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4 Reconstruction of Paleolithodynamic Formation Conditions of Cambrian–Ordovician Sandstones in the Northwestern Russian Platform

G. Berthault[a], **A. V. Lalomov**[b], **and M. A. Tugarova**[c]
[a]28 boulevard Thiers, 78250 Meulan, France
e-mail: berthault.guy@orange.fr
[b]Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences,
Staromonetnyi per. 35, Moscow, 119017 Russia
e-mail: lalomov@mail.ru
[c]St. Petersburg State University, Universitetskaya nab. 7/9, St. Petersburg, 198904 Russia
e-mail: tugarova@mail.ru

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Abstract—Analysis of the paleohydrodynamic characteristics of sedimentation environments allowed us to reconstruct formation conditions of the Cambrian–Ordovician sandstone sequence (COS) in the Leningrad 4 district. Reconstruction of the paleolithodynamic parameters showed that the real timing of the sequence (sedimentation duration) is considerably less than the related stratigraphic scale interval. Such a situation is also encountered in other sedimentary formations. Determination of the real sedimentation rate can affect the assessment of mineral resources in a sedimentation basin.

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1 Lithodynamic processes represent one of the most important factors in the formation of terrigenous sed- 2 imentary sequences. Therefore, the study of paleolithodynamics allows us to elucidate formation con- 3 ditions of clastic rocks. Of special interest is the assess- 4 ment of quantitative parameters of paleolithodynamic processes. Such a possibility is provided by recent studies in the field of hydraulic engineering, hydrodynamics, and geological engineering, which reveal relationships between hydrodynamic characteristics of depositional environments, parameters of the sediment drift (hereafter, just drift), and textural–structural characteristics of rocks. The established regularities (with regard to corrections for the solution of a reverse problem) are used in the reconstruction of 1 parameters of lithodynamic processes in paleobasins.

The study was carried out in several stages to solve the problem:

(1) Reconstruction of hydrodynamic parameters of depositional environments based on the grain size composition and rock textures. Relationships between drift rate (scouring velocity and initial precipitation rate of sediments of the given size) and grain size characteristics of sediments were established based on experimental and natural observations (Hjulstrom, 4 1935; Grishin, 1982). In paleolithodynamic reconstructions, one should take into account that the minimal drift rate is recorded during settling of the trans- 3 ported clastic material on the bottom layer. There is no question that the drift rate was greater during the stable transportation of material (especially in the erosion phase) than that during the formation of a routine sedimentary layer. Since it is impossible to establish the excess value with sufficient reliability in most cases, the drift rate obtained during calculations is minimal.

(2) Based on the calculated values of the paleodrift rate in the facies zone under study the dependence of 5 sediment load on hydrodynamic characteristics of the environment, and the grain size composition of sediments, one can assess the drift capacity.[1] Here, we should take into account that such dependences are commonly empirical, each having its own field of application. For instance, the Chezy equation yields 6 the most reliable results for deep drifts with a relatively fine material if the ratio between drift depth and particle diameter tends to infinity (Julien, 1995); the Bagnold equation (Bagnold, 1956) is applicable to a completely turbulent environment at a great power of drifts; and so on. The validity of choosing a method for the reconstruction of lithodynamic parameters of a 1 specific zone in the basin under consideration determines the accuracy of the results obtained.

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[1] The *drift capacity* means the maximum amount of the material that can move in a unit of time in the alongshore drift of sediments. The *drift power* characterizes the real sediment transport rate. The drift *capacity* and *power* coincide for saturated drifts if the drift is provided with loose material (*Morskaya*..., 1980).

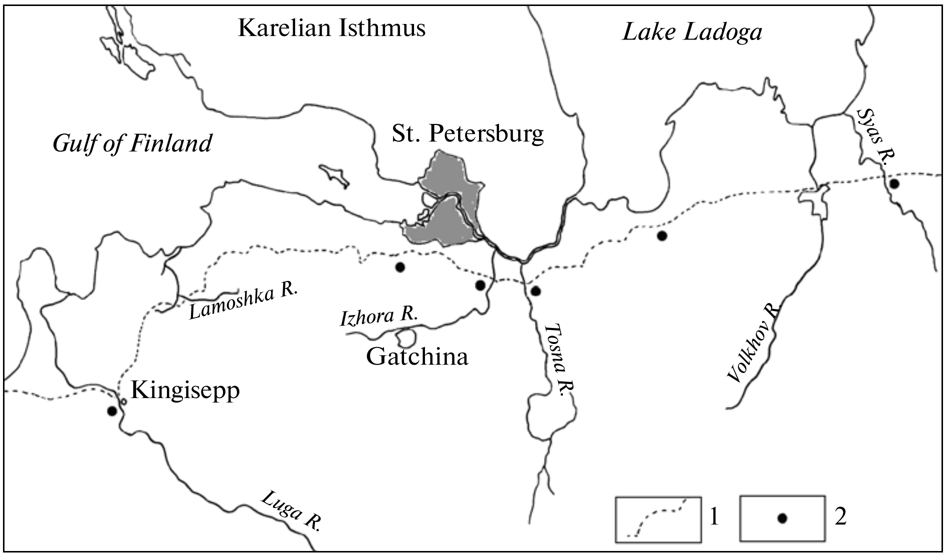

Fig. 1. Sketch map of the study region.
(1) Baltic–Ladoga Glint; (2) location of reference sections.

