

RECONSTRUCTION OF PALEOHYDRAULIC CONDITIONS OF DEPOSITION OF THE UPPER PERMIAN STRATA OF THE KAMA REGION

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Paleohydraulic sedimentary conditions of the Upper Permian basin of the East European platform region were reconstructed based on the data of grain size and structural analyses of the strata. Calculation of the paleolithodynamic parameters indicated that real duration of the sedimentation of the strata was much less than corresponding interval on the stratigraphic time-scale. Similar ratios are typical for other sedimentary formations in both platform and folded geological areas that correspond to an injective type of sedimentogenesis. This regularity should be taken into account in the interpretation of the stratigraphic chart and forecasting of sedimentary mineral deposits (hydrocarbon, in the first place).

Keywords: paleohydrodynamics, reconstruction, velocity of sedimentation, stratigraphic chart, mineral deposits

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Introduction

Study of the lithological structure of sedimentary rocks and determination of hydraulic conditions of sedimentation through observations in nature and in laboratory experiments provide necessary information for the reconstruction of paleohydraulic conditions of deposition. Flume experiments show that in the presence of a variable current, stratified superposed beds prograde simultaneously in the direction of the current (Berthault, 2002). The results, on the scale of strata, also conform, on the scale of facies to Golovkinsky, Inostranzev and Walther's law (Middleton, 1973, Romanovsky, 1988a), according to which the extension of facies of the same sequence is the same in both the lateral and vertical direction.

Results of engineering geological investigations applied for paleohydrodynamic reconstructions allow one to provide quantitative estimates for sedimentation processes. In this respect, the relation between hydraulic conditions and configuration of deposits (submarine ripples and dunes and horizontal beds) of contemporary deposits have been the object, especially recently, of well-known observations and experimentation. Rubin and McCulloch (1980) reported data on the San Francisco Bay environment, while Southard and Boguchwal (1990) presented results of flume experiments. Meanwhile, Hjølstrom and his successors (Hjølstrom, 1935; Lebedev,

1959; et al.) have determined a minimum velocity of erosion and sedimentation for each particle size at a given depth. Erosion parameters were researched during the laboratory experiments in VNIIG (Russian National Research Hydraulic Institute), Saint-Petersburg (Berthault et al., 2010). These relations can be applied particularly to detrital rocks, such as sandstone, the first stage of a transgressive marine sequence resulting from a process of erosion, transport, and sedimentation, driven by an initially erosive powerful current in shallow water. The *competence*, i.e., the paleovelocity of current below which particles of a given size deposit, and the corresponding *capacity* of sedimentary transport of the current can be determined. These two criteria determine the time for sequence to deposit.

The area under investigation corresponds to the zone of development of the Kazan Stage of the Middle Permian (Roadian Stage of Guadalupian Series in ISC version) sedimentary sequence of Kama region which was described in the middle of 19th century by Russian geologist Nikolai Golovkinsky. Based on the results of this research, Golovkinsky discovered the law of correlation of facies. He made observations and quality description of the rocks that suffice for quantitative estimates of sedimentary processes. We studied the Middle Permian sedimentary sequence of the Kama region both in a vertical and in a lateral direction to obtain quantitative parameters for the reconstruction of paleohydraulic conditions involved in strata formation.

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The results obtained made possible the reconstruction of paleohydraulic conditions and a determination of the duration of sedimentation in the Kazan Stage of the Kama region by using Einstein's procedure (Einstein, 1950).

Geological structure of sequence under investigation

In the beginning of the Middle Permian Epoch, the territory between the East European platform and the Urals Fold System had moderate negative tectonic movements accompanied by compensatory filling of the sedimentary basin with sediments. The sedimentary basin was divided into two parts by a sub-meridian orientated series of ridges of Tatarian Arch. The Western Basin was characterized by shallow marine – lagoon carbonate–sulfate–clay sedimentation. The Eastern (Sub-Ural) Basin was characterized by terrigenous sedimentation of sand–clay red beds formed in the aerated desalinated Sub-Ural Basin (Geology of Tatarstan ..., 2003). The Kazan Stage is divided into Lower and Upper Sub-stages $P_2\text{ kz}_1$ и $P_2\text{ kz}_2$ (Fig. 1).

