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Institute of Geology of Ore Deposits Russian Academy of Science
(IGEM RAS) and Research – Exploration Centre "Monitoring"
(Khanty–Mansiisk, West Siberia)

"PALEOCHANNELS OF URAL FOLDED BELT AND PIEDMONT AREA: RECONSTRUCTION OF PALEOHYDRAULIC CONDITIONS"

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Content

Introduction

Methods of determination of paleohydraulic conditions of sedimentary rock formation refer to observation and experiments on relationships between present hydraulic conditions and sedimentary deposits. Whereas data on these relationships are numerous for transport and sedimentation, there is a lack as regard erosion. For the purpose to fill this blank it is necessary to continue available experiments and observations in erosion.

Available in the hydraulic literature data of erosion are concerning mostly to incohesive soils. Preliminary parameters of maximum permissible velocities for solid rocks were obtained from hydraulic literature and expounded in the VNIIG report 2006 on technical research programme "Research of erosion of consolidated soils by high-energy water flow Part I: analytical review of available data". Experiments with cohesive rocks will be realized on the base of St.-Petersburg All-Russian Research Institute of Hydraulic Engineering. Using of the obtained experimental regularities allows determination of paleohydraulic conditions.

Research of erosion processes in the geological history of the Earth was concerning to studying of ancient paleochannels in the Middle and South Ural and piedmont area. In spite of this region is quite detail researched, only a small number of papers and monographs are concerning with paleochannels, because the most part of geological researches are concerning to final part of successive sedimentological triad erosion – transport – sedimentation. This third stage of sedimentation process has obvious material evidences as sedimentary layers. Paleochannels very seldom are subjects of research because they are associated with erosion areas that are represented as blank spot on the geological maps (Rindsunskaya et al., 1985). Paleochannels belong mostly to erosion and transport stages.

In the Ural region paleochannels are of wide temporal interval from modern and recent to Permian (cutting folded strata of Ural and sedimentary cover of Russian platform), but Late Mesozoic – Earlier Cenozoic and Quaternary paleochannels are most accessible for research. Depending on hydraulic activity they are filled with different sediments from conglomerates to sands. Grain size of filling sediments allows determining minimal parameters of the currents which formed the channels, because deposition of given particles began when parameters of the current decreased below meaning of critical shear stress (Julien, 1995). Thus, largest clasts of the sediments reflect paleohydraulic conditions most correctly. Erosion properties of enclosing rocks also could be using as informative factor for reconstruction of paleohydraulic conditions. Here it will be necessary to use results of experiments in erosion.

Important information for paleohydraulic reconstructions could be obtained from studying of geomorphology of the channels. The paleochannels have different shape depending of ratio of hardness of enclosing rocks for erosion and parameters of erosive currents (Kashmenskaya, 1975).

This research was carried out in co-operation with Institute of Geology of Ore Deposits of Russian Academy of Science (IGEM RAS), which study mineral resources associated with paleochannels (placers of gold, diamonds, heavy metals, infiltration uranium deposits and so on), Ural Geological Institute (Ekaterinburg) and Scientific – Exploration Center "Monitoring" (Khanty – Mansiisk, West Siberia).

2. Geological history and structure of Ural Folded Belt

The geology of the Ural starts in early as the Precambrian as sub-meridian orientation ocean basin between Siberian and West European cratons. In the Silurian a subduction zone developed at the west side of the Siberian craton. This means that the oceanic plate which formed in the rift zone slid underneath Siberian craton. The result is the formation of intrusions, in the case of the Urals mainly granitic intrusions and volcanism.