(3) Based on geometric parameters of the formation under study (length in two perpendicular directions and average thickness), estimates of the drift capacity within the paleofacies zone, the partial erosion section of this rock complex, and the stability of paleodrift direction, we can assess the real sedimentation timing for this formation using the model of “reservoir sedimentation” (Julien, 1995).

INVESTIGATION OBJECT

1 The lithodynamic reconstruction was carried out for the sandy part of the Cambrian–Ordovician sequence located in the Leningrad district. First geological data on the section were obtained as early as the 19th century. Stratigraphic, paleontological, and lithological results of later investigations (Rukhin, 1939; Ul’st, 1959, and others), as well as information published recently (*Geologiya...*, 1991; Popov et al., 1989; Dronov and Fedorov, 1995, and others) allowed a substantial lithostratigraphic subdivision of the section, but this statement mainly concerns with the Ordovician clay–carbonate part. The sandy part of the Cambrian–Ordovician sequence remains a complicated object for stratigraphers and is poorly subdivided into individual layers that could be traced from one exposure to another.

Field works on the study of Cambrian and Ordovician rocks in the Leningrad district were carried out in sections considered as reference ones for the region. Most attention was concentrated on exposures in the Tosna and Sablinka river valleys, where the terrigenous sandy sequence between Lower Cambrian “blue clays” and Lower Ordovician black shales of the Pakerorot Horizon is completely exposed. A series of exposures in the Izhora, Volkhov, and Syas river valleys were also studied (Fig. 1).

In terms of tectonics, the sequence under study is located at the northwestern periphery of the Moscow Syneclise that was formed in the terminal Proterozoic. This area was predominated by epeirogenic movements that governed its regressive–transgressive nature (Geisler, 1956). In the early Paleozoic, a shallow-water sea basin with a high hydrodynamic activity existed within the northwestern Russian Platform. The northern boundary of the basin was governed by the position of the Baltic Shield, which served as a source of clastic material for the sedimentation area. Weathering 3
crusts have not been established in the Baltic Shield proper, but mineralogical maturity of the clastic 3
material transported to the sedimentation basin (the content of unstable minerals in the heavy fraction of COS does not exceed 10–15%) indicates a deep chemical weathering of rocks in the provenance (Gurvich, 1978).

The sequence is divided into the following three formations from the bottom to top (Fig. 2).

The Middle Cambrian Sablinka Formation (Є$_2$sb). Classic exposures of the formation are located in the Tosna River valley near the Settlement of Ul’yanovka. The Sablinka Formation is composed of light gray, pinkish, yellowish (ferruginized in places), well-graded, fine-grained, poorly cemented quartzy sandstones with plastic brownish gray clay interlayers 0.5–1 cm thick.

The Sablinka Formation is divided into two subformations that are similar in the lithological composition but different in textures: horizontal parallel-bedded structures with ripple marks and fine criss-cross lamination predominate in the lower subformation;