Consecutive changing of the facies from mostly terrigenous in the east to carbonate-clay, carbonate and carbonate-sulfate in the west is complicated by shallow sea lenses of sand and gravel, which indicates active geodynamic structures of the Tatarian Arch that divides the paleobasin into eastern and western parts. The barrier zone was characterized by numerous paleoflows that formed cross-bedded sandstones.

Our research focuses on the Western Basin from the Arch (Elabuga – Krasny Bor) to the sequence of the right bank of the Volga River near Kazan (Pechischi Outcrop). Two different zones (western and eastern) are recognized in the Basin: the western zone is characterized by biochemical sedimentation and the eastern zone by the development of mainly terrigenous sediments in a shallow sea (Berthault et al., 2008).

Examination of the grain size of the sediments and cross-bed parameters allows reconstruction of paleohydrodynamic conditions. Research and mapping of the cross-beds and other sedimentation textures makes it possible to determine the order and the parameters of the paleoflows in the zone of the Tatarian Arch. In the northern part of Tatarian Arch, the paleoflows of southwest direction prevailed. In the southern part, both southeast and southwest orientated paleoflows are revealed, both of which contributed to the moderate development of Tatarian Arch structures.

Detailed investigation of textures indicates that the intensity of hydraulic processes decreased from the eastern to the western part of the sequence. Whereas in the eastern part of the region high dynamic features such as cross-bed series up to 1.5 m thick (Fig. 2), and basal gravels above local erosion surfaces (Fig. 3) can be observed, in the central and especially in the western part, silts with clay interlayers (Fig. 4), marls and limestones with gypsum interlayers (Fig. 5) are mostly observed. Taking into account that at the same time we observe decreasing of the sand particles dimension while the sequence increases in thickness, it is reasonable to conclude that the sedimentary basin increases in depth from east to west.

Boulders up to 5 cm in diameter and cross-bed series of sandstones up to 1 m thick in the intermediate levels of the sequence testify that the speed of the bottom current in the sedimentary basin reached 1.4-1.8 m/s according to diagram of Hjultstrom (1935) and Rubin and McCulloch (1980). Activity of hydrodynamic parameters decreased both laterally (spatially) from east to west as the distance from the shoreline confined to Tatarian Arch increased, and vertically (temporally) as the transgression developed. It changed the order of the facies both laterally and vertically.

