REPORT

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"Research of paleohydraulic conditions and determination of actual time of sedimentation of Cambrian – Ordovician sandstones of St.-Petersburg region".

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CONTENT

INTRODUCTION.

Cambrian – Ordovician sandstones (COS) of St.-Peterburg (SPb) area have regional extension (more than 300 km from west-southwest to east-northeast) and relatively small thickness (20–40 m). The sequence consists of several Members, which usually are divided by erosion surfaces. Structure of the Members has sufficient variations in lateral direction; therefore individual layers usually are not traced more than few hundred meters. They have obvious evidences of deposition in conditions of moderate to intensive hydrodynamic activity with lateral transport of sediments – cross beds, ripple marks and inverted beds. Thus, conventional stratigraphy based on the principles of superposition and continuity stated by Nicolas Stenon and paleontological method supposes that the Members were deposited one after another during 25 million years. Inasmuch as very fast sedimentation of the sandstone sequence became obvious for geologists, they tried to explain this contradiction by long interrupts in sedimentation between the Members and/or numerous cycles of erosion and re-deposition of the sands. Both processes (interrupts and re-deposition) have inherent geological evidences: evidences of long stagnation is high concentration of organic carbon; erosion surfaces could be result of changing of velocity of the current, re-deposition of the sands is accompanied with concentrations of sustainable heavy minerals.

Study of textures, granulometric, mineralogical and geochemical features of COS allows determining of paleohydrodynamic conditions of the sedimentary basin and consecution of geological events of COS formation. All these data allow determination of the time of sedimentation of the sequence taking into account duration of possible stagnation periods as well as erosion and re-deposition of the sediments.

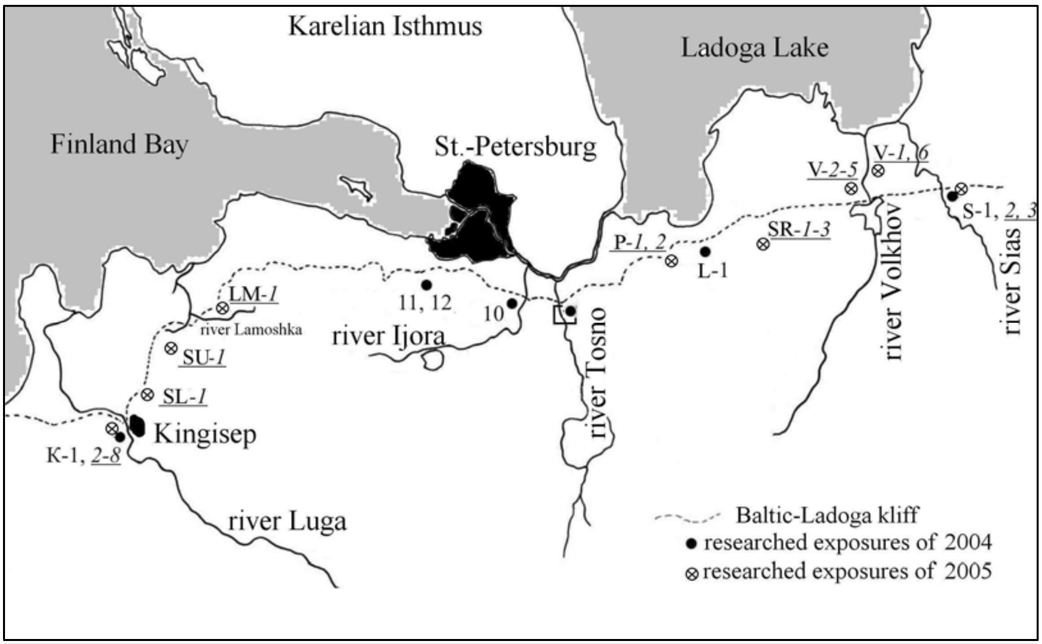

Fig. 1. Scheme of researched exposures in 2004 and 2005 field seasons. Scale approximately 1:2 000 000.

GEOLOGICAL POSITION OF STUDY SEQUENCE

Study area is located on the border of two large structural – geological zones: south part of the Precambrian Baltic Crystalline Shield and northwestern part of Palaeozoic Russian Plateform (fig.1). Rock of the crystalline basement immerse under a platform sedimentary cover.

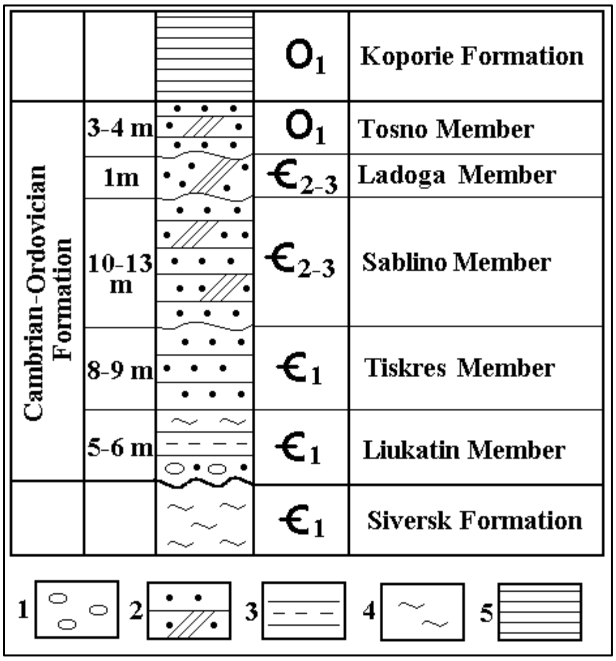

Fig. 2. Generalized stratigraphic column of COS SPb region.

Highly metamorphic rocks of Baltic Crystalline Shield are represented on the northern territory of Karelian Isthmus and Ladoga Lake.

The cover of Russian Platform in the SPb region begins from Upper Proterozoic (Riphean and Vendian) rocks (Karelian Isthmus, east coast of the Ladoga Lake) up to Carboniferous System with common thickness 2500 m. Strata of the cover have monocline dip to south-east with angle 10–12°.

Most part of SPb region is covered by Quaternary deposits, therefore study of Palaeozoic rocks is possible within the limits of Baltic – Ladoga glint (cliff of the ancient sea) and in the valleys of rivers: Luga, Ijora, Tosno, Lava, Volkhov and Syas. Thus, research of COS is available along the glint having extent about 300 kms from west on east of the SPb region along southern coasts of the Finnish gulf and Ladoga lake.

COS overlie Lower Cambrian “blue clay” of Siversk Formation which has average thickness 100 – 120 m. with erosion surface. Ordovician black shales of Koporie Formation concordantly overlie it.

STRATIGRAPHY OF CAMBRIAN-ORDOVICIAN SANDSTONES

COS are subdivided on several Members (fig. 2).

Liukatin Member (Lower Cambrian, $Є_1$ *lk*) is located in northeast Estonia Republic and in west of the SPb region (up to the river Luga). It has erosion contact with underlying Siversk Formation and concordant contact with overlying Tiskres *Member*. Liukatin Member consists of alteration of glauconite sandstone, quarts silt and green-gray clay. Sometimes in the basis of the Member conglomerate is observed. Thickness is about 5–6 m.

Tiskres Member (Lower Cambrian, $Є_1$ *ts*) is distributed in north of Estonia Republic and in the west of the SPb region up to town Gatchina above *Liukatin Member*. *Tiskres* consists of quartz and feldspar sandstones and siltstones with thin clay layers. Thickness is about 8–9 m.

Sablino Member (Middle Cambrian, $Є_2$ *sb*). Stratatype of the Member is situated in the valley of Tosna-River 40 km to the south-east from St.-Petersburg. The Formation is located along SPb region to the east from Luga-River, here it overlies Lower Cambrian “blue clay” of *Siversk Formation*. *Sablino* consists of light-grey, yellow-grey tine-grained sandstones with iron oxide patches. Cross-beds with horizontal interlayer borders are prevailing.

Depending on presence of phosphate-calcium shells of *Brachiopods* this Member is divided to two units.