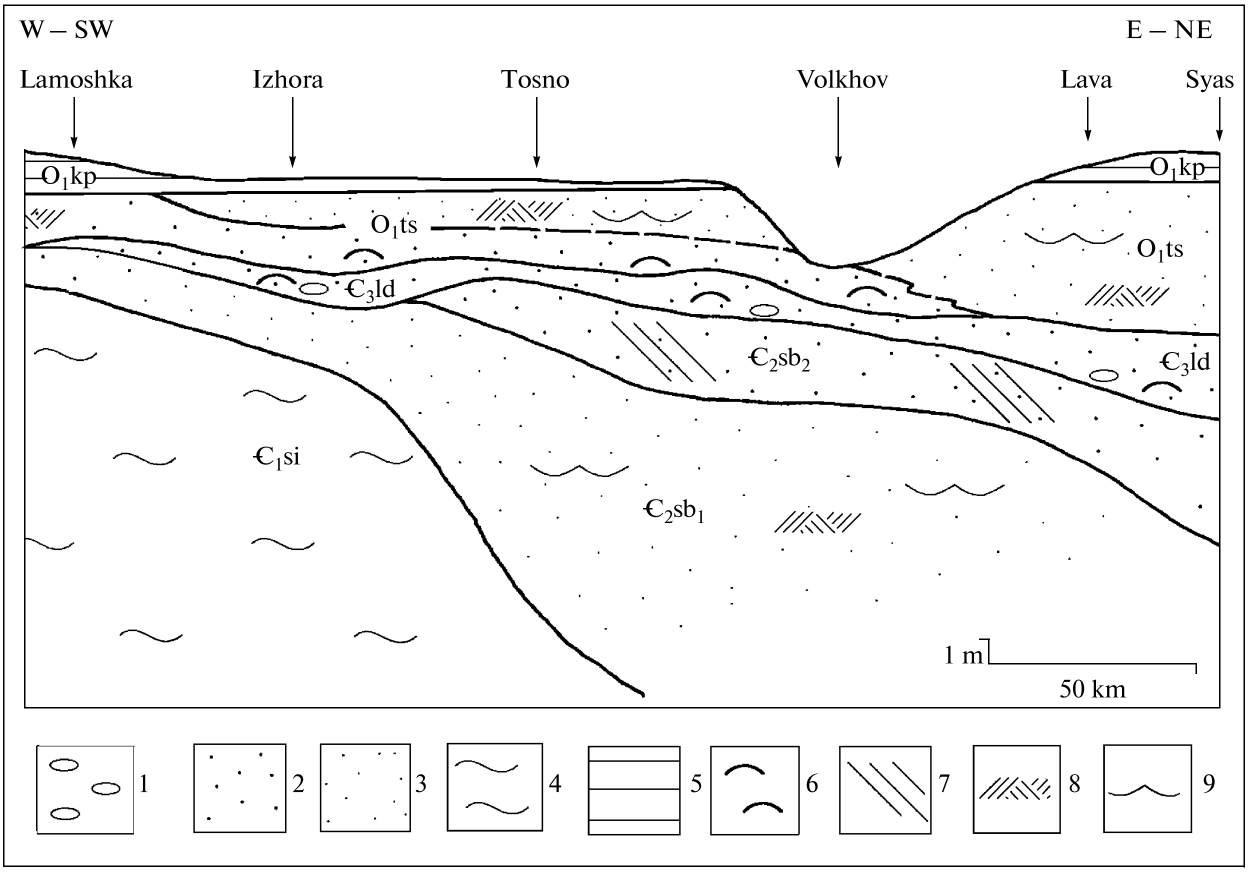

Fig. 2. Section of Cambrian–Ordovician sandstones in the Leningrad district.

(1) Pebble; (2) coarse- to medium-grained sand; (3) fine-grained sand; (4) clay; (5) shale; (6) shell detritus; (7) unidirectional cross-bedded series; (8) criss-cross bedding; (9) ripple marks. (Sb_1) Sablinka Formation, lower subformation; (Sb_2) Sablinka Formation, upper subformation; (Ld) Ladoga Formation; (Ts) Tosna Formation.

unidirectional cross-bedded structures are characteristic of the upper subformation. The detailed textural analysis of the COS sequence is given in the next section.

The formation extends over the whole Leningrad district east of the Luga River and occurs with erosion on the Lower Cambrian “blue clays.” The erosion boundary is relatively even and downcuttings are wide with gentle slopes. The paleorelief amplitude is several meters. Thickness of the Sablinka Formation increases eastward from 2–3 to 10–13 m.

The *Ladoga Formation* (€$_3$ld)occurs with erosion on the Sablinka sandstones. It is represented by yellowish gray, medium- to fine-grained, well graded, quartzy and quartz–feldspar, and poorly cemented sandstones with *Lingula* shells along with lenses and isometric spots enriched in ferric oxides.

The lower boundary of the formation is clearly erosional. Downcuttings of the Ladoga Formation floor (up to 5–10 m wide and 1 m deep) are observed within individual exposures. Downcuttings of the erosional paleorelief include basal pebble-beds of brownish gray clay balls encountered in the underlying Sablinka Formation. In the lower part, sand becomes medium-grained; cross-bedded structures and ripple marks are encountered. Massive or flat-bedded fine-grained sandstones (with clay interlayers up to 0.5–1 cm thick) are found higher in the section.

Rocks of the Ladoga Formation are thin: up to 1–1.2 m in the western part of the Leningrad district and up to 3 m in its eastern part.

The *Tosna Formation* (€$_1$ts) is established throughout the whole Leningrad district. It occurs with erosion on sandstones of the Ladoga Formation and lies with conformity under the Kopor Formation represented by black mudstones of the same age. The Tosna Formation is composed of coarse- to medium-grained, mainly quartzy, and poorly cemented sandstones with valves of inarticulate brachiopods and detrital material. The trough and cross bedding is characteristic of the rocks. Thickness of the formation varies from 2 to 5 m.

STRUCTURAL ANALYSIS OF ROCKS FROM THE CAMBRIAN–ORDOVICIAN 5 SANDY SEQUENCE AND FACIES–DYNAMIC CONDITIONS OF THEIR FORMATION

Cambrian and Ordovician sandy rocks of the Leningrad district exhibit sedimentation textures that are interesting and important for understanding the sequence formation—first of all, different types of bedding and ripple marks, as well as inter- and intrastratal erosional surfaces. When studying textures, most attention was concentrated on the shape and spatial position of joints and laminas inside lamina series (if possible, in two perpendicular cross-sections), as well as series extension and thickness. Azimuth and dip angles of laminas were also measured. Based on measurements of the cross bedding, rose diagrams were compiled for each of the distinguished age units: recurrence percentage for cross-bedded series was plotted on diagrams. Terminology and classification of bedded structures and ripple marks are given after V.N. Shvanov (1987).

The *Sablinka Formation, lower subformation* ($\text{Є}_2\ \text{sb}_1$). Flat-bedded structures distinguished at its base give way to cross-bedding higher in the section. In general, flat, parallel, and multidirectional cross bedding is characteristic of the subformation. The upper part of the subformation shows surfaces with ripple marks with the ripples 3.5–4.5 cm high and the spacing between them 20 cm wide (Fig. 3).

According to numerous measurements in rocks exposed in valleys of the Tosna and Lava rivers, dip azimuths of the cross-bedded laminas exhibit two opposite directions: west-northwestward and east-southeastward (Fig. 4a).

The data obtained allow us to establish the genetic type of textures. Linearity and, as a rule, parallelism of joint series, shape of laminas, bedding pattern in perpendicular sections, and narrow rays of rose diagrams directly indicate the generation of these textures due to the migration of rectilinear transverse sand ridges under the influence of bottom currents. Moreover, inclined joints suggest the migration of ridges during a pulsating input of the material (Kutyrev, 1968), whereas symmetrical ripple marks formed in the wave agitation zone indicate the shallow-water nature of the basin (Frolov, 1992).