In the Early Carboniferous the plates collided. This is called the Hercynian orogeny. During this era more mountains are formed all over the world. In the Urals the layers of marine sediment and ultrabasic extrusive rocks are altered into metamorphic rocks. This metamorphose is accompanied by many granitic intrusions. At this stage, in the Late Carboniferous the Urals look very similar to what the Alps or the Himalaya look like today. From then on not much happened to the Ural main ridge, except for a lot of erosion. But the geological Urals are a little wider that the mountains we know today. The area's both east and west of the Urals where filled with sediments. West of the Ural, the so called Priuralye, the basins filled up with sediments from the eroding Urals, as well as with evaporite material (salt and limestone) from the ancient ocean. A good example are the salt mines of Perm region. These Piuralye basins have ages from Upper Carboniferous to Triassic, but no surprise they are predominantly Permian, named after the city of Perm. East of the Ural, the Zauralye are part of the Siberian continent. This part was only covered with sediments as late as the Early Tertiary.

Obviously, Paleozoic orogen had own fluvial paleosystem developed on pre-orogenic folded strata, but following geological processes results to almost complete destruction of the paleosystem on the mountain area. Only on the territory of surrounding platform on the west Ural piedmont we can see remnants of Permian valleys.

Later, in Late Paleozoic – Early Mesozoic time Hercynian Ural Mountain System was eroded down to formation of peneplain. In the Jurassic – Cretaceous interval weathered crusts were developed on the surface of the peneplain. Complex of metamorphic rock was transformed to kaolinite – montmorillonite clay with laterite, quartz and sustainable heavy minerals up to 20 – 50 m thick. This planation surface is observed on the flat tops of mountains and plateaus on the altitude of 300 – 800 m in dependence of intensity of tectonic uprise.

Activation of block tectonic movements and raising of the territory of Ural Folded belt in the beginning of Oligocene results to erosion of weathered crusts and underlying consolidated rocks. Oligocene fluvial paleosystems were researched on the territories of west and south Ural (2006) and east Ural piedmont (2007).

One more separate erosion – sedimentation cycle took place in the Quaternary period. Most researchers believe that it was concerning with the end of glacial epoch when grandiose ice sheet of the north of East European platform began to melt.

3. Geomorphology and sediments of studied fluvial paleo-systems of Ural region

Geomorphological structure of studied area assigns relations between hydraulic conditions of the flow and lithological characters of the sediments filling the channel. Whereas we can not study paleohydraulic conditions directly, research of geomorphology of paleovalleys and filling sediments could provide us necessary data. Three fluvial paleosystems of Ural region were researched in the framework of the project (fig.1).

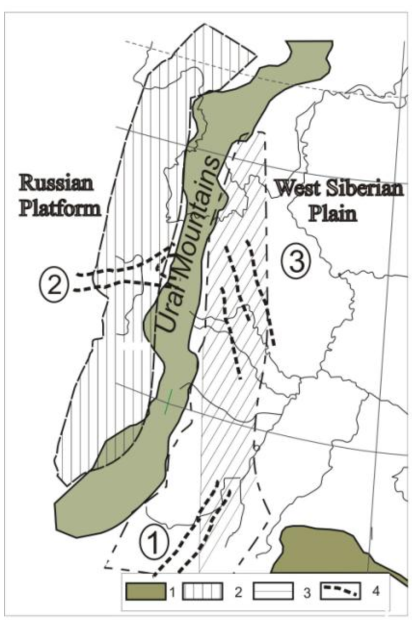

Fig.1. Studied fluvial paleosystems of Ural.

Legend: 1 – Ural Mountains. 2 – West Ural piedmont. 3 – East Ural piedmont. 4 – Paleosystems: (1) - Bebacle of Turgay plateau in the South Ural; (2) - Oligocene – Quartenary paleovalley of the western slope of Central – North Ural; (3) Sheet Quartenary fluvial paleosystem of eastern piedmont of Ural (Zauralie).

3.1 Debacle of Turgay plateau in the South Ural.

Turgay plateau is located in the south-east part of Ural Mountains. It divides West Siberian plain and Aral depression. True altitude of the plateau is about 300 m. Whereas surrounding plains have altitude about 100 m, relative height of the plateau is up to 200 m. Plateau consist of Paleozoic metamorphic rocks and Early Cenozoic (Early and Middle Paleogene $Pg_{1\text{-}2}$) sedimentary strata (sands, clays and marls) with basal gravels.

