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Sedimentological Conditions of Early Paleozoic Paleobasin in the Northwestern Russian Platform: Reconstruction of Paleolithodynamics and Mineral Resources

Alexander Lalomov[1*], Guy Berthault[2]
[1]Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry of Russian Academy of Science, Moscow, Russia
[2]French Polytechnic School engineer, Meulan, France
Email: [*]lalomov@mail.ru

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ABSTRACT

Reconstruction of characteristics of sedimentary environments of the Lower Paleozoic Sandstone (hereafter LPS) sequence in the northwestern Russian platform based on granulometric and texture analyses reveals high paleohydrodynamic conditions of sedimentation which decrease to moderate in south-east direction. Determination of quantitative paleolithodynamic parameters showed that the real sedimentation duration was considerably less than the related stratigraphic scale interval that is evidence of long interrupt of sedimentation and re-deposition of the clastic material. Study of paleolithodynamics is significant both for reconstruction of the paleobasin history and assessment of mineral resources.

Keywords: Paleohydrodynamic Analysis; Lower Paleozoic Sandstones; Northwestern Russian Platform; Mineral Deposits

1. Introduction

Study of paleolithodynamics (and assessment of quantitative parameters especially) allows elucidating of formation conditions of the clastic rocks. Such a possibility is provided by recent studies in the field of 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 are used in the reconstruction of parameters of lithodynamic processes in paleobasins.

The study was carried out in two stages:

1) Reconstruction of hydrodynamic parameters of depositional environments based on the grain size composition and rock textures. Whereas the features of the sediments correspond to deposition phase that was certainly less active than previous erosion and transportation phases, obtained lithodynamic characteristics of the basin are minimal.

2) Based on the calculated values of the paleodrift rate in the facies zone under study the dependence of sediment load on hydrodynamic characteristics of the environment, and the grain size composition of sediments, one can assess the drift capacity and sedimentation duration for the Formation.

Reconstruction of paleohydrodynamic parameters allows forecasting of mineral deposits of the sedimentary basin such as "heavy mineral sands" (hereafter HMS).

2. Investigated Object

The lithodynamic reconstruction was carried out for the Cambrian–Ordovician sandstone sequence located in the northwestern part of Russian platform. 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. It is possible for investigation along narrow sub-latitudinal paleocliff ("glint"); in the southern direction LPS sequence is overlied with cover of platform deposits. This area was predominated by epeirogenic movements that governed its regressive–transgressive nature [1]. In the early Paleozoic, a shallow-water sea basin 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. The sequence is divided into following three Members from bottom to top (**Figure 1**).

[*]Corresponding author.