Flat-bedded structures in the lower part of the subformation suggest that this part of the section was accumulated under relatively deep-water conditions below the wave agitation zone (without bottom currents) during the settling of sediments from suspension delivered from the adjacent shallower regions of the shelf. Sedimentation conditions changed during deposition of the upper part: cross-bedded series with opposite dip directions of oblique lamina and ripple marks indicate that the textures formed in shallow-water, hydrodynamically active marine conditions in the wave agitation zone with periodic bottom (most probably, tidal) currents. Each tide or ebb cycle formed its own ridge system, which partially or completely destroyed earlier ridges and buried them as cross-bedded series. Although relationship between the flow direction and the inclination of cross-bedded series is ambiguous (Kutyrev, 1968), the rose diagram of cross bedding can approximately reflect the clastic 3 material transport in the paleobasin. For the studied sequence characterized by two opposite directions of material transport, the resultant component is directed eastward and indicates an alternating (intertidal?) regime during the alongshore eastward drift of sediments[2].

Fig. 3. Ripple marks in sediments of the Sablinka Formation.

The *Sablinka Formation, upper subformation* ($\text{Є}_2\ \text{sb}_2$). The upper part of the Sablinka Formation shows asymmetrical ripple marks with the following parameters: 30–50 cm long, 3–6 cm high, ripple indexes varying from 6–7 to 10, and gentle/steep slope ratio ranges within 1–3.

Relatively thick and chiefly extended unidirectional (predominantly to the east) cross-bedded series impart a specific appearance to the member (Fig. 5). Thickness of the series is 25–35 cm and length is no less than 10 m. Joints are straight and subhorizontal.

Deformed and overturned cross-bedded structures of the synsedimentary syngenetic nature appear in sandstones in the western part of the Leningrad district (Fig. 6). This fact most likely indicates the destruction of sand ridges during increase of the flow rate above the critical value possible for their existence (Reineck and Singh, 1978). The general eastern direction of cross-bedded series inclination is retained within the entire domain of the Sablinka Subformation.

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[2] The *alongshore drift of sediments* means a resultant unidirectional alongshore transport of sediments over a long time interval. The drift of sediments may proceed both under the influence of wave energy and diverse currents (for instance, wind-borne or tidal) (*Morskaya*... 1980).

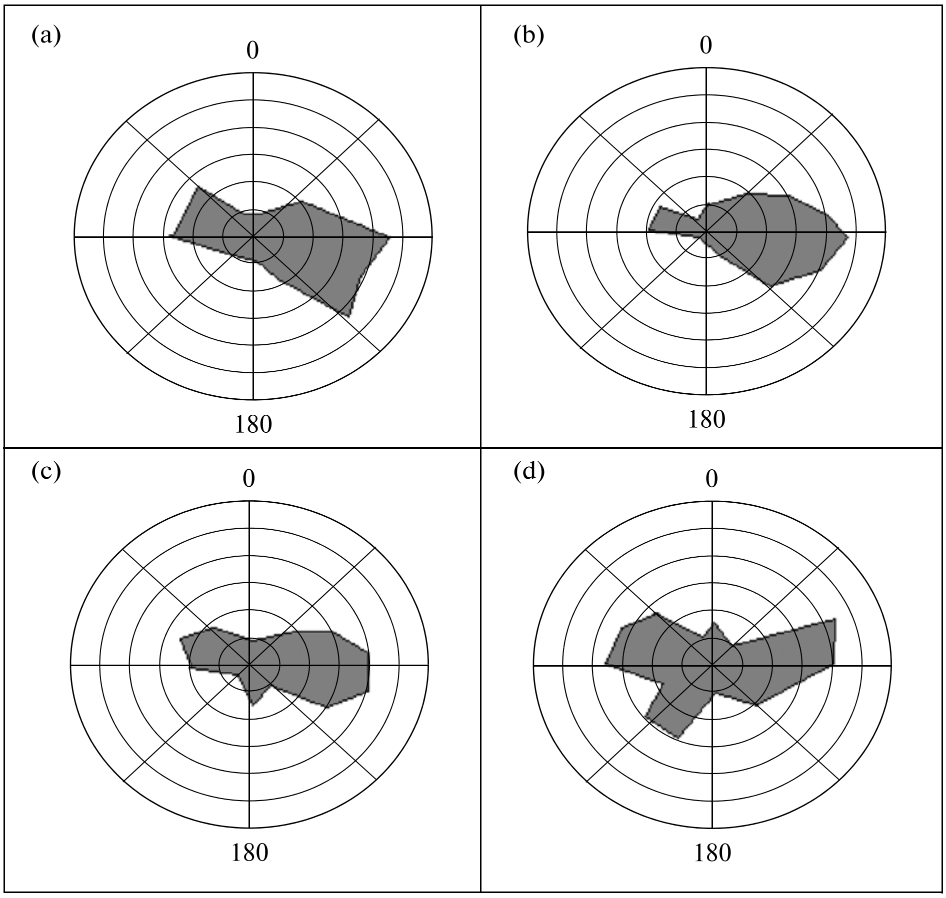

Fig. 4. Rose diagrams of cross-bedding directions in the Cambrian–Ordovician sandstone sequence in the Leningrad district: (a) Sablinka Formation, lower subformation; (b) Sablinka Formation, upper subformation; (c) Ladoga Formation; (d) Tosna Formation.

The nature of textures suggests that the sequence was formed in a stable hydrodynamic regime under the influence of mainly unidirectional long-term drift, with intensity decreasing from west to east. The eastward drift direction substantially dominated (Fig. 4b).