From north to south Turgay plateau is eroded by thin valley 200 km long called "Turgay's Debacle". In the thinnest central part the valley has width not more 50 km while on the north and south extremities the width is 100 and 125 km correspondingly. Highest point of the valley's bottom in the central part of the plateau is 125 m and decline to the south and north to 80 – 100 m (level of surrounding plains).

The valley has complex morphology given by consecution of erosion events (fig. 2). In the cross section two steps divided by erosion cliffs represent it.

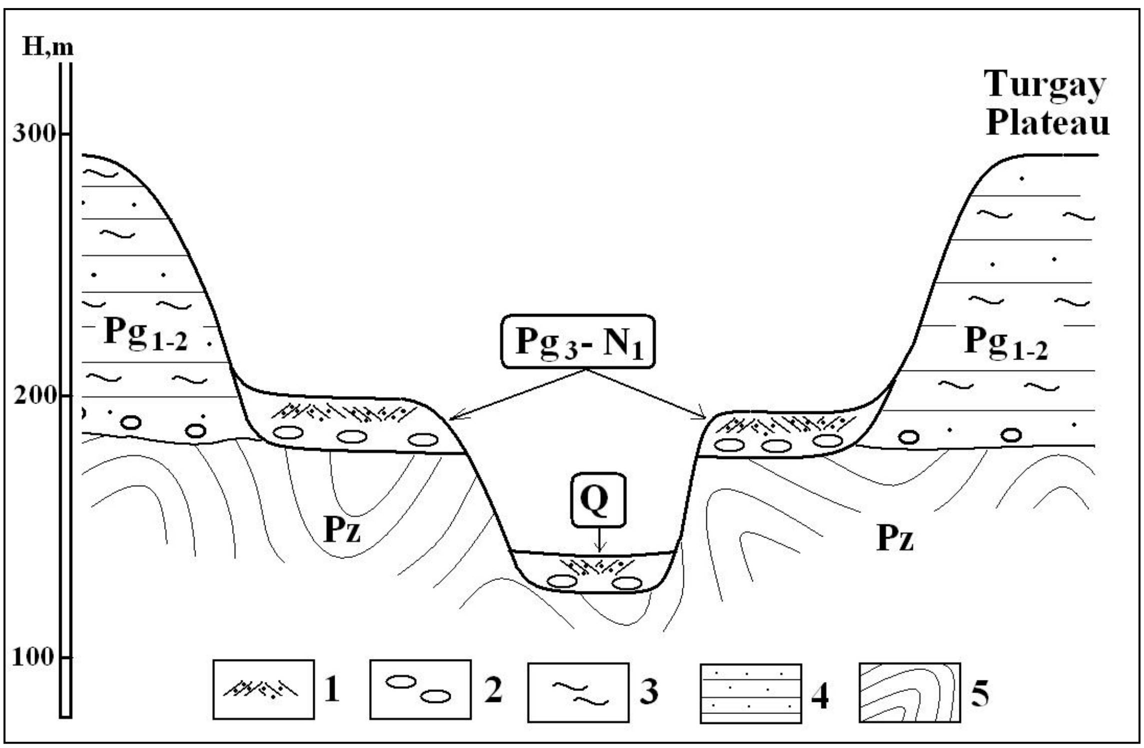

Fig. 2. Generalized cross section of Turgay valley. Legend: 1 – Cross bedding. 2 – Gravel with boulders. 3 – Clay. 4 – Sand. 5 – Metamorphic Paleozoic rocks.