In the eastern terrigenous part of the paleobasin,

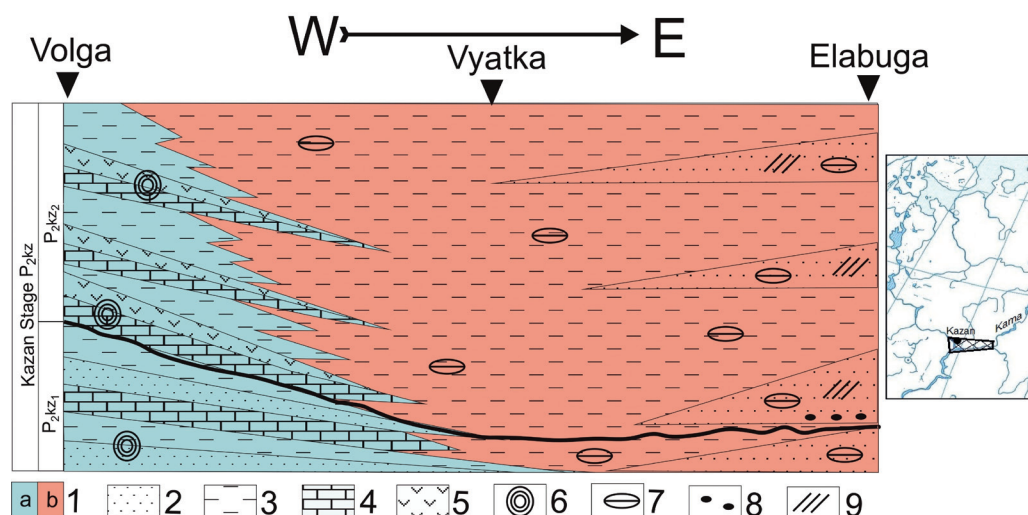


Fig. 1. The scheme of a joining of lithofacies of the Kazan Stage of the lower current of the Kama River (Geological heritage of Tatarstan Republic, 2007, with additions). 1-5 – sediments: 1a – sea and lagoon, 1b – continental red color; 2 – sandy; 3 – marl-clay with lenses of sandstone, 4 – sea carbonate, 5 – lagoon carbonate and gypsum; 6-7 – fauna: 6 – sea, 7 – not sea; 8 – gravel; 9 – cross-bed series in sandstones

the average size of the sand clasts varies from 0.10 to 0.14 mm that corresponds to fine-grained sand (Tabl.1). A relatively large standard deviation (0.56-0.90 mm) is evidence of bad sorting of the sediments: the deposit has a two- or three-modal grain-size distribution curve with peaks in the areas of less than 0.01 mm (silt-clay area), 0.05-0.10 mm and 0.15-0.30 mm for coarse varieties. This provides evidence of several (two, at least) modes of sediment transport. In the upper part of the sequence, average dimension decreases and sorting increases. Basal sands and gravels are more poorly sorted than overlying finer deposits.

Granulometric characteristics of the deposits were researched for terrigenous layers of the west clay-carbonate part of the basin in the outcrops of Soroch'i Gory and Kamskie Polyany. As content of the terrigenous units in the sequence does not exceed 10-20 %, averaged granulometric characteristics of the deposits give too high value of the reconstructed paleohydrodynamic parameters.



Fig. 2. Cross-bed series in sandstones of Tatarian Arch zone near Krasny Bor (far eastern part)



Fig. 3. Basal gravels above erosion surface in the sandstone zone of Tatarian Arch near Elabuga (eastern part)



Fig. 4. Silt-clay sequence of the central part of Western basin (Kamskie Polyany)



Fig. 5. Carbonate deposits with gypsum interlayers in the western part of the Western basin (Soroch'i Gory)

	West zone (Soroch'i Gory – Kamskie Polyan)		East zone (Elabuga – Krasny Bor)	
	Lower Kazan Stage (P ₂ kz ₁)	Upper Kazan Stage (P ₂ kz ₂)	Lower Kazan Stage (P ₂ kz ₁)	Upper Kazan Stage (P ₂ kz ₂)
Ma (d _s), mm	0.11	0.08	0.14	0.10
σ, mm	0.68	0.49	0.90	0.56
As	1.46	1.46	0.28	0.73
Ex	1.25	2.62	0.51	0.38
Cv	6.2	6.1	6.4	5.6
Hr	0.68	0.62	0.61	0.67
Number of samples	7	6	10	7

Table 1. Granulometric characteristics of terrigenous deposits of the Western Basin of the Kazan Stage of the Permian System. Note: (Ma) arithmetic mean for grain size, (σ) standard deviation, (As) asymmetry of grain-size distribution curve, (Ex) excess of grain-size distribution curve, (Cv) coefficient of variation, (Hr) relative entropy of distribution

basic ones, which pretend to be complex and universal, and their simplified versions are less refined and more oriented to the solution of particular problems with a simpler mathematical apparatus. ⁶

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 constraints determined by the solution of a reverse problem: a 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 basic methods in geoenvironmental lithodynamic calculations. The method is applicable for the 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:

$$q_t = \sum i_i q_{i_i}, \quad (3)$$

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

Gathering necessary information about bottom sediments of a paleobasin is the first step in the method application. Deposits of Lower Kazan Stage (P₂ kz₁) and Upper Kazan Stage (P₂ kz₂) were interpreted separately. The results of the grain size analysis for 19 size classes within the range from >2 mm to <0.01 mm (30 samples) were averaged and grouped for further analysis 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 w in the 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 (Re_p) $C_D = 24/Re_p$ (Julien, 1995).