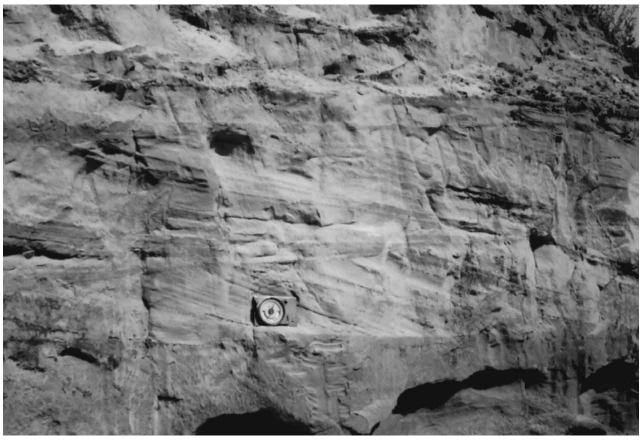

Fig. 5. Unidirectional cross-bedded series in sandstones of the Sablinka Formation.

The *Ladoga Formation* ($Є_3$ ld) occurs with hiatus on the Sablinka sandstones with basal pebble beds (clay balls) at the base. They are overlain by the cross-bedded sandstones with a series of small thickness (15–20 cm) and length (1–1.5 m). The cross bedding is flat, crisscross, and multidirectional. Laminas are emphasized by linguloid shells. Symmetrical ripple marks (probably wave-related) are developed at the top of cross-bedded sandstones.

It is apparent that the basal layer of the Ladoga Formation was deposited under conditions of the supracritical erosional rate of the flow. Then, the sediments of the Ladoga Formation were mainly deposited in less active hydrodynamic conditions (probably related to deepening of the basin) under the influence of differently oriented waves and tidal currents. Azimuths of cross-bedded lamina dip indicate the alternating sublatitudianal migration of sand material during the resultant alongshore eastward drift of sediments (Fig. 4c).

The *Tosna Formation* (O_1 ts). The trough and crisscross-bedded horizon (1–1.2 m thick), which occurs either on the basal cross-bedded sandstones (about 20 cm thick) or without them above the contact with the Ladoga Formation, represents the main textural parameter determining the appearance of the Tosna Formation. This bedding type was attributed in literature to the migration of crescent sand ridges along the bottom, which are formed under the influence of a strong but mainly turbulent flow (Kutyrev, 1968; Shvanov, 1987). The height of paleoridges is likely comparable with the thickness of cross-bedded series and varies from 8–9 to 20 cm.

From the bottom to top, bedded structures vary from cross-bedded to trough-bedded; the trough bedding passes into the cross, flat, parallel or alternate bedding with an upsection thinning of cross-bedded series up to the appearance of small obscure cross-bedded structures.

The rose diagram of lamina dip in sandstones of the Tosna Formation demonstrates two cross directions of the sediment transport: the main sublatitudinal dip (Fig. 4d) with the prevailing eastward direction and the additional submeridional dip with the prevailing south-southwestward direction.

We can assume that sands of the Tosna Formation were formed under the influence of an intense turbulent flow grading with time into the temperate laminar one. The alternate sediment migration proceeded under conditions of the basic eastward transport of the material.

Hence, the studied Cambrian–Ordovician terrigenous sequence shows a regular increase in the hydrodynamic activity during sedimentation within the Sablinka Formation from its bottom to top and a successive decrease in the activity during deposition of the Ladoga and Tosna formations. In general, the intensity of hydrodynamic processes decreased eastward in the area, probably, due to an increase in the paleobasin depth.

Table 1 demonstrates average values of grain size characteristics of the studied sediments for the distinguished Middle Cambrian–Lower Ordovician formations in the Leningrad district. Analysis of grain size parameters of sediments along the strike suggests that they are mainly marked by decrease in size and increase in the degree of grading (σ) and structural maturity (excess) from west to east.

Fig. 6. Deformed cross-bedded sedimentation structures in rocks of the Sablinka Formation.

The sequences in the section are generally characterized by the cyclic nature of variation in grain size characteristics during small fluctuations of these parameters, with amplitude increasing to the top of the section.

CALCULATION OF DRIFT PARAMETERS

Many formulas have been proposed for the calculation of drift parameters over the last fifty years. However, no universal method has been elaborated so far, and each of the available equations has its own sphere of application. Standing out amidst several calculation models are some basic ones, which pretend to be complex and universal, and their simplified versions that are less refined and oriented to the solution of particular problems with a simpler mathematical apparatus.

In the proposed methods, the drift capacity is calculated based on grain size characteristics of sediments and parameters of depositional environments. Parameters of the environment for paleohydrodynamic reconstructions can be established with some

Table 1. Grain size parameters of the main stratigraphic units

	Sablinka Formation (Є$_2$sb)			Ladoga Formation (Є$_3$ld)			Tosna Formation (O_1ts)		
	west	center	east	west	center	east	west	center	east
Ma, mm	0.28	0.18	0.16	0.13	0.23	0.12	0.30	0.26	0.21
σ, mm	0.56	0.61	0.62	0.41	0.59	0.48	0.57	0.53	0.64
As	2.22	1.5	1.76	1.12	1.9	1.35	2.25	1.9	1.58
Ex	10.9	9.6	12.8	4.4	5.4	6.2	17.5	15.3	21.5
Hr (entropy)	0.65	0.59	0.54	0.72	0.61	0.64	0.61	0.64	0.56

Note: Data on grain sizing of clay interlayers were not taken into account.
(Ma) Arithmetic mean for grain size, (@[sigma]) standard deviation, (As) asymmetry of distribution, (Ex) excess, (Hr) relative entropy of distribution.

constraints determined by the solution of a reverse problem: calculation based on grain size characteristics of sediments under study reflects hydrodynamic characteristics of the flow at the sedimentation stage, flow intensity at the sediment transport stage being probably higher.