Lower Unit ($Є_2$ sb_1) does not contain shells. It consists of medium- to fine grained quartz friable sandstone. Color of the rock varies from gray, yellow and pink to brown-red depending on content of iron oxides. Thin (up to 1 – 2 cm) interlayers and lenses of green-blue clay are observed.

Lamination of the sandstones is of two kinds: the first one is characterized by flat or moderate undulating and moderate inclined surfaces of the strata with opposite directed inclined beds. The second one is differ by essential inclination of borders of the cross-bed series. Flat lamination is also occurring. Sometimes ripple-marks (height up to 2 cm) are observed on the surface of strata. Thin layers of clay cover it. Thickness of the unit is about 13 m.

Upper Unit ($Є_2$ sb_2) allocates in the south part of Tosno area (exposures T1, T2). It contains shells of *Brachiopods*. Lower surface of the unit is very uneven. Pebbles of ferriferous sandstones are observed in the pockets of bedrock.

Size of sand particles decreases upward from coarse-medium to fine well-sorted sand. In the lower part of the unit thick (25 – 35 cm) and extensive (more than 10 m long) unidirectional cross-bed series are typical. Surfaces of the layers are straight and subhorizontal. It is possible to see here very interesting and rare patterns of inner textures – “inversed lamination” or “roiling and folding textures”. In the upper part thickness of cross-beds decrease and transform to horizontal lamination. Thickness of the unit is 2 m.

In the valley of river Lava large ripple-marks (4 cm height and up to 50 cm length, are observed. Thickness of Sablino Member here increase up to 8 m.

Ladoga Member (Middle Cambrian, $Є_2$ *ld*) has erosion border with underlying *Sablino*. The surface has erosion pockets. The pockets contain pebbles of coarse grained sandstones, angular clasts and iron oxide oolites of brown and violet colour.

The Member consists of fine-grained sandstone with rare cross-beds and thin clay interlayers. Iron concretions are usual. Thickness vary from 0.3 m in the west to 3.0 m in the east of SPb area.

Tosno Member (Lower Ordovician, O_1 *ts*) is located everywhere in SPb region. It overlies *Sablino* with erosion border and concordantly overlying with black shales of Lower Ordovician *Koporie Formation*. It consists of coarse- to medium-grained quartz sand with content of *Brachiopods* shells up to 50% in the lower part of the formation. Trough-shape and cross-bed lamination is character to the sands. In the bottom of the Member in organic detritus layer we often see one series of inclined beds up to 20 cm thick and 2 – 3 (and more) meter length. On the upper surface of detritus layer sometimes large ripple-marks (7 cm height and up to 65 cm length) are observed. In the middle part of the Member we see cross-beds with opposite inclined dips. Up to the sequence thickness of cross-beds decreases, and in the uppermost strata we see parallel lamination. Thickness is about 3–6 m.

TEXTURES OF SEDIMENTS AND DYNAMIC CHARACTERISTICS OF SEDIMENTATION ENVIRONMENT OF CAMBRIAN – ORDOVOCIAN BASIN

Research of granulometric composition and textures of the sandstones allow determining of dynamic characteristics of sedimentation environment. Detail investigation of textures indicates that intensity of hydraulic processes is decreases from the west to the east of the Formation. Whereas in the east part of the region we see high dynamic features such as cross-bed series up to 1 m thick (figure 3), large ripple marks (figure 4) and inverted lamination (figure 5), in the central and especially east part massive sandstones with clay and silt interlayers are mostly observed. Taking into account that at the same time we observe fining of the sands and increasing of the thickness of the Formation, conclusion of deepening of the sedimentary basin in the east direction looks quite reliable.

Research of textures such as orientation of cross-beds and ripple marks allow determining direction of the flow. The orientation varies in different Members. Whereas in Lower Sablino, Ladoga and especially Tosno Member we observe alternate orientation of the cross-bed dips with prevalent direction to east - southeast, in the Upper Unit of Sablino Member we see mostly unidirectional flow (figure 6). Study of the textures in connection with grain-size analysis in the vertical sequence reveal the sedimentary cycle of deposition that develops from the bottom of Sablino Member to the lower boundary of Ladoga Member (regressive phase) and from Ladoga to Tosno (and overlying Koporie shales) as transgressive phase.

Fig. 3. Unidirectional large-scale cross beds of upper part of Sablino Member.

Fig. 4. Large-scale ripple marks of Sablino Member.

Fig. 5. Inverted lamination as a result of slumping of subaqual dunes.

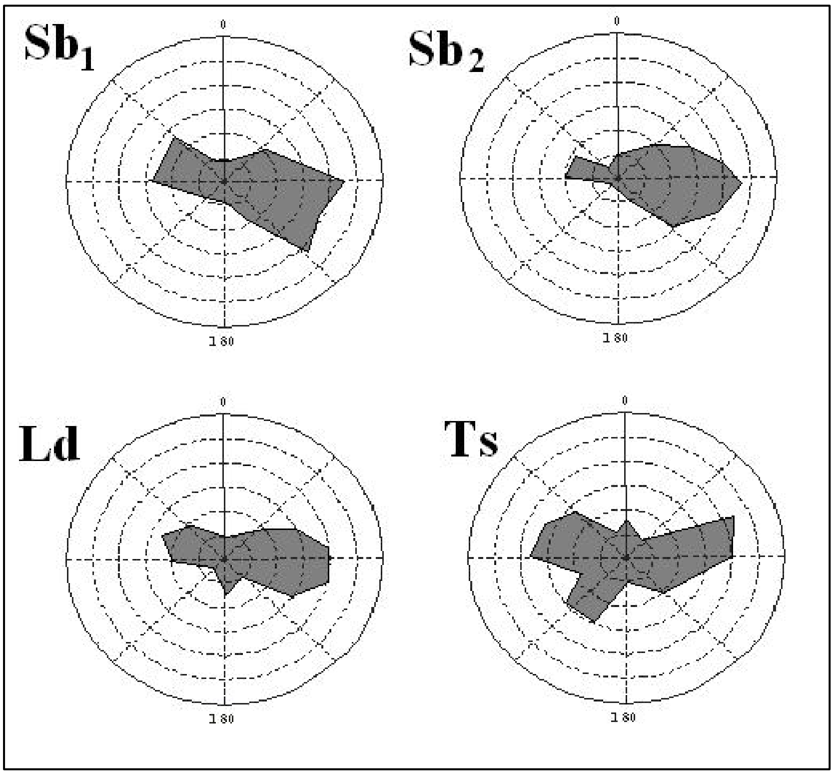

Fig. 6. Orientation of cross-beds in Cambrian-Ordovician sandstones of SPb region.

Variations of the cross-bed dips in the vertical sequence of COS are illustrated on figure 7. Rhythmical alternations of the azimuth of the dips allows proposition of Kulyamin and Smirnov [1973] about tidal nature of these variations and correspondingly about very short (not more than 200 tidal cycles) actual time of deposition of the sequence.

Average dimension of the sand clasts vary from 0.14 to 0.40 mm that corresponds to fine- and middle-grained sand. The dimension decreases from west to east and increase from the bottom to the top of the sequence. Standard deviation and excess of grain-size distribution curve increase from west to east that is evidence of increasing of sorting and maturity of the sand deposits. Changing of granulometric characteristics of researched strata in lateral direction shows that the parameters have sustainable trend: from west to east we see tendency to decreasing of average dimension of sand particles and increasing of standard deviation. Taking into account parallel trend of the other parameters (asymmetry, excess and entropy of grain-size distribution curve) we can conclude that degree of treatment of the sediments by hydrodynamic processes increase in the east direction. That coincides with direction of the flow determined by texture analysis.