A calculation was made for each grain-size class, and the obtained results are summed up. A detailed description of the Einstein method for practical calculations is given in the book of P. Julien (1995). Results of an analogous calculation made for the Cambrian-Ordovician sandstones of the north-eastern area of the Russian Plate (Leningrad district) allowed

rain size, mm		Grain size composition in researched units, %				Hydraulic size (fall velocity in water) w , mm/s
Fractions	Average (d_s)	P_2kz_1w	P_2kz_1e	P_2kz_2w	P_2kz_2e	
>0.4		0.03	0	0.01	0.15	
0.4-0.1	0.25	47.29	31.21	49.02	37.96	31
0.1-0.01	0.05	37.60	34.07	31.56	33.36	2.7
0.01-0.001	0.01	15.07	34.71	19.4	28.33	0.17
<0.001		0.01	0.01	0.02	0.2	
Percentile	d_{16}	0.010	0.004	0.008	0.005	
	d_{35}	0.090	0.010	0.070	0.010	
	d_{50}	0.100	0.050	0.100	0.080	
	d_{65}	0.110	0.090	0.110	0.120	
	d_{84}	0.140	0.160	0.150	0.180	
I_b^*		0.00017	0.00010	0.00020	0.00010	

Table 2. Bed sediment information for Einstein's sediment transport method (Julien, 1995). Notes: P_2kz_1w , P_2kz_1e , P_2kz_2w , P_2kz_2e – “ P_2 ” Middle Permian (Guadalupian) Series, “ kz_1 ” and “ kz_2 ” – Kazan (Roadian) Stage (Lower and Upper subdivisions respectively), “ e ” and “ w ” east and west parts of the paleobasin. Percentiles d_{16} , d_{35} etc. denote the particle size (mm), relative to which 16, 35, etc. % of particles have smaller sizes. I_b^* – inclination of the bottom of sedimentary basin

us to determine the specific capacity of the paleodrift for the Low Paleozoic sedimentary basin of northeastern Russian Plate (Berthault et al., 2011).

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. Analyses of the orientation of cross-beds allows quantitative estimation asymmetry of the drift that is represented by the coefficient of effectiveness of the drift C_f . An alternate oriented drift value of C_f tends to zero as symmetry of the variations rise, for unidirectional drift $C_f = 1$ (Berthault, 2011). The calculated C_f for the Kazan sequence is represented in Table 3. We used it to estimate the summary effectiveness of the drift.

The detailed analysis of erosional surfaces shows that erosional boundaries within a studied sequence can be divided into two types. Erosional interlayer surfaces inside formations are discontinuous and non-persistent 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. The erosion surface between Lower and Upper Kazan subdivisions has a sustained character and is traced along most of the paleobasin, thus indicating the regional character of the interruption of sedimentation.

Taking into account peculiarities of erosion contacts between formations, one can infer that sheet erosion

was more common than deep local erosion. Under these conditions, the base level of the erosion of the sequences under study is not always reliably established. Therefore, to obtain a more precise value for 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), the coefficient of effectiveness of the drift (C_f), the length of the sequence in the direction of the drift (L) (about 100 km for west zone and 120 km for east zone in the segment accessible for study), and the maximal established thickness of the sequence (H_{max}), the sedimentation duration for the Kazan sequence of studied paleobasin (t_s) can be calculated by the formula:

$$t_s = (H_{max} L) / (q_t C_f). \quad (5)$$

The calculation results are presented in Table 3.

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. It is necessary to take into account that values obtained correspond to the duration of sedimentation for the present terrigenous part of the sequence. Sheet erosion and sedimentation of the biogenic-chemogenic part of the sequence were not estimated.