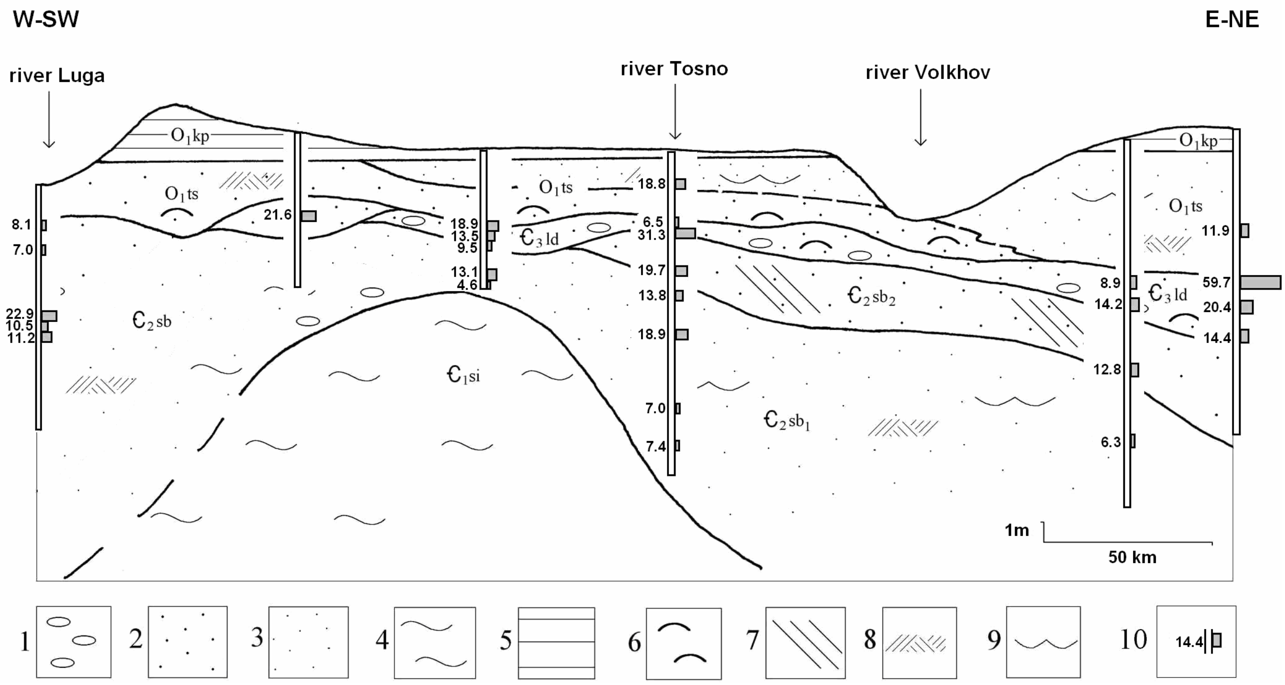

Figure 1. Section of Lower Paleozoic sandstones in the northwestern Russian platform. (1) Pebble; (2) coarse-to medium-grained sand; (3) fine-grained sand; (4) clay; (5) shale; (6) shell detritus; (7) unidirectional cross-bedded series; (8) criss-cross bedding; (9) ripple marks; (10) content of heavy minerals, kg/m^3. (si) Lower Cambrian Siversk Formation, "blue clay"; (sb_1) Middle Cambrian, Sablinka Member, lower subdivision; (sb_2) Middle Cambrian, Sablinka Member, upper subdivision; (ld) Upper Cambrian, Ladoga Member; (ts) Lower Ordovician, Tosno Member: (kp) Lower Ordovician, Koporie Formation ("black shales").

The Middle Cambrian *Sablinka Member* ($Є_{2sb}$) overly with erosion on the Lower Cambrian "blue clays" of Siversk Formation. It composed of light gray, well-graded, fine-grained, poorly cemented quartzy sandstones with plastic brownish gray clay interlayers 0.5 - 1 cm thick.

The textures are horizontal parallel-bedded structures with ripple marks and fine criss-cross-lamination in the lower sub-member; unidirectional cross-bedded structures are characteristic of the upper sub-member. The paleorelief amplitude is several meters. Thickness of the Sablinka Member increases eastward from 2 - 3 to 10 - 13 m.

The *Ladoga Member* ($Є_{3ld}$) 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. Thickness increase from 1 - 1.2 m in the western part to 3 m in its eastern part.

The *Tosna Member* (O_{1ts}) overly with erosion on sandstones of the Ladoga Member It is composed of coarse- to medium-grained, mainly quartzy, and poorly cemented sandstones with trough and cross bedding textures. Thickness of the Member varies from 2 to 5 m.

Studied Cambrian–Ordovician terrigenous sequence shows a regular increase in the hydrodynamic activity during sedimentation within the Sablinka Member from its bottom to top and a successive decrease in the activity during deposition of the Ladoga and Tosna Members. In general, the intensity of hydrodynamic processes decreased eastward in the area, from high level in the west to moderate in the south-east part, 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 Members. 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.

Texture analysis allows determining that sediment drift was orientated from west-northwest to east-south-east. Whereas in the western area the drift had unidirectional character, eastward it had alternate directional mode.

3. Calculation of the Drift Parameters and Sedimentation Duration of the Sequence

The Einstein method [2] is one of the basic ones 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 capacity of drift 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 [3]:

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

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

Calculated values of specific capacity of drift are 6.6, 5.1 and 3.7 m^3/day per 1 m width of the channel for Sablinka, Ladoga and Tosno Member consequently. Calculated velocities of flow decrease from west to east for every Member of the sequence. Taking into account parameters of the Members and lithodynamic characteristics of the drift, and using method of "reservoir sedimentation" [3], calculated duration of LPS sequence is not more than 5000 years [4]. It is evidence that sedimentation of the sequence was geologically momentary episode within the Middle Cambrian – Early Ordovician interval of the stratigraphic time-scale.

Thus, the calculated real time of formation (sedimentation duration) corresponds to less than 0.05% taking into account that the sedimentation duration based on the Einstein method is of the conservative nature. Other researchers [5,6] received similar conclusion based on texture and sedimentation analyses of the sequence. They explain the discrepancy by long interrupt of sedimentation or numerous erosion and re-deposition of clastic material.