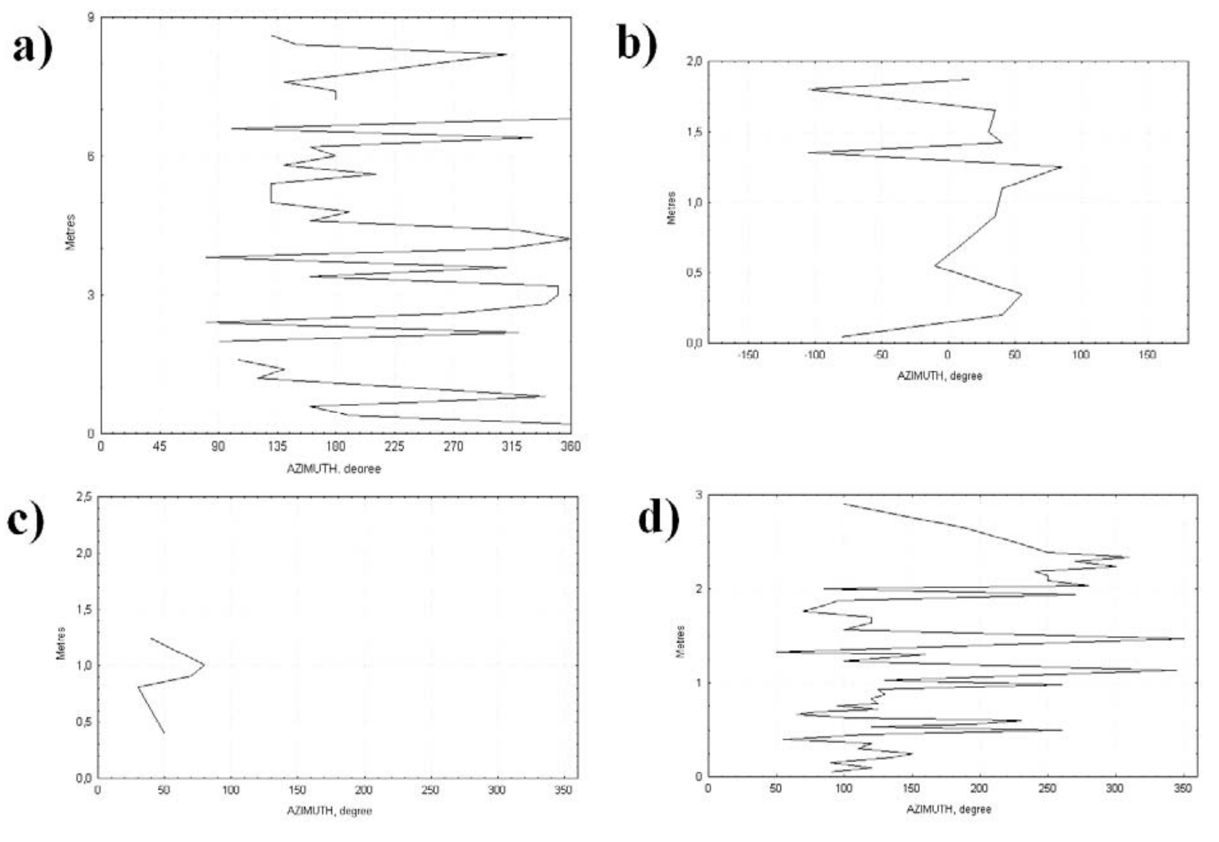

Fig. 7. Azimuth degree of variations of the cross-bed dips in the vertical sequence. Members: (a) Upper Sablino; (b) Lower Sablino; (d) Tosno; (c) Ladoga.

Table 1. Granulometric characteristics of designated Members and variation of the parameters in lateral direction.

	$Є_2$ *sb*,			$Є_3$*ld*			O_1*ts*		
	West	Centre	East	West	Centre	East	West	Centre	East
Average dimension D, mm	0.28	0.18	0.16	0.13	0.23	0.12	0.3	0.26	0.21
Standard deviation σ, mm	0.56	0.61	0.62	0.41	0.59	0.48	0.57	0.53	0.64
Asymmetry of grain-size distribution curve (As)	2.22	1.5	1.76	1.12	1.9	1.35	2.25	1.9	1.58
Excess of grain-size distribution curve (Ex)	14.9	9.6	12.8	4.4	14	6.2	17.5	15.3	21.5
Entropy of grain-size distribution curve (Hr)	0.65	0.59	0.54	0.72	0.61	0.64	0.61	0.64	0.56

MINERAL CHARACTERISTICS OF CAMBRIAN – ORDOVICIAN SANDSTONES

Almost single mineral of light fraction (specific weight less than 2.8) is quartz. Average total content of heavy minerals in fraction 0.05 – 0.1 mm is 0.49% (variation from 0.04 to 1.94 %); in fraction 0.1 – 0.25 mm it is 0.11 % (variation from 0.02 to 0.57 %). Content of heavy minerals in the other size fractions is much less. Size fraction 0.05 – 0.1 usually contains more than 60 % of total heavy minerals.

Table 2. Concentration of heavy minerals (zircon + ilmenite + rutile + leucoxene) in Cambrian – Ordovician sandstones of northwestern Russian platform.

Member	Districts (from west to east)						Average in Formation
	Luga	Dudergof	Ijora	Tosno	Lava	Syas	
Tosno	$\frac{0.53}{0.99}$	$\frac{0.38}{0.44}$	$\frac{0.38}{0.42}$	$\frac{1.01}{4.30}$	$\frac{1.76}{2.93}$	$\frac{0.77}{2.71}$	0.74
Ladoga	$\frac{2.72}{4.93}$	$\frac{3.70}{4.31}$	$\frac{1.16}{2.16}$	$\frac{2.97}{7.16}$	$\frac{2.63}{3.24}$	$\frac{7.19}{13.64}$	3.79
Sablino 2	–	–	–	$\frac{2.30}{4.50}$	$\frac{2.93}{2.93}$	$\frac{0.53}{0.89}$	1.92
Sablino 1	$\frac{1.12}{1.61}$	$\frac{0.38}{0.38}$	$\frac{1.70}{3.39}$	$\frac{1.49}{4.33}$	$\frac{1.17}{1.45}$	–	1.17
Tiskres	$\frac{3.40}{5.24}$	–	–	–	–	–	3.40

Numerator – average content of sum of heavy minerals, kg/m^3; denominator – maximal content, kg/m^3.

Heavy fraction is very simple. Sum of ilmenite, leucoxene and zircon usually have 50 – 90 % of heavy fraction. Average content of zircon 29.5 % of heavy fraction, ilmenite and leucoxene – 21.5 and 13.4 % correspondingly. Leucoxene forms in result of substitution of ilmenite that is confirmed by sustainable negative correlation of these minerals. Content of tourmaline vary from 0.2 to 21 % (average 9.7 %), rutile 0.1 – 8.4 % (average 2.6 %), anatase 0.2 – 24.7 % (average 2.8 %). Staurolite, sphen, amphiboles, pyroxenes, garnets and some other minerals are found routinely, but their contents do not exceeds 0.5 %.

Research of concentrations of Ti-Zr heavy minerals both in vertical sequence reveals that it is under control of stratigraphic factors (see Table 2). Both average content of sum of placer minerals and extremely concentrations are sufficiently more in Ladoga formation. It corresponds to regressive character of the Member. Laterally within Ladoga Member total content of Ti-Zr minerals has tendency to increase from west to east. It roughly corresponds to direction of transport of the material.

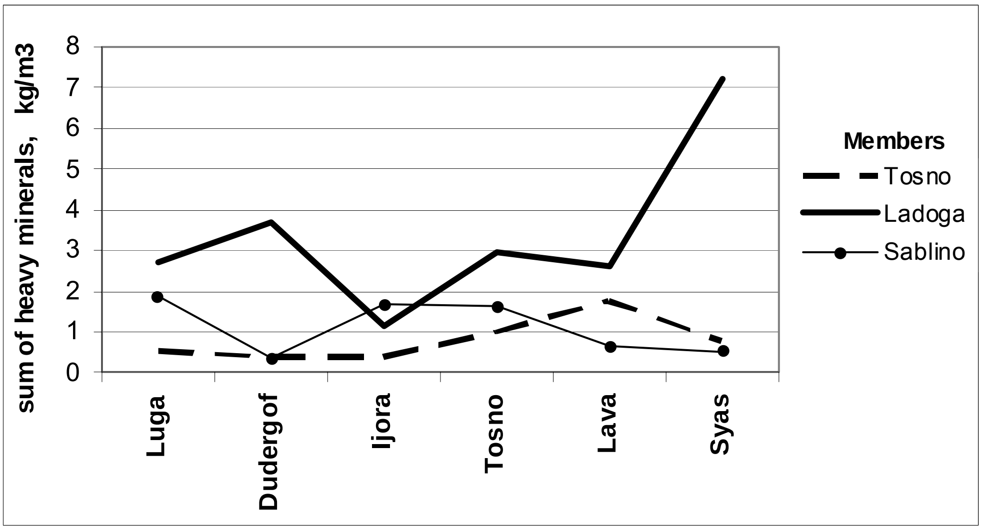

Fig. 8. Concentration of heavy minerals in different Members.