Relationship between sedimentological and stratigraphic data

Thus, we observe a situation in which the duration of sedimentation differs substantially from the duration

Researched sequence		q_t m ² /24 hours	C_f	L km	H_{max} m	TR	t_s , years
West zone	P ₂ kz ₁	3.9	0.5	100	24	0.4	2810
	P ₂ kz ₂	4.4	0.5	100	20	0.2	2989
Total duration of sedimentation for west zone							5863
East zone	P ₂ kz ₁	5.1	0.67	120	26	1.0	1539
	P ₂ kz ₂	2.6	0.67	120	22	0.9	6039
Total duration of sedimentation for east zone							6654

Table 3. Parameters of the formation of Kazan paleobasin based on the Einstein method (1950) and Julien model of "reservoir filling" (1995). Notes: q_t – specific capacity of drift (sediment discharge) per drift width unit (calculation based on the Einstein method); C_f – coefficient of effectiveness of the drift; L – reliably established length of the studied sequence within the study region; H_{max} – maximal thickness of the sequence; TR – terrigenous part of the sequence deposits; t_s – sedimentation time based on formula (3)

of the stratigraphic time interval (hereafter, stratigraphic duration) assigned to the sequence under study, which varies from 2.6 to 3.5 Ma according to different assessments.

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

$$V = kH/(T - T^*)p, \quad (6)$$

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:

$$T^* = T - kH/(Vp). \quad (7)$$

We calculate the sedimentation rate V as q_t/L . Substituting in formula (7) the values $T = 3$ Ma, $V = 0.01$ 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 48 m. Thence, the time corresponding to hiatuses for the Kazan sequence sedimentation makes up:

$$T^* = 3 \times 10^6 \text{ yr} - 1.2 \times 48 \text{ m} / 0.01 \text{ m/yr} = 2\,995\,080 \text{ yr}.$$

Thus, the calculated real time of formation (sedimentation duration) corresponds to about 0.16% of the stratigraphic age of this sequence. It should be noted that the sedimentation duration based on the Einstein method is a conservative estimate. If we proceed from sedimentation characteristics of sediments, the duration obtained for their formation appears to be extremely small on the geological time-scale. Based on an analysis of intertidal cycles, Kulyamin and Smirnov (1973) showed that the "pure" sedimentation time for Cambrian-Ordovician sandstones 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, 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 similar Cambrian-Ordovician sandstones 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.

The duration of deposition of the Upper Jurassic conglomerates of Crimea Peninsula also is much less than the corresponding stratigraphic time interval (Lalomov, 2007).

Such a situation is not unique. S.V. Meyen wrote: "Due to a wide development of concealed hiatuses... only a negligible (0.01-0.001%) share of total sedimentation time is commonly documented" (Meyen, 1989, p. 24). Since the relationship between the 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 takes place during flooding and at its recession (Chalov, 2008). The coastline deformation during a year is mainly produced by two or three most intense storms (Rukovodstvo po metodam issledovaniya i rascheta ... [Manual for the Study and Calculation of Dislocations ...], 1975).

Major hydrodynamic events in paleobasins related (presumably) to megatsunamis 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 largescale turbidity 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 assigned to this sedimentary 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 bulk 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. Romanovsky 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" (Romanovsky, 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 (Romanovsky, 1977, 1988; Litogeodinamika i minerageniya ... [Lithogeodynamics and Minerageny ...], 1998; Baikov and Sedletskii, 2001; and others), and this is related not a matter of strictly scientific concern. For many mineral resources, the optimal relationship between sedimentation rate and section increment rate is the governing factor for their formation. 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 (Lalomov et al., 2015), biochemogenic deposits, coals and hydrocarbons (Sitdikova, Izotov, 2002). 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 mineral resources of the sedimentation series.

Conclusions

The application of lithodynamic geoengineering calculations to assess the sedimentation duration of the terrigenous part of Kazan stage sequence showed

that these deposits were formed instantaneously from the geological standpoint, and that the sedimentation duration of the sequence does not exceed 0.16% of its stratigraphic age interval. This is especially important for a reconstruction of sedimentary conditions of the eastern part of the paleobasin which consists mainly of terrigenous sediments.

The conditions under which the sedimentation time essentially differs from the stratigraphic one characterize 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) an understated value (Berthault, 2012).

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

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