First stage of erosion assigned Oligocene – Miocene (Pg_3 – N_1) results to formation of external wide and relatively shallow channel eroded in Early Cenozoic sedimentary cover (sands, clays and marls). Bottom and sediments of the Oligocene - Miocene valley is observed now in the terraces located 60 – 80 m below surface of Turgay plateau. The strata consist of heterogranular cross bedded sands with basal layers and lenses of pebbles. Pebbles (mostly quartz) are 1-3 cm in diameter; sometimes 10 cm boulders are observed. In the central part the cross beds are orientated to the south. In the south part orientation of the beds is south, south-east and south-west. Cross beds are up to 5 m thick (fig.3). The cross bed layers of coarse sediments are alternated with horizontal layers of finer sands. This is typical *stream structure* that indicated powerful unidirectional pulsating flow. Total thickness of Oligocene – Miocene deposits is up to 30 m.

Fig.3. Cross bedding of Miocene sands.

Thin inner channel assigned to Quaternary period occupies central part of Oligocene - Miocene valley. It is incutted into metamorphized Paleozoic deposits (sandstones, marbles and different igneous rocks) and Oligocene – Miocene sediments. Height of the erosion cliff is 40 – 60 m. Width of the inner valley varies from 10 -15 km in the central part to 80 – 100 km in the south. Bottom of the valley is relatively flat with series of shallow remnant lakes. Thalweg of the valley declines from the central part of the plateau (altitude 125 m) to periphery down to altitude 80 – 100 m.

Bottom sediment cover is represented by gravel and cross-bedded sand. Pebbles are of two types: bad rounded pebbles and boulders of local rocks and well-rounded exotic pebbles of unknown source. Largest boulders are up to 20 cm. Thickness of cross-bed series is 0.5 – 3 m. Total thickness of the complex do not exceeds 10 meters.

3.2 Oligocene – Quaternary paleovalley of the western slope of Central – North Ural

Study of processes of flow erosion took place on the Kijim River on the western slope and piedmont of Ural Mountains (Priuralie). Data of geomogphology and lithology of the valley of Kijim were obtained in result of field investigations, studying of reports on geological prospecting of gold placers of the valley and research of publishing geological literature.

Fig.4a. Gold placer mine on the tributary of Kijim River in the Low piedmont zone.

Fig. 4b. Piece of placer gold.