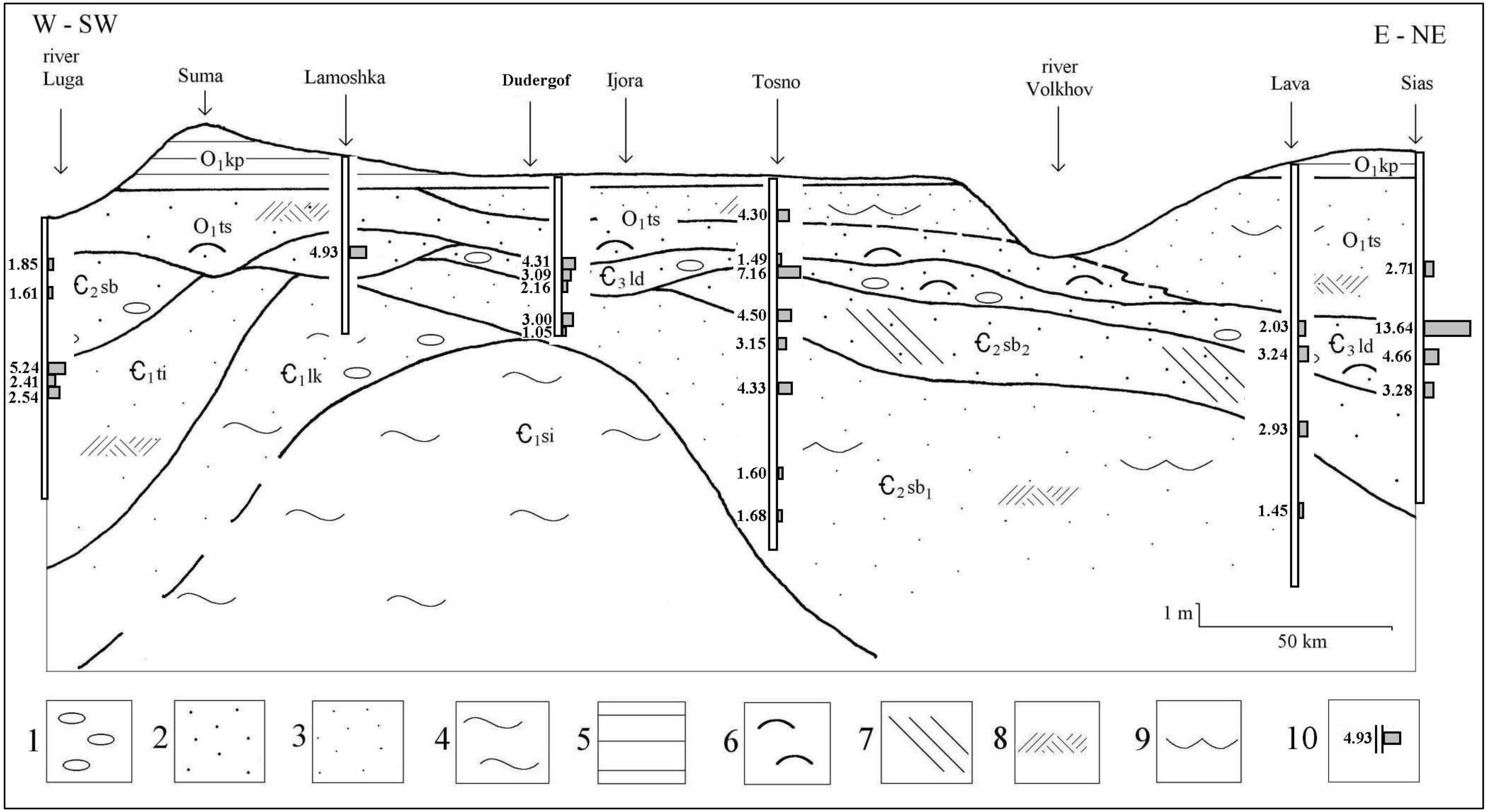

Fig. 9. Cross section of COS with overlying and underlying deposits. Legend: 1-pebbles; 2 - coarse sand; 3 – fine sand; 4 – clay; 5 – shale; 6 – organic detritus; 7 – large-scale unilateral cross beds; 8 – cross beds with different orientations; 9 – ripple marks and trough lamination; 10 – concentration of heavy Ti – Zr minerals, kg/m^3 minerals (samples with content more than 1 kg/m^3 are presented). Cambrian System: $C_{1\ si}$ – Siversk Formation; $C_{1\ lk}$ – Liukatin Member; $C_{1\ ti}$ – Tiskres Member; C_{2sb} – Sablino Member; $C_{3\ ld}$ – Ladoga Member; $C_{3\ lm}$ – Lamoshka Member. Ordovician System: $O_{1\ ts}$ – Tosno Member; $O_{1\ kp}$ – Koporie Formation.

TOTAL BED SEDIMENT LOAD CALCULATION IN APPLYING EINSTEIN PROCEDURE.

Preliminary estimation of the duration of deposition based on lithological features and velocity of sedimentation of present-day analogues of COS (Lisitsin, 1971) demonstrated sufficient difference between calculated and stratigraphic time assigned for the sequence (Kulyamin and Smirnov, 1973; Tugarova et al., 2001). Here we calculate the duration with applying Einstein procedure.

The total bed sediment discharge for unit width q_T can be calculated from the sum of the unit bed sediment discharge q_b and the unit suspended sediment discharge q_s.

$$q_T = q_b\,[1 + I_1 \ln(30h/\mathrm{d_s}) + I_2] \qquad (1)$$

where h – flow depth; $\mathrm{d_s}$ – sediment size; I_1 and I_2 integrals that can be solved numerically or with the use of nomographs preparing by Einstein.

Einstein introduces several corrections factors accounting for hydraulically smooth boundaries, sediment transport by size fractions, hiding factors, grain resistance instead of total resistance, velocity and pressure corrections. This method is expected to work best when the bedload constitutes the most significant portion of the total load. According to analysis of textures and grain size analysis of the sediments we could to conclude that the condition is available for COS.

This complex method is given in detail in Appendix of [Julien, 1995].

Einstein's bed sediment discharge function gives the rate at which flow of any magnitude in a given channel transports the individual sediment sizes found in the bed material. Therefore equation (1) could be presented as:

$$q_T = \Sigma\, i_T q_{Ti} \qquad (2)$$

where i_T is content of a fraction of total bed material; q_{Ti} – discharge of i-fraction.

The first step of the procedure is to receive the bed sediment and the channel information for following calculation. These data are presented in the Table 3.

Four sustainable extended sedimentary bodies are marked out in COS – Lower and Upper Units of Sablino Member, Ladoga Member and Tosno Member. Results of 19-fraction grain size analysis for these bodies were averaged and collected for following calculation into three size fraction which contains not less than ninety percent of the bed material (0.45 – 0.22, 0.22 – 0.11, 0.11 – 0.055 mm). Addition parameters (average grain size for the fractions, percentiles and setting velocities) were calculated.

Inasmuch as width of the channel was certainly much more than the depth, it is possible to equate hydraulic radius (R_b) to the depth of the channel (y_0). The channel slope was obtained from difference of the altitude of the bottom surface of the Formations within the bounds of SPb region.

Table 3. Bed sediment information for Einstein's sediment transport method.