Study of lithodynamic conditions is important not only for historical geology reconstructions but also for forecasting of mineral deposits of sedimentary basin.

4. Mineral Deposits in LPS Sequence

Shallow marine epicontinental basins are collectors of wide spectrum of mineral deposits of sedimentation series that are directly or indirectly depend of lithodynamic conditions of sedimentation. Indirect connection is usual for post-sedimentation mineral deposits (chemical infiltration deposits and oil) due to collector features of the sediments. Direct connection is character for con-sedimentational mineral deposits such as "heavy mineral sands" (HMS) that is main source of titanium and zirconium for world industry.

4.1. Geological Features of HMS

HMS consists of well-sorted mostly quartz sands with considerable concentration of sustainable for weathering heavy minerals (ilmenite, leucoxene, zircon, rutile, monacite etc). Heavy minerals content is of several per cent up to 20% - 30% and more: in HMS of Chavara placer deposit (south-west coast of India) the content sometimes reaches 50% - 60%, so the sands have character black color.

HMS in the most number of cases has sustainable size of mineral grains: light minerals (quartz and feldspars) usually are of 0.1 mm in average diameter, heavy minerals are of 0.07 mm. Such particles have hydraulic equivalence - the same fall velocity in water.

The concentrations form due to wave and current re-deposition of sands in beach and shallow sea zone with moving away of light minerals. Favorable conditions are: preliminary disintegration of source rocks, destruction of unsustainable minerals due to weathering, and moderate tectonic regime of area of erosion and sedimentation, but determinative factor is lithodynamic conditions suitable for separation of sediments to light and heavy fractions.

Table 1. Grain size parameters of the main stratigraphic units.

	Sablinka Member ***(Є$_2$ sb)***			Ladoga Member ***(Є$_3$ ld)***			Tosno Member ***(O$_1$ ts)***		
	west	center	east	west	center	east	west	center	east
Ma	0.28	0.18	0.16	0.23	0.14	0.12	0.30	0.26	0.21
σ	0.56	0.61	0.62	0.59	0.41	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	0.65	0.59	0.54	0.72	0.61	0.64	0.61	0.64	0.56

Ma – average size of grains (mm), σ - standard deviation, As – asymmetry, Ex – excess, Hr – relative entropy of the distribution.

In the zone of natural outcrops in the north part concentration of heavy minerals is not of economic significance in spite of general favorable geological situation. Our research allows to give answers: why researched deposits do not contain high concentrations of heavy minerals and where is perspective territories?

4.2. Favorable Lithodynamic Conditions for Concentrations of Heavy Minerals of HMS

Whereas light and heavy minerals are hydraulically equivalent, they have not differentiation in suspension. Special research of separation process allows determining that because of difference of critical shear velocities for particles of different density, the separation occurs during horizontal moving of the particles.

It begins on 10 cm/s when light minerals begin moving on the surface of sediments and stops when heavy mineral grains pass into suspension together with light grains on velocity of bottom flow about 18 cm/s [7].

Critical shear velocity for rolling and dragging particles (v_{0x}) for mineral grains of appointed size and specific gravity could be calculated with Knorroz equation [8]

$$v_{0x} = 3.75\upsilon^{0.3} (g \ \rho^*)^{0.35} d^{0.05}, \quad (2)$$

where υ – dynamic viscosity of fluid, g – gravity acceleration, d – diameter of particles, ρ^* – relative density of particles:

$$\rho^* = (\rho_s - \rho)/\rho, \quad (3)$$

where ρ_s and ρ are densities of solid phase and liquid respectively (kg/m^3). In the case of ρ_s= 2.7 g/cm^3 (density of quartz) v_{0x} corresponds to horizontal moving of the particles and beginning of separation process.

Critical shear velocity for saltation and suspension (v_{0zx}) is [9]:

$$v_{0zx} = 1.4 \ v_{0x} \quad (4)$$

For density of ilmenite (4.6 g/cm^3) it determines erosion of bottom sediments, transport of both light and heavy minerals in suspension and cessation of differentiation of minerals by specific weight.

4.3. Lower Paleozoic HMS of Northwestern Russian Platform

Thus, there is limited hydrodynamic interval of the flow velocities favorable for HMS formation. Reconstruction of paleohydrodynamic condition of the basin allows forecasting of most perspective territories for HMS exploration. Based on available granulimetric analysis and Equations (1) - (4) the velocities of the flow of paleobasin were calculated. Isolines of paleovelocities were interpolated for buried part of LPS.