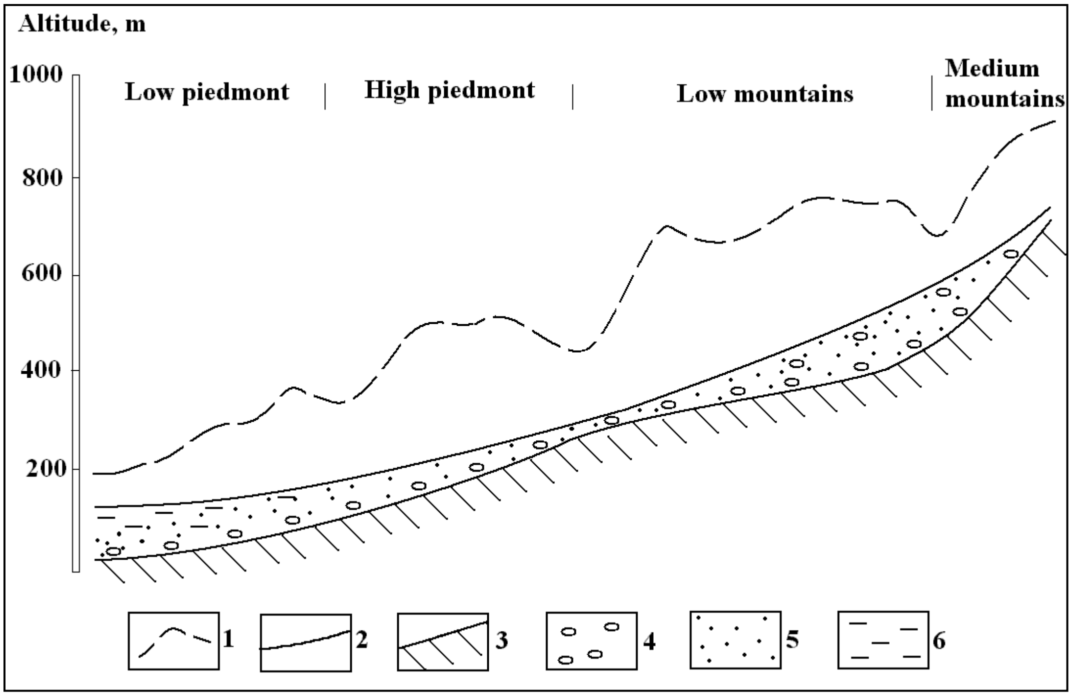

Fig. 5. Lengthwise cross section of the valley of Kijim River. Legend: 1. Relief of surrounding mountains. 2. Relief of the river bed. 3. Relief of bedrocks. 4. Coarse alluvium (mostly pebbles and boulders). 5. Medium – size alluvium (sand gravels). 6. Fine alluvium (mostly sand and silt with small pebbles).

Valley of Kijim River has latitudinal orientation. It crosses different orogenic zones of Ural from medium orogenic relief to lower piedmont (fig. 5). Bedrock of the valley consists mostly of medium metamorphic shales, sandstones, limestones with rare intrusions.

On the lengthwise cross section of the valley in dependence of geomorphological zonality we can mark out four types of the morphology. Each of the types has typical characters of the relief which is concerning with relation of erosion – sedimentation processes.

Zone A (medium mountains). In this zone the valley has typical erosive V-shaped cross-section (fig. 7a) with very thin cover of bad-sorted and bed-rounded alluvial sediments. Bedrocks are usually observed in the riverbed or pedestal terraces. Sediment transport capacity (P_t) exceeds on sediment supply (Q_s). Sedimentary cover has transitional dynamic (or residual – big blocks) character. Width of the valley is about 0.4 – 0.6 km, depth vary from 60 to 100 m. Length of the zone is 10 km.

Zone B (Low mountains). The zone is characterized by exceeds of sediment supply on sediment transport capacity that result to accumulation of the sediments in this zone on the present-day hydraulic and geomorphological conditions. Earlier eroded valley is filled by sediments of different grain-size from boulders and gravel in the basal layers to coarse sand and fine sediments in the middle and upper part of the alluvial sediment sequence respectively. Bedrock is not observed, but drilling data showed that thickness

Fig.6. Bedrock in the bottom of gold placer mine (zone C). Boulders up to 30 cm are observed.

of the sediments is 40 – 60 m. Width of the valley is about 0.8 – 1.0 km, depth (taking into account bedrock) vary from 80 to 120 m. Length of the zone is about 20 km.

Zone C (High piedmont). In the zone sediment transport capacity (P_t) exceeds sediment supply (Q_s), therefore erosion processes prevail on sedimentation. Earlier deposited sediments are partly eroded, so in the river channel we meet exposures of the bedrock and thin (up to 10 – 15 m) sedimentary cover composed of boulders, gravel and coarse sand (fig.6.). Earlier deposited alluvial sediments are observed on lateral terraces. Width of the valley do not exceeds 1.2 km; depth from local watershed to the thalweg bedrock is about 120 m. Length of the zone is 25 km.

Zone D (Low piedmont). Valley in this zone is characterized by well-developed profile with moderate lateral terraces. Here we see full alluvium sequence from boulder horizon (in the bottom) to gravel, sand and silt. Wide flood-land up to 800 m is typical in the zone. Total width of the valley is up to 1.5 km, depth from local watershed to the thalweg bedrock is about 150 m. Length of the zone is 20 km.