Average grain size			Distribution of size fraction %				Setting velocity (w)	
Limits of size fraction	d_s							
	mm	ft	Sb_1	Sb_2	Ld	Ts	mm/s	ft/s
>0.45			0.64	2.52	3.87	7.12		
0.45-0.22	0.34	0.00110	21.97	40.21	24.08	36.88	42	0.138
0.22-0.11	0.17	0.00054	49.02	28.48	31.87	44.21	19	0.062
0.11-0.055	0.08	0.00027	22.47	24.34	32.97	9.44	5	0.016
<0.055			5.90	4.44	7.21	2.35		
in mm								
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		
in ft								
D_{16}			0.00027	0.00029	0.00023	0.00035		
D_{35}			0.00037	0.00037	0.00031	0.00049		
D_{50}			0.00044	0.00056	0.00038	0.00062		
D_{65}			0.00055	0.00071	0.00053	0.00072		
D_{84}			0.00072	0.00082	0.00082	0.00092		
The channel slopes S_f			0.00012	0.00003	0.00003	0.00002		

Note: Sb_1 – Lower Unit of Sablino Member; Sb_2 – Upper Unit of Sablino Member;
Ld – Ladoga Member; Ts – Tosno Member.

The sediment transport calculation are made for the individual size fraction that has a representative grain size equal to the geometric mean grain diameter of each fraction. The water viscosity is $\nu = 1.0 \times 10^{-5}$ ft^2/s and the specific gravity of the sediment is 2.65.

Important hydraulic parameters are given in Appendix 1. The bed sediment transport is than calculated for each grain fraction of the bed material at each given flow depth. Results of the calculation of specific sediment discharge for each sediment body are given in Appendix 2–5. Detail definitions and methods of calculation for each parameter are given in Julien [1995], Tables A.2. and A.3.

CALCULATION OF THE TIME OF DEPOSITION

Total bed sediment load calculation in applying Einstein procedure as a single parameter do not allows determining possible deposition time for all sequence of Cambrian-Ordovician sandstones of St.-Petersburg region. Einstein procedure is suitable for steady unidirectional flow. Real flow was not steady neither direction not intensity. Analysis of textures result to conclusion of alternate mode of the flow, therefore we should take this fact into account. Also, it is necessary to consider partial erosion of strata on the border of the Members.

Inasmuch as specific sediment discharge is calculated, knowledge of full thickness of the Member taking into consideration of partial erosion, resulting vector of transport and extension of the Member in the direction of the flow let us possibility to calculate duration of deposition of the Member.

Taking into account of variation of the flow direction

Orientation of cross-beds indicates that during the deposition of COS the flow was orientated mainly from west – northwest to east – southeast. At the same time, the flow was not steady: we see variations of the orientation within the sequence that is evidence of changing of direction of the flow in time. Therefore for calculation of the duration of deposition we should use resulting vector of the flow (sum of the vectors). The resulting vector is taken into account by coefficient of effectiveness of the flow (C_f) that is equal 0.8 for Upper Unit of Sablino Member; 0.5 for Lower Unit of Sablino Member; 0.4 for Ladoga Member and 0.3 for Tosno Member.

Taking into account of partial erosion of strata

Detail analysis of structure of COS and erosion surfaces on extended territory shows that boundaries between Members have mostly plane character without deep erosion troughs. Most obvious and pronounced erosion surface within COS sequence is in the bottom of Ladoga Member. It has shallow erosion pockets with pebbles of clay. Others contacts between Member have not so obvious evidences of erosion. In our calculation we should take into account erosion of some parts of the sequence. For this purpose we take into calculation not average thickness but sum of maximal thicknesses of the Member containing COS.

Whereas multiplying erosion and deposition should result to increasing of concentration of heavy minerals in the sand sediments up to industrial important placers [Placer deposits … , 1997], we have possibility to estimate rate of erosion and re-deposition on the base of content of heavy minerals. Relatively significant concentration of heavy minerals we see only in Ladoga Member (Table 2) that confirm proposal that the Member has close relation to erosion processes. Ladoga sandstones have concentration of heavy minerals about three times more that in underlying deposits of Sablino Member. Therefore it is possible to suppose that initial thickness of Ladoga Member was about three times more that the final one: light minerals (mostly, quarts) were removed by the flow that result to increasing of content of heavy fraction in three times correspondingly. Thus, we put into calculation thickness of Ladoga Member reformed by coefficient of erosion $C_e = 3$. For other Formations $C_e = 1$.

Resulting calculation

Using, specific sediment discharge per unit width according to Einstein procedure (q_T); maximal thickness of the Member (H_{max},) multiplying by coefficient of erosion (C_e); extension of the Members in direction of the flow (L) and coefficient of effectiveness of the flow (C_f) we can obtain duration of deposition of the Member (T_d) by formula (3):

$$T_d = \frac{H_{max}\, C_e\, L}{q_T\ C_f} \qquad (3)$$

Results of the calculation are shown in the Table 4.

Table 4. Result of calculation duration of deposition time for Cambrian – Ordovician sandstones of St.-Petersburg region in applying Einstein procedure.

Member (Unit)	q_T			C_f	L	H_{max}	Duration of deposition (T_d)	
	lb/s x ft from tables 3 – 6	t/day x m	m^3/day x m				days	years
Sb_1	0.688	77.25	38.62	0.5	100	8	41424	114
Sb_2	0.152	17.03	8.52	0.8	80	4	46969	129
Ld	0.091	10.23	5.11	0.4	100	9*	439907	1205
Ts	0.066	7.45	3.72	0.3	120	5	537012	1471
TOTAL:						26		**2919**

Definitions: q_T, Specific sediment discharge per unit width according to Einstein procedure; H_{max}, maximal thickness of the Member, m; L, extension of the Member in direction of the flow, km; C_f, coefficient of effectiveness of the flow.
* value reformed by coefficient of erosion.

Relative error of the calculation is too large for exact determining of the duration of sedimentation because of approximate estimation of some parameters such as the channel slope, direction of the flow, extension of Formation and coefficient of effectiveness, therefore we can definitely determine only order of the value of the duration. Thus we can suppose that according to Einstein procedure with our additions, the duration of deposition of all sequence of Cambrian-Ordovician Sandstones of SPb region did not exceeds 3000 years, that is about 0.001% of 25 million years that is assigned to the sequence by stratigraphic chart.

Reliability of the calculation is confirmed by independent sedimentological methods based on modern analogues of the strata that provide the estimation even shorter than Einstein procedure. Based on the analysis of tidal cycles, Kulyamin and Smirnov established that the pure deposition period of Cambrian – Ordovician sandstones in the Baltic region is approximately 170 days, including a mere of 130 days for Middle – Upper Cambrian Sablino sandstones and 40 days for Lower Ordovician Pakerort sandstones (analogue of Tosno Member) [Kulyamin and Smirnov, 1973]. Study of analogous sediments in the SPb district also showed that the pure deposition time of Lower Paleozoic sands is estimated at 100 – 200 yr., while stratigraphic duration of the Sablino Member is 10 – 15 Ma [Tugarova *et al.*, 2001].

The effect of large difference between sedimentological and stratigraphical age of strata is observed in many natural objects not only in researched region but also over the world. They explain this effect by erosion of significant part of the sediments in geological sequences and by the multiple rewashing of sediments in shallow-water zones with an active lithodynamics characterized by alternations of sedimentation and seafloor abrasion depending on the force of gales and currents. Meyen believed that only a tiny share (0.01- 0.001%) of the total time of sedimentation in shallow-water zones is usually documented because of the abundance of latent hiatuses [Meyen, 1989].

We took into account alternation of direction of the flow by coefficient of effectiveness of the flow that allows eliminating influence of multiplying migration of the sediments in the point of observation. Also, we consider partial erosion of the strata. As we took into calculation maximal values of the parameters, so the calculation gives us maximal duration; real time of deposition could be less.

Accumulation of thick fine grained layers of clay with significant content of organic carbon that are evidence of long interrupts of sedimentation (stagnation) are not observed in the COS sequence. In the Sablino Member, which maximal thickness is 15 м, total thickness of clay interlayers vary from few centimetres (in the valley of river Tosna) up to few tens of centimetres (in the valley Lava). Content of organic carbon is about 0.1 – 0.3%; the content is invariable in the vertical sequence that is evidence of lack of stagnation periods.