Study of available natural outcrops reveals that within the stratigraphic sequence highest concentrations of heavy minerals are strongly attracted to Ladoga sands. The Member marks changing of regressive sedimentation of Sablinka sands to erosion, re-deposition, enrichment of the sand by heavy fraction and sedimentation of the Ladoga sands in the beginning of the transgressive regime (deposition of Tosno sands).

Concentration of heavy minerals in Ladoga sands increases eastward parallel to decreasing of the sand coarseness (**Figure 1, Table 1**).

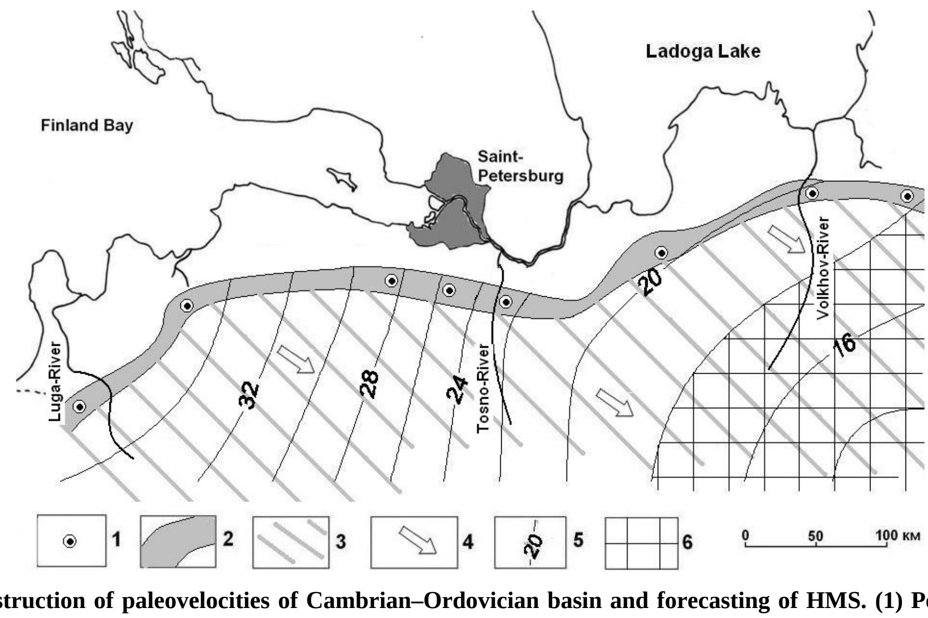

Figure 2. Reconstruction of paleovelocities of Cambrian–Ordovician basin and forecasting of HMS. (1) Points of sampling; (2). LPS Formation available for direct research; (3) LPS Formation under sedimentary cover; (4) directions of paleoflows; (5) isolines of paleovelocities, cm/s; (6) perspective territory for HMS.

Reconstruction of hydro- and lithodynamic conditions of the paleobasin reveals, that the velocities suitable for HMS formation (10 - 18 cm/s) prevail only in the south-east part of LPS location under sedimentary cover of platform deposits (**Figure 2**). Detail researched territory along "glint" is not perspective for heavy minerals concentration, because bottom velocities there exceeded favorable limits: placer-forming heavy minerals were carried away from this zone and deposited in the south-east part of the basin where the velocities decreased beneath critical shear velocity for (at least) suspension.

Availability of this area for HMS was confirmed by research of core samples of separate drilling holes that reveals heavy mineral concentration of economic importance in the south-east slope of Baltic Shield [10].

5. Conclusions

Using of equations obtained in engineering geology and hydrodynamics allows determination of sedimentary conditions of paleobasins based on granulometric analysis and textural features of the deposits. It is of significant importance both for study of fundamental regularities of historical geology and research of mineral deposits of sedimentary paleobasins.

Reconstruction of paleolithodynamics of Early Paleozoic terrigeneous basin of northwestern Russian platform allows conclusion that present-day observed strata assigned to Middle-Late Cambrian – Early Ordovician were deposited during short sedimentation episode that accounts 0.05% of stratigraphic interval.

Geological conditions of studied paleobasin were favorable for formation of heavy mineral placer deposits, but they are not revealed yet. Study of hydrodynamic conditions favorable for heavy minerals concentration and reconstruction of paleohydraulic environment allow forecasting HMS deposits of economic importance in the southeastern part on the basic under sedimentary cover of Russian platform.

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