The Einstein method (Einstein, 1950) is one of the
1 basic methods in geoengineering lithodynamic calculations. The method is applicable for calculation of the total discharge of sediment load (tractional and suspended). Its application is constrained by the predominance of bed load transported by traction and saltation over the suspended load, as well as a considerable width of water channel relative to its depth, where the hydraulic radius of the channel (R_h) equal to the cross section area/“wet perimeter” length (width plus double depth) ratio is nearly equal to the channel depth. These peculiarities of the Einstein method suggest that the error of its application is minimal for bottom currents in a shallow sea basin composed of sandy material.

The specific total sediment discharge per flow width unit q_t can be calculated according to the Einstein method as the total discharge of bed load q_b and suspended q_s load that can be expressed by the equation:

$$q_t = q_b + \int_0^h C v_x dz, \quad (1)$$

where h is the flow depth; C is the suspended load concentration; v_x is the horizontal component of the velocity in the flow direction (x); z is the vertical coordinate.

Omitting complicated mathematical transformations presented in the monograph *Erosion and Sedimentation* (Julien, 1995), we obtain the equation:

$$q_t = q_b[1 + I_1 \ln(30h/d_s) + I_2], \quad (2)$$

where d_s is the medium size of suspended load, and two integrals I_1 and I_2 have a numerical solution or can be calculated using nomograms elaborated by Einstein.

The function suggested by Einstein for the calculation of drift capacity takes into account the relationship between different grain size classes of sediment in flows of different intensities. On this basis, the equation (1) can be presented as:

$$q_t = \Sigma i_t q_{ti}, \quad (3)$$

where i_t is the content of i-grain size class in sediment; q_{ti} is the specific discharge of i-grain size class.

Gathering of necessary information about bottom sediments of a paleobasin is the first step in the method application. We distinguished four spatially stable sedimentary complexes: the lower and upper subformations of the Sablinka Formation, as well as the Ladoga and Tosna formations. The results of the grain size analysis for 19 size classes within the range from >2 mm to <0.01 mm (in total, about 450 samples) were averaged and grouped for the further treatment in three grain size classes, each representing no less than 19% of the total material volume (0.45–0.22, 0.22–0.11, 0.11–0.055 mm). We also calculated other necessary parameters (average size of particles in the class; settling velocity for particles of this size; and percentiles d_{16}, d_{35}, d_{50}, d_{65}, d_{84}) (Table 2).

The hydraulic size in Table 2 was calculated by the formula:

$$w = (4(G - 1)gd_s/3C_D)^{0.5}, \quad (4)$$

where G is the specific weight of particles; g is the free fall acceleration; d_s is the diameter of sediment particles, C_D is the drag coefficient related to the Reynolds number for ball-shaped particles ($\mathrm{Re_p}$) $C_D = 24/\mathrm{Re_p}$ (Julien, 1995).

The calculation is made for each distinguished grain size class, and the obtained results are summed up.

A detailed description of the Einstein method for practical calculations is given in (Julien, 1995). Results of an analogous calculation made for the COS of the Leningrad district allowed us to determine the specific capacity of drift for each of four studied sequences (Table 3).

CALCULATION OF SEDIMENTATION DURATION IN THE SEQUENCE UNDER STUDY

Parameter of the specific capacity of drift is insufficient for calculating the sedimentation duration for the sequence under study, since this parameter in the pure state is applicable only in the case of unidirectional and temporally stable drift. In actual practice, parameters of drifts are changeable with time and space. The structural analysis of sediments presented above suggests periodic changes in the drift direction and variations in its intensity that are manifested as inter- and intraformation erosion boundaries (increase in drift intensity) and clay interlayers (decrease in drift intensity) that should be taken into account in calculations.

Orientation of the cross-bedding indicates a periodic change in the drift direction in all of the studied sequences, with the ESE direction generally being the predominant one. With such a drift regime, the input of material to a unit cell of the active layer and increment of the section thickness are determined by the difference in opposite vectors of material transport relative to the general hydrodynamic energy in the unit cell (the sum of all vectors).

For assessing the total drift efficiency based on the rose diagram of cross-bedding directions, we have proposed the coefficient of asymmetry (K_{as}) calculated by the formula:

$$K_{\mathrm{as}} = |V_{+\mathrm{i}} - V_{-\mathrm{i}}|/\Sigma V_i, \quad (5)$$

Table 2. Grain size characteristics of Cambrian–Ordovician sandstones

Grain size, mm		Grain size composition in time units, %				Hydraulic size (fall velocity in water, w), mm/s
Fractions	average (d_3)	Sb_1	Sb_2	Ld	Ts	
>0.45		0.64	2.52	3.87	7.12	
0.45–0.22	0.34	21.97	40.21	24.08	36.88	42
0.22–0.11	0.17	49.02	28.48	31.87	44.21	19
0.11–0.055	0.08	22.47	24.34	32.97	9.44	5
<0.055		5.90	4.44	7.21	2.35	
Percentile	d_{16}	0.082	0.088	0.070	0.106	
	d_{35}	0.112	0.112	0.095	0.150	
	d_{50}	0.134	0.170	0.117	0.190	
	d_{65}	0.168	0.217	0.162	0.220	
	d_{84}	0.220	0.250	0.250	0.280	