CONCLUSION

Detail research of Cambrian – Ordovician Sandstones of St.-Peterburg region shows that the sequence is result of single deposition cycle that develops from clay of Siversk Formation (underluing to Sablino Member) to the lower boundary of Ladoga Member (regressive phase); and from Ladoga to Tosno (and overlying Koporie shales) as transgressive phase according to changing of paleohydraulic conditions. Inner erosion surfaces were result of variations of intensity and competence of the flow rather than long interrupt of sedimentation and erosion of strata in subaerial conditions. During all period of deposition resulting vector of paleoflow had prevail direction from west-northwest to east-southeast.

Range of erosion processes was moderate: though we cannot to determine initial thickness of the Members certainly, indirect indicators show that the initial thickness of three main Members (Sablino, Ladoga and Tosno) did not exceeds 26 m (Table 9).

Calculation of total bed sediment load of the paleoflow in applying Einstein procedure indicates that specific sediment discharge per unit width had variations from approximately 40 m^3/day per unit width in Lower Unit of Sablino Member to about 4 m^3/day/m in Tosno Member. Applying of the discharge to available volume of the Members allows to suppose that duration of deposition of all sequence of Cambrian-Ordovician Sandstones of SPb region did not exceeds 3000 years, that is about 0.001% of 25 million years that is assigned to the sequence by stratigraphic chart. Neither interrupts of sedimentation (stagnation) nor erosion of part of the strata could explain this lack of coincidence. Absence of 99.999% of assumed sedimentary sequence is reason for questioning of the conventional chronostratigraphy based of Stenon’s principles that should be revised on the foundation of modern observations and experiments [Berthault, 2004, 2006].

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Appendix 1. Hydraulic calculation in applying Einstein procedure.

R_b'	V_*'	δ'	k_s/δ'	X	Δ	V	Ψ'	V/V_*''	V_*''	R_b''	R_b	y_0	Z_0	P_b	A	Q	X_{av}	Y	B_x	$(B/B_x)^2$	P_E
Lower Unit of Sablino Member (Sb$_1$)																					
0,5	0,04	0,0026	0,21	0,70	0,0008	2,89	10,18	8,5	0,12	3,47	3,97	3,97	156	253	1005	988	0,0037	0,10	1,70	0,37	11,94
1,0	0,06	0,0019	0,29	0,90	0,0006	0,98	5,09	12,0	0,13	4,25	5,25	5,25	159	325	1708	2625	0,0026	0,25	1,65	0,38	12,47
2,0	0,09	0,0013	0,42	1,20	0,0005	1,54	2,54	18,0	0,13	4,56	6,56	6,56	162	400	2624	6268	0,0018	0,36	1,63	0,40	12,98
3,0	0,11	0,0011	0,51	1,35	0,0004	2,39	1,70	23,0	0,13	4,61	7,61	7,61	164	460	3495	10717	0,0015	0,45	1,59	0,41	13,24
4,0	0,12	0,0009	0,59	1,48	0,0004	3,07	1,27	30,0	0,12	3,85	7,85	7,85	164	474	3721	13615	0,0013	0,56	1,57	0,43	13,37
5,0	0,14	0,0008	0,66	1,55	0,0004	3,66	1,02	40,0	0,10	2,83	7,83	7,83	164	473	3704	15497	0,0012	0,60	1,54	0,44	13,41
6,0	0,15	0,0008	0,72	1,58	0,0003	4,18	0,85	50,0	0,09	2,25	8,25	8,25	165	497	4099	19101	0,0011	0,70	1,51	0,46	13,48
Upper Unit of Sablino Member (Sb$_2$)																					
0,5	0,02	0,0053	0,13	0,40	0,0018	0,45	40,7	5,0	0,09	8,28	8,78	8,78	166	528	4633	2071	0,0074	0,1	1,64	0,39	11,92
1,0	0,03	0,0037	0,19	0,65	0,0011	0,72	20,4	6,5	0,11	12,84	13,84	13,84	178	829	11479	8305	0,0052	0,2	1,70	0,36	12,86
2,0	0,04	0,0026	0,27	0,85	0,0008	1,13	10,2	8,0	0,14	20,63	22,63	22,63	198	1386	31368	35402	0,0037	0,22	1,67	0,38	13,62
3,0	0,05	0,0022	0,33	1,00	0,0007	1,46	6,8	10,0	0,15	22,05	25,05	25,05	204	1547	38752	56522	0,0030	0,27	1,65	0,39	13,88
4,0	0,06	0,0019	0,38	1,10	0,0006	1,74	5,1	12,0	0,15	21,88	25,88	25,88	206	1603	41489	72342	0,0026	0,32	1,63	0,40	14,01
5,0	0,07	0,0017	0,42	1,20	0,0006	2,00	4,1	14,0	0,14	21,22	26,22	26,22	207	1626	42630	85399	0,0023	0,38	1,62	0,40	14,11
6,0	0,08	0,0015	0,46	1,30	0,0005	2,24	3,4	16,0	0,14	20,39	26,39	26,39	208	1638	43217	96991	0,0021	0,4	1,61	0,40	14,20
Ladoga Member (Ld)																					
0,5	0,02	0,0053	0,10	0,30	0,0018	0,45	34,10	5,0	0,09	8,29	8,79	8,79	166	528	4643	2076	0,0074	0,10	1,64	0,39	11,92
1,0	0,03	0,0037	0,14	0,40	0,0013	0,71	17,05	7,0	0,10	10,62	11,62	11,62	173	695	8076	5722	0,0052	0,10	1,62	0,40	12,49
2,0	0,04	0,0026	0,20	0,70	0,0008	1,14	8,53	9,0	0,13	16,61	18,61	18,61	189	1127	20968	23891	0,0037	0,15	1,71	0,36	13,52
3,0	0,05	0,0022	0,25	0,80	0,0007	1,47	5,68	11,0	0,13	18,45	21,45	21,45	196	1310	28100	41247	0,0030	0,20	1,68	0,37	13,80
4,0	0,06	0,0019	0,28	0,90	0,0006	1,76	4,26	14,0	0,13	16,34	20,34	20,34	193	1237	25168	44242	0,0026	0,22	1,67	0,38	13,86
5,0	0,07	0,0017	0,32	1,05	0,0005	2,03	3,41	16,0	0,13	16,70	21,70	21,70	196	1325	28756	58397	0,0023	0,25	1,69	0,37	14,08
6,0	0,08	0,0015	0,35	1,10	0,0005	2,27	2,84	17,0	0,13	18,45	24,45	24,45	203	1507	36842	83561	0,0021	0,30	1,67	0,38	14,24
Tosno Member (Ts)																					
0,5	0,02	0,0065	0,11	0,30	0,0024	0,35	80,85	4,0	0,09	12,00	12,50	12,50	175	748	9349	3285	0,0090	0,10	1,60	0,41	11,97
1,0	0,03	0,0046	0,16	0,55	0,0013	0,58	40,43	5,0	0,12	20,86	21,86	21,86	197	1336	29218	16924	0,0064	0,15	1,71	0,36	13,13
2,0	0,04	0,0032	0,22	0,72	0,0010	0,91	20,21	6,5	0,14	30,16	32,16	32,16	223	2037	65525	59326	0,0045	0,20	1,68	0,37	13,79
3,0	0,04	0,0026	0,27	0,80	0,0009	1,16	13,48	7,8	0,15	34,67	37,67	37,67	238	2436	91774	106908	0,0037	0,22	1,64	0,39	14,05
4,0	0,05	0,0023	0,31	1,00	0,0007	1,41	10,11	8,5	0,17	42,77	46,77	46,77	263	3129	146337	206309	0,0032	0,25	1,67	0,38	14,49
5,0	0,06	0,0020	0,35	1,07	0,0007	1,62	8,09	9,5	0,17	45,06	50,06	50,06	273	3391	169770	274589	0,0028	0,30	1,65	0,39	14,63
6,0	0,06	0,0019	0,38	1,18	0,0006	1,82	6,74	10,0	0,18	51,22	57,22	57,22	295	3981	227825	413562	0,0026	0,33	1,65	0,38	14,86

Definitions: R_b'- bed hydraulic radius due to grain roughness, ft; V_*'- shear velocity due to grain roughness, ft/s; δ'- thickness of the laminar sublayer, ft; k_s- roughness diameter, ft = D_{65}; X- correction factor in the logarithmic velocity distribution; Δ- apparent roughness diameter, ft; V- average flow velocity, ft/s; Ψ'- intensity of shear on representative particles; V_*''- shear velocity due to form roughness, ft/s; R_b''- bed hydraulic radius due to form roughness, ft; R_b- bed hydraulic radius, ft; y_0 – average flow depth, ft; Z_0 – stage, ft; P_b – bed wetter perimeter, ft; A- cross-sectional area, ft^2; Q- flow discharge; X_{av}- characteristic distance; Y- pressure correction term; B, B_x – coefficients; P_E – Einstein's transport parameter. [Jilien, 1995, tabl.A.2., p.265].

