carboniferous Stratigraphy “The Historical Type Sections, Proposed and Potential GSSP of the Carboniferous in Russia”, August 11–18, 2009, *Stratigr. Geol. Correl.*, 2010, vol. 18, no. 5, pp. 555–559.

Alekseev, A.S., Goreva, N.V., Kulagina, E.I, and Puchkov, V.N., Carboniferous system and its “Golden Nails”, *Priroda*, 2010, no. 7, pp. 42–49.

Alekseev, A.S., Kossovaya, O.L., and Goreva, N.V., State and prospects of improvement of the general stratigraphic scale of the Carboniferous System of Russia, in *Obshchaya stratigraficheskaya shkala Rossii: sostoyanie i perspektivy obustroistva* (General Stratigraphic Scale of Russia: Current State and Prospects for Development), Moscow, 2013, pp. 165–177.

Alekseev, A.O., Kabanov, P.B., Alekseeva, T.V., and Kalinin, P.I., Magnetic susceptibility and geochemical characterization of an upper Mississippian cyclothemic section Polotnyanyi Zavod (Moscow Basin, Russia), in *Magnetic Susceptibility Application: A Window Onto Ancient Environments and Climatic Variations, Spec. Publ.—Geol. Soc. London*, 2015, vol. 414, pp. 181–196.

Alekseev, A.S., Goreva, N.V., and Kosovaya, O.L., Ctratigraficheskie skhemy kamennougol’noi sistemy Vostochno-Evropeiskoi platformy: sovremennoe sostoyanie, in *Mater. soveshch. VNIGNI “Sostoyanie stratigraficheskoi bazy tsentra i yugo-vostoka Vostochno-Evropeiskoi platformy”* (Proc. Conf. All-Russ. Res. Geol. Oil Inst. “The State of Stratigraphic Basis of the Centre and Southeast of the East European Platform”), Moscow: All-Russ. Res. Geol. Oil Inst., 2016, pp. 56–63.

Alekseeva, T.V., Alekseev, A.O., and Gubin, S.V., Palaeoenvironments of the Middle–Late Mississippian Moscow Basin (Russia) from multiproxy study of palaeosoils and palaeokarsts, *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 2016, vol. 450, pp. 1–16.

Gabdullin, R.R., Sequence-stratigraphic approach during engineering–geological works, *Moscow Univ. Geol. Bull.*, 2010, vol. 65, no. 6, pp. 410–414.

Gabdullin, R.R., Kopaevich, L.F., and Ivanov, A.V., *Sekventnaya stratigrafiya* (Sequence Stratigraphy), Moscow: Maks-Press, 2008 [in Russian].

Gabdullin, R.R., Ivanov, A.V., Koshelev, A.V., and Kopaevich, L.F., *Trening po sekventnoi stratigrafii. Uchebnoe posobie po povysheniyu kvalifikatsii spetsialistov* (Sequence Stratigraphy Training: Study Guide for Further Education of Specialists), Moscow: Moscow State Univ., 2010 [in Russian].

Heckel, P.H. and Clayton, G., The Carboniferous system. Use of the new official names for the subsystems, series, and stages, *Geol. Acta*, 2006, vol. 4, pp. 403–407.

Kabanov, P., Serpukhovian Stage stratotype in Zaborje quarry (Moscow region). Pt. 2: Subaerial exposure profiles and cyclicity, *Stratigr. Geol. Correl.*, 2004, vol. 12, no. 3, pp. 253–261.

Kabanov, P.B., Gibshman, N.B., Barskov, I.S., et al., Zaborje section. Lectostratotype of Serpukhovian Stage, in *Type and Reference Carboniferous Sections in the South Part of the Moscow Basin. Field Trip Guidebook of Int. I.U.S.C. Field Meet. August 11–12, Moscow*, Moscow, 2009, pp. 45–64.

Kabanov, P.B., Alekseeva, T.V., and Alekseev, A.O., Serpukhovian Stage (Carboniferous) in the type area: sedimentology, geochemistry, mineralogy, and section correlation, *Stratigr. Geol. Correl.*, 2012, vol. 20, no. 1, pp. 15–41.

Kabanov, P.B., Alekseev, A.S., Gabdullin, R.R., et al., Progress in sequence stratigraphy of Upper Visean and lower Serpukhovian of Southern Moscow: Basin, Russia, *Newsl. Carboniferous Stratigr.*, 2013, vol. 30, pp. 55–65.

Kabanov, P.B., Alekseev, A.O., and Zaitsev, T., The upper Visean–Serpukhovian in the type area for the Serpukhovian Stage (Moscow Basin, Russia). Pt. 2: Bulk geochemistry and magnetic susceptibility, *Geol. J.*, 2014. doi 10.1002/ gj.2623

Kabanov, P.B., Alekseev, A.S., Gibshman, N.B., et al., The upper Visean–Serpukhovian in the type area for the Serpukhovian Stage (Moscow Basin, Russia): Pt. 1: Sequences, disconformities, and biostratigraphic summary, *Geol. J.*, 2016, vol. 51, no. 2, pp.163–194.

Kulagina, E.I., Ranges and boundaries of subdivisions of the international stratigraphic scale of the Carboniferous System in the South Urals, in *Geol. Sb.* (Coll. Sci. Works), 2008, no. 7, pp. 205–218.

Makhlina, M.Kh., Vdovenko, M.V., Alekseev, A.S., et al., *Nizhnii karbon Moskovskoi sineklizy i Voronezhskoi anteklizy* (Lower Carboniferous of the Moscow Syncline and Voronezh Anticline), Moscow: Nauka, 1993 [in Russian].

Makhlina, M.Kh., Goreva, N.V., Alekseev, A.S., et al., *Srednii karbon Moskovskoi sinelklizy (yuzhnaya chast')* (Middle Carbonioferous of the Moscow Suncline (Southern Part)), Moscow: Nauchn. mir, 2001.

Ulomov, V.I., Instrumental observations of seismic impacts of East Carpathian earthquakes on the territory of Moscow, *Seism. Stroit. Bezopasn. Sooruzh.*, 2009, no. 3, pp. 34–42.

Translated by E. Maslennikova