Note: (Sb_1) Sablinka Formation, lower subformation; (Sb_2) Sablinka Formation, upper subformation; (Ld) Ladoga Formation; (Ts) Tosna Formation. Percentiles d_{16}, d_{35}, etc. denote the particle size (mm), relative to which 16, 35, etc. % of particles have smaller sizes.

where V_i is the unit vector of the dip of cross-bedded series, $\Sigma|V_{+i} - V_{-i}|$ is the sum of absolute values of vector differences for opposite directions, and ΣV_i is the sum of values of all rose diagram vectors. For symmetrical distribution, $K_{as} = 0$; for unidirectional distribution, $K_{as} = 1$. The calculated coefficients of asymmetry for the studied sequences are presented in Table 3.

The detailed analysis of erosional surfaces shows that erosional boundaries within the studied Cambrian–Ordovician sequence can be divided into two types. Erosional interlayer surfaces inside formations are discontinuous and nonpersistent along the strike. Such textures are determined by the turbulent nature and local pulsation of drift velocities (Berthault, 2002).They exert no substantial influence on the total thickness of the sequence.

Taking into account peculiarities of erosion contacts between formations, one can infer that sheet erosion essentially dominated over riverbed (deep-sea) erosion. Under these conditions, baselevel of the erosion of sequences under study is not always reliably established. Therefore, in order to get a more correct value of the primary volume, we take into account the maximal revealed thickness of the sequence (H_{max}) assuming that the primary thickness of sediments and, correspondingly, the formation volume could be greater.

Using the calculated value specific capacity of drift (q_t), coefficient of asymmetry for the drift (K_{as}), length of the sequence in the direction drift direction (L) (about 200 km in the segment accessible for study), and the maximal established thickness of the sequence (H_{max}), the sedimentation duration for the COS sequence in the Leningrad district (t_s) can be calculated by the formula:

$$t_s = (H_{max}L)/(q_t K_{ac}). \qquad (6)$$

The calculation results are presented in Table 3.

Table 3. Parameters of the formation of Cambrian–Ordovician sandstones in the Leningrad district based on the Einstein method (1950) and Julien model of "reservoir filling" (1995)

Studied sequence	q_1,m^2/day	K_{as}	L, km	H_{max}, m	t_s, yr
Sb_1	4.7	0.34	200	8	2755
Sb_2	8.5	0.63	200	4	409
Ld	5.1	0.49	200	3	656
Ts	3.7	0.47	200	4	1565
Total:				26	5384

Note: (q_1) Specific capacity of drift (sediment discharge) per drift width unit (calculation based on the Einstein method); (K_{as}) asymmetry coefficient for rose diagram of cross bedding; (L) reliably established length of the studied sequence within the study region; (H_{max}) maximal thickness of the sequence; (t_s) sedimentation time based on formula (3); (Sb_1) Sablinka Formation, lower subformation; (Sb_2) Sablinka Formation, upper subformation; (Ld) Ladoga Formation; (Ts) Tosna Formation.

The relative error of parameters involved in the calculation can be rather high. In some cases, the relative error of primary parameters is extremely hard to estimate. Therefore, we can state with confidence only the *order* of the value under calculation.

Values of the specific capacity of drift obtained for different COS units confirm the inference based on the suggesting a cyclic regressive–transgressive structure of the sequence. Such a similarity of the results obtained by independent methods indicates the real assessment of sedimentation parameters for the paleobasin.

RELATIONSHIP BETWEEN SEDIMENTOLOGICAL AND STRATIGRAPHIC DATA

Thus, we observe a situation when the sedimentation duration substantially differs from the duration of stratigraphic time interval (hereafter, stratigraphic duration) correlated to the sequence under study, which varies from 20 to 30 Ma according to different assessments.

To determine the time of hiatuses (sediment rewashing), we use the following formula (Romanovskii, 1977):

$$V = kH/(T - T^*)p, \tag{7}$$

where V is the sedimentation rate, k is the coefficient including the thinning of primarily formed layers (correction for compaction), H is the maximal thickness of rocks within the distinguished stratigraphic unit, T is the unit duration (Ma), and T^{**} is the total time of hiatuses, and p is the measure considering the intensity of interlayer washouts during the sequence formation. Then, the hiatus time can be calculated by the formula:

$$T^* = T - kH/(Vp). \tag{8}$$

Substituting in formula (8) the values $T = 25$ Ma, $V = 26 \times 10^{-4}$ m/yr, and k = 1.2 (the average compaction value for sands is taken to be 20%), we reckon p = 1 (intralayer washouts are of the local nature) and thickness is 26 m. Thence, the time corresponding to hiatuses for COS sedimentation makes up:

$T^* = 25 \times 10^6$ yr $- 1.2 \times 26$ m$/26 \times 10^{-4}$ m/yr $= 24.988 \times 10^6$ yr.

Thus, the calculated real time of formation (sedimentation duration) corresponds to about 0.05% of the stratigraphic age of this sequence. It should be noted that the sedimentation duration based on the Einstein method is of the conservative nature. If we proceed from sedimentation characteristics of sediments, the duration obtained for their formation appears to be extremely low in the geological scale. Based on the analysis of intertidal cycles, Kulyamin and Smirnov (1973) showed that the "pure" sedimentation time for similar COS in the Baltic region is estimated at approximately 170 paleodays (133 for the Middle–Upper Cambrian Sablinka sandstones and 40 for the Lower Ordovician Pakerort sandstones). The above authors write: "The values obtained are shocking" (Kulyamin and Smirnov, 1973, p. 699). They attribute such results to an infinitesimal preservation of sediments in analogous sections with respect to the stratigraphic time range.