Appendix 2. Bed sediment load calculation in applying the Einstein procedure for Lower Unit of Sablino Member (Sb_1).

D	i_b	R_b’	Ψ	D/X_{av}	ξ	Ψ_*	Φ_*	$i_b\ q_b$	10^3E	Z	I_1	$-I_2$	$P_E\ I_1+I_2+1$	$i_T\ q_T$	$\Sigma\ i_T\ q_T$
0,00110	0,22	0,5	30,25	0,30	15,0	16,59	0,02000	0,00019	0,55	7,85	0,02	0,20	1,04	0,0002006	0,0002038
		1	15,13	0,42	6,0	8,72	0,20000	0,00193	0,42	5,55	0,04	0,40	1,04	0,0020016	0,0020150
		2	7,56	0,60	2,0	2,16	3,00000	0,02897	0,34	3,93	0,07	0,70	1,21	0,0350115	0,0351104
		3	5,04	0,73	1,6	1,51	4,00000	0,03863	0,29	3,21	0,15	0,90	2,09	0,0806008	0,0815451
		4	3,78	0,85	1,3	1,18	4,50000	0,04345	0,28	2,78	0,20	0,95	2,72	0,1183581	0,1359752
		5	3,03	0,95	1,2	0,96	5,00000	0,04828	0,28	2,48	0,25	1,40	2,95	0,1425849	0,1815646
		6	2,52	1,04	1,1	0,90	5,00000	0,04828	0,27	2,27	0,30	1,50	3,55	0,1711630	0,2513506
0,00054	0,49	0,5	14,85	0,07	120,0	65,17	0,00001	0,00000	0,27	3,53	0,15	1,30	1,49	0,0000001	
		1	7,43	0,10	100,0	71,32	0,00001	0,00000	0,21	2,49	0,26	1,50	2,74	0,0000002	
		2	3,71	0,15	80,0	42,38	0,00010	0,00000	0,16	1,76	0,30	2,70	2,19	0,0000016	
		3	2,48	0,18	40,0	18,49	0,01000	0,00007	0,14	1,44	0,40	3,00	3,30	0,0002444	
		4	1,86	0,21	25,0	11,10	0,08000	0,00059	0,14	1,25	0,70	4,50	5,86	0,0034731	
		5	1,49	0,23	22,0	8,68	0,20000	0,00148	0,14	1,12	1,10	7,00	8,75	0,0129746	
		6	1,24	0,25	20,0	7,99	0,25000	0,00185	0,13	1,02	2,00	8,00	19,97	0,0369926	
0,00027	0,22	0,5	7,43	0,04	150,0	40,73	0,00010	0,00000	0,14	0,91	3,00	11,00	25,81	0,0000031	
		1	3,71	0,05	135,0	48,14	0,00010	0,00000	0,10	0,64	11,00	28,00	110,16	0,0000132	
		2	1,86	0,07	120,0	31,78	0,00010	0,00000	0,08	0,46	70,00	100,00	809,57	0,0000972	
		3	1,24	0,09	110,0	25,42	0,00050	0,00000	0,07	0,37	100,00	160,00	1165,48	0,0006999	
		4	0,93	0,10	100,0	22,19	0,00800	0,00001	0,07	0,32	125,00	200,00	1472,10	0,0141440	
		5	0,74	0,12	93,0	18,35	0,01000	0,00001	0,07	0,29	180,00	250,00	2165,28	0,0260051	
		6	0,62	0,13	87,0	17,39	0,01500	0,00002	0,07	0,26	200,00	300,00	2397,71	0,0431950	

Definitions: D, representative grain size, ft, given in Table 1; i_b, fraction of bed material given in Table 1; R_b’- bed hydraulic radius due to grain roughness, ft; Ψ, intensity of shear on a particle; D/X_{av} – dimensionless ration, X_{av} given in Table 2; ξ, hiding factor; Ψ_*, intensity of shear on individual grain size; Φ_* - intensity of sediment transport on individual grain; $i_b\ q_b$ – bedload discharge per unit width for a size fraction, lb/s x ft; E – ratio of bed layer thickness to water depth; Z – exponent for concentration distribution; I_1, I_2 – integrals obtained from figs A.4. and A.5., of Julien, 1995; $P_E\ I_1+I_2+1$ – factor between bedload and total load, using P_E from Table 2; $i_T\ q_T$ – bed material load per unit width of stream for a size fraction, lb/s x ft = $i_b\ q_b$ x ($P_E\ I_1+I_2+1$); $\Sigma\ i_T\ q_T$ – total bed load discharge per unit width for all size fractions. [Julien, 1995, table A.3., p.266 - 267].

Appendix 3. Bed sediment load calculation in applying the Einstein procedure for Upper Unit of Sablino Member (Sb_2).

D	i_b	R_b'	Ψ	D/X_{av}	ξ	Ψ_*	Φ	$i_b q_b$	10^3E	Z	I_1	$-I_2$	$P_E I_1+ I_2 + 1$	$i_T q_T$	$\Sigma i_T q_T$
0,00110	0,40	0,5	121,00	0,30	15,0	66,37	0,00010	0,00000	0,55	7,85	0,02	0,20	1,04	0,0000018	0,0000022
		1	60,50	0,42	6,0	34,87	0,00010	0,00000	0,42	5,55	0,04	0,40	1,04	0,0000018	0,0000034
		2	30,25	0,60	2,0	8,63	0,20000	0,00352	0,34	3,93	0,07	0,70	1,21	0,0042496	0,0042601
		3	20,17	0,73	1,6	6,03	0,40000	0,00703	0,29	3,21	0,15	0,90	2,09	0,0146747	0,0146898
		4	15,13	0,85	1,3	4,70	0,60000	0,01055	0,28	2,78	0,20	0,95	2,72	0,0287321	0,0287534
		5	12,10	0,95	1,2	3,86	0,80000	0,01406	0,28	2,48	0,25	1,40	2,95	0,0415359	0,0415674
		6	10,08	1,04	1,1	3,58	1,00000	0,01758	0,27	2,27	0,30	1,50	3,55	0,0623261	0,0623653
0,00054	0,28	0,5	59,40	0,07	120,0	260,66	0,00001	0,00000	0,27	3,53	0,15	1,30	1,49	0,0000001	
		1	29,70	0,10	100,0	285,27	0,00001	0,00000	0,21	2,49	0,26	1,50	2,74	0,0000001	
		2	14,85	0,15	80,0	169,52	0,00001	0,00000	0,16	1,76	0,30	2,70	2,19	0,0000001	
		3	9,90	0,18	40,0	73,95	0,00001	0,00000	0,14	1,44	0,40	3,00	3,30	0,0000001	
		4	7,43	0,21	25,0	44,38	0,00010	0,00000	0,14	1,25	0,70	4,50	5,86	0,0000025	
		5	5,94	0,23	22,0	34,72	0,00010	0,00000	0,14	1,12	1,10	7,00	8,75	0,0000037	
		6	4,95	0,25	20,0	31,97	0,00010	0,00000	0,13	1,02	2,00	8,00	19,97	0,0000085	
0,00027	0,24	0,5	29,70	0,04	150,0	162,91	0,00001	0,00000	0,14	0,91	3,00	11,00	25,81	0,0000003	
		1	14,85	0,05	135,0	192,56	0,00001	0,00000	0,10	0,64	11,00	28,00	110,16	0,0000014	
		2	7,43	0,07	120,0	127,14	0,00001	0,00000	0,08	0,46	70,00	100,00	809,57	0,0000104	
		3	4,95	0,09	110,0	101,68	0,00001	0,00000	0,07	0,37	100,00	160,00	1165,48	0,0000150	
		4	3,71	0,10	100,0	88,77	0,00001	0,00000	0,07	0,32	125,00	200,00	1472,10	0,0000189	
		5	2,97	0,12	93,0	73,39	0,00001	0,00000	0,07	0,29	180,00	250,00	2165,28	0,0000278	
		6	2,48	0,13	87,0	69,54	0,00001	0,00000	0,07	0,26	200,00	300,00	2397,71	0,0000308	

Definitions: the same as for Appendix 2.

Appendix 4. Bed sediment load calculation in applying the Einstein procedure for Ladoga Member (Ld).

D	i_b	R_b'	Ψ	D/X_{av}	ξ	$Ψ_*$	Φ	$i_b q_b$	$10^3 E$	Z	I_1	$-I_2$	$P_E I_1 + I_2 + 1$	$i_T q_T$	$Σ i_T q_T$
0,00110	0,24	0,5	121,00	0,30	15,0	66,37	0,00010	0,00000	0,55	7,85	0,02	0,20	1,04	0,0000011	0,0000016
		1	60,50	0,42	6,0	34,87	0,00010	0,00000	0,42	5,55	0,04	0,40	1,04	0,0000011	0,0000032
		2	30,25	0,60	2,0	8,63	0,20000	0,00211	0,34	3,93	0,07	0,70	1,21	0,0025498	0,0025642
		3	20,17	0,73	1,6	6,03	0,40000	0,00422	0,29	3,21	0,15	0,90	2,09	0,0088048	0,0088255
		4	15,13	0,85	1,3	4,70	0,60000	0,00633	0,28	2,78	0,20	0,95	2,72	0,0172392	0,0172680
		5	12,10	0,95	1,2	3,86	0,80000	0,00844	0,28	2,48	0,25	1,40	2,95	0,0249215	0,0249640
		6	10,08	1,04	1,1	3,58	1,00000	0,01055	0,27	2,27	0,30	1,50	3,55	0,0373956	0,0374476
0,00054	0,32	0,5	59,40	0,07	120,0	260,66	0,00001	0,00000	0,27	3,53	0,15	1,30	1,49	0,0000001	
		1	29,70	0,10	100,0	285,27	0,00001	0,00000	0,21	2,49	0,26	1,50	2,74	0,0000001	
		2	14,85	0,15	80,0	169,52	0,00001	0,00000	0,16	1,76	0,30	2,70	2,19	0,0000001	
		3	9,90	0,18	40,0	73,95	0,00001	0,00000	0,14	1,44	0,40	3,00	3,30	0,0000002	
		4	7,43	0,21	25,0	44,38	0,00010	0,00000	0,14	1,25	0,70	4,50	5,86	0,0000028	
		5	5,94	0,23	22,0	34,72	0,00010	0,00000	0,14	1,12	1,10	7,00	8,75	0,0000042	
		6	4,95	0,25	20,0	31,97	0,00010	0,00000	0,13	1,02	2,00	8,00	19,97	0,0000097	
0,00027	0,33	0,5	29,70	0,04	150,0	162,91	0,00001	0,00000	0,14	0,91	3,00	11,00	25,81	0,0000005	
		1	14,85	0,05	135,0	192,56	0,00001	0,00000	0,10	0,64	11,00	28,00	110,16	0,0000019	
		2	7,43	0,07	120,0	127,14	0,00001	0,00000	0,08	0,46	70,00	100,00	809,57	0,0000143	
		3	4,95	0,09	110,0	101,68	0,00001	0,00000	0,07	0,37	100,00	160,00	1165,48	0,0000206	
		4	3,71	0,10	100,0	88,77	0,00001	0,00000	0,07	0,32	125,00	200,00	1472,10	0,0000260	
		5	2,97	0,12	93,0	73,39	0,00001	0,00000	0,07	0,29	180,00	250,00	2165,28	0,0000382	
		6	2,48	0,13	87,0	69,54	0,00001	0,00000	0,07	0,26	200,00	300,00	2397,71	0,0000423	

Definitions: the same as for Appendix 2.

Appendix 5. Bed sediment load calculation in applying the Einstein procedure for Tosno Member (Ts).

D	i_b	R_b'	Ψ	D/X_{av}	ξ	$Ψ_*$	$Φ_*$	$i_b q_b$	$10^3 E$	Z	I_1	$-I_2$	$P_E I_1 + I_2 + 1$	$i_T q_T$	$Σ i_T q_T$
0,00110	0,37	0,5	181,50	0,30	15,0	99,56	0,00010	0,00000	0,55	7,85	0,02	0,20	1,04	0,0000017	0,0000019
		1	90,75	0,42	6,0	52,30	0,00010	0,00000	0,42	5,55	0,04	0,40	1,04	0,0000017	0,0000024
		2	45,38	0,60	2,0	12,95	0,03000	0,00049	0,34	3,93	0,07	0,70	1,21	0,0005896	0,0005937
		3	30,25	0,73	1,6	9,04	0,12000	0,00195	0,29	3,21	0,15	0,90	2,09	0,0040722	0,0040800
		4	22,69	0,85	1,3	7,05	0,30000	0,00488	0,28	2,78	0,20	0,95	2,72	0,0132886	0,0133633
		5	18,15	0,95	1,2	5,79	0,40000	0,00651	0,28	2,48	0,25	1,40	2,95	0,0192103	0,0193203
		6	15,13	1,04	1,1	5,37	0,50000	0,00813	0,27	2,27	0,30	1,50	3,55	0,0288258	0,0289544
0,00054	0,44	0,5	89,10	0,07	120,0	390,99	0,00001	0,00000	0,27	3,53	0,15	1,30	1,49	0,0000001	
		1	44,55	0,10	100,0	427,91	0,00001	0,00000	0,21	2,49	0,26	1,50	2,74	0,0000002	
		2	22,28	0,15	80,0	254,28	0,00001	0,00000	0,16	1,76	0,30	2,70	2,19	0,0000001	
		3	14,85	0,18	40,0	110,92	0,00010	0,00000	0,14	1,44	0,40	3,00	3,30	0,0000022	
		4	11,14	0,21	25,0	66,57	0,00010	0,00000	0,14	1,25	0,70	4,50	5,86	0,0000039	
		5	8,91	0,23	22,0	52,08	0,00010	0,00000	0,14	1,12	1,10	7,00	8,75	0,0000058	
		6	7,43	0,25	20,0	47,96	0,00010	0,00000	0,13	1,02	2,00	8,00	19,97	0,0000133	
0,00027	0,09	0,5	44,55	0,04	150,0	162,91	0,00001	0,00000	0,14	0,91	3,00	11,00	25,81	0,0000001	
		1	22,28	0,05	135,0	192,56	0,00001	0,00000	0,10	0,64	11,00	28,00	110,16	0,0000005	
		2	11,14	0,07	120,0	127,14	0,00001	0,00000	0,08	0,46	70,00	100,00	809,57	0,0000039	
		3	7,43	0,09	110,0	101,68	0,00001	0,00000	0,07	0,37	100,00	160,00	1165,48	0,0000056	
		4	5,57	0,10	100,0	88,77	0,00010	0,00000	0,07	0,32	125,00	200,00	1472,10	0,0000708	
		5	4,46	0,12	93,0	73,39	0,00010	0,00000	0,07	0,29	180,00	250,00	2165,28	0,0001042	
		6	3,71	0,13	87,0	69,54	0,00010	0,00000	0,07	0,26	200,00	300,00	2397,71	0,0001153	

Definitions: the same as for Appendix 2.