Based on the sedimentation analysis of the COS from the Leningrad district, "pure" sedimentation time for Lower Paleozoic sands can be estimated at 100–200 yr. The paradox is that geological time of the Sablinka sequence formation amounts to 10–20 Ma (Tugarova et al., 2001, p. 89). The authors explain this paradox by the rewashing of sediments in shallow-water marine conditions with active lithodynamics, where processes of accumulation and seafloor erosion occur side by side and replace one another depending on parameters of storms and currents.

Such a situation is not unique. S.V. Mayen wrote: "Due to a wide development of concealed hiatuses..., only a negligible (0.01–0.001%) share of total sedimentation time is commonly documented" (Mayen, 1989, p. 24).

Since relationship between erosion and transport parameters of the drift is exponential, the main volume of geological work (erosion–transfer–deposition) under intense hydrodynamic conditions is accomplished during activation and is far in excess of geological work performed under stable conditions. For instance, all erosional work and the most part of accumulation in alluvial channels take place during flood and at its recession (Chalov, 2008). The coastline deformation during a year is mainly governed by two or three most intense storms (*Rukovodstvo...*, 1975). Major hydrodynamic events in paleobasins related (presumably) to megatsunami caused by tectonic processes can play a crucial role in the deposition of the lower (marine) molasse, which terminates the complete sedimentological evolution of deep ocean trenches (Lalomov, 2007). On continental slopes with intense dynamic processes, such as landslides or large-scale turbid flows, thick sedimentary sequences can be deposited instantly from the geological standpoint.

All these objects are characterized by a sharp inconsistency between the stratigraphic duration prescribed to this sediment complex and the real time of sedimentation. Along with elements formed under intense (sometimes catastrophic) sedimentation conditions, which make up the main part of the section, the rock complexes include (to be more exact, must include) evidence of long-term hiatuses or erosion of the most part of deposited sediments. The evidence is not always present in the explicit form, and this statement is valid not only for terrigenous rocks. As S.I. Romanovskii writes, "...even a monotonous limestone sequence includes concealed breaks (diastems), which account for much of the time responsible for the section formation. However, since there is no possibility to get even rough estimates of the hiatus duration, geologists have to ignore this issue. ...In oceans, a considerable part of time falls on hiatuses.... Erosion cannot be considered here as the main cause of section incompleteness, although other causes cannot also be pointed out exactly. Marine geologists have found a fortunate avoidance of this complicated problem and designated the hiatus as the period of nondeposition of sediments. Thus, the geological record ... fixes short activation intervals separated by essentially longer intervals of inactivity" (Romanovskii, 1988, pp. 22, 23).

The relationship between such notions as "sedimentation rate," "sediment deposition rate," and "section increment rate" is the subject of wide speculation in the geological literature at present (Romanovskii, 1988; *Lithogeodinamika...*, 1998; Baikov and Sedletskii, 2001; and others), and this is related not only to pure scientific interest. For many mineral resources of the sedimentary genesis, the optimal relationship between sedimentation rate and section increment rate is the governing factor for their formation. For instance, titanium–zircon placers represent a product of the enrichment of mineralogically mature sandy sediments under conditions of stable 1 lithodynamic processes of moderate intensity (Patyk-Kara et al., 2004). It is relatively fast (by geological standards) sedimentation of the COS that probably is responsible for the following fact: commercial Ti–Zr placers have not been revealed in the region so far despite the concurrence of many favorable factors (availability of the source of heavy ore minerals in igneous and metamorphic rocks of the Baltic Shield, presence of intermediate collectors of Ti–Zr minerals in the Late Precambrian and Early Cambrian sedimentary complexes, and mineralogical maturity of the COS in the northwestern Russian Platform).

The sedimentation rate has a direct influence on the formation of mineral resources at the stage of sedimentation. This shows up in the process of placer formation and, most probably, chemogenic sediments of the sedimentation series. Therefore, the knowledge of the real sedimentation rate is important not only for lithology and sedimentology, but also for the study of processes responsible for the formation of sedimentary mineral resources.

CONCLUSIONS

1 Thus, the application of lithodynamic geoengineering calculations for assessing the sedimentation duration of the sandy portion in the COS in the Leningrad district showed that these sandstones were formed instantaneously from the geological standpoint, and the sedimentation duration of the sequence does not exceed 0.05% of its stratigraphic age interval. This work has confirmed ideas of former researchers about a rather fast formation of the sequence and presents the quantitative assessment of sedimentation.

Conditions, under which the sedimentation time essentially differs from the stratigraphic one, are characteristic not only for the shallow-water platform terrigenous formations (e.g., the COS of the northwestern Russian Platform), but also a series of other sedimentary formations. Therefore, the traditional method of calculating the sedimentation rate by subdivision of the sequence thickness into the duration of the comparable stratigraphic scale interval can yield a fortiori understated value.

Since the sedimentation rate has a direct influence on the formation of sedimentary mineral resources of the sedimentogenic series (placers and partially chemogenic ores), the real sedimentation rate should be taken into account in the study of sedimentary ore genesis.

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SPELL: 1. Lithodynamic, 2. paleolithodynamics, 3. clastic, 4. paleolithodynamic, 5. facies, 6. Chezy