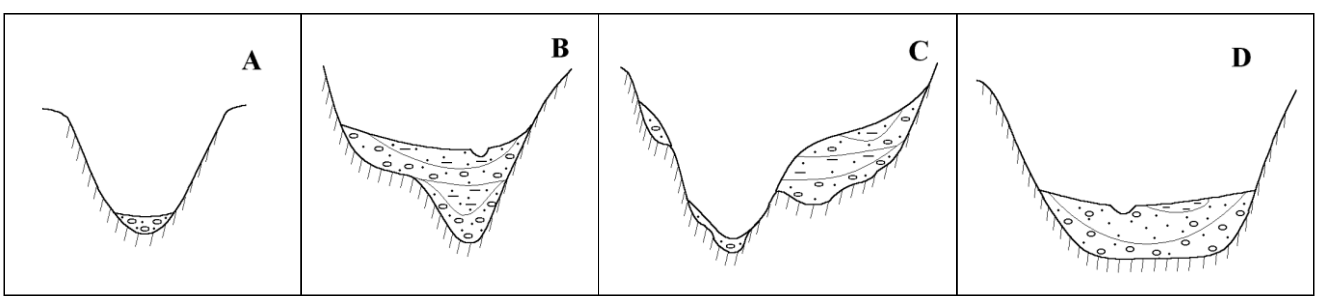

Fig. 7. Cross-sections of the valley of Kijim River in Medium mountain zone (A), Low mountain zone (B), High piedmont zone (C) Low piedmont zone (D). Legend the same as on the fig.5.

3.3 Areal Quartenary fluvial paleosystem of eastern piedmont of Ural (Zauralie)

Eastern piedmont of Ural consists of planar pediplain inclined to the east. Thickness of sedimentary cover assigned to Late Mesozoic and Cenozoic vary from tens meters (close to uplifted blocks of Ural mountains) to 100 – 200 m on the west border of depression West Siberian plain. Oligocene fluvial paleosystems are recognized under the sedimentary cover by geophysical methods and drilling holes only, therefore morphology of the erosion surface and reconstruction of paleohydraulic conditions of the flows is difficult to research.

Fig.8. Natural outcrop of Quaternary deposits in West Siberia piedmont of Ural.

On the other hand, areal erosion surface between Oligocene and Quarter is well observed in the natural outcrops and artificial pits (figs. 8, 9). It allows us to trace the system of channels developed on the territory of the contact of east piedmont of Ural Mountains and West Siberia plain.

The surface has undulating character; difference between lowest and highest points of the surface do not exceeds 40 – 50 m. We did not reveal certain channels, but weakly expressed elongated depressions orientated from north – northwest to south – southeast are observed.

Underlying Oligocene deposits consist of sand, silt and dense plastic clay. Above the erosion surface Quaternary sediments are represented by coarse sand with pebbles and boulders (up to 10 – 15 cm in diameter) of quartz (fig. 10),

Fig.9. Artificial prospecting pit in West Siberia piedmont of Ural.

Fig.10. Well-rounded quartz gravel above the erosion surface.

Fig.11. Boulder of metamorphic rock transported (at least) over 200 km from Ural.

and other exotic rocks of metamorphic and magmatic origin (fig. 11). Apparently, they has source in the mountain part of North and Middle Ural. Sands above erosion surface are cross stratified (fig. 12). Thickness of cross bed series is up to 2 m with angle of inclination 15 – 30^0.

Fig.12. Cross-stratification of stream character in Quarter sand.

4. Geological history of the valleys

4.1. Outburst (debacle) of Turgay plateau.

In the South Ural region (Turgay plateau) we can reveal three erosion - sedimentation cycles:

- Pre-Cenozoic (apparently, Late Mesozoic) sheet erosion of metamorphic Paleozoic rocks followed by marine transgression and deposition of sand – clay Lower – Middle Paleogene series. (Razumova, 1961). This cycle is out of the framework of the research.
- Oligocene erosion cycle resulted to formation of external valley incutted mainly into weakly consolidated and friable Paleogene deposits. Intensive flow was orientated from north to the south; in the widen south part we observe radiation of the flows as debris cone.

  Total vertical interval of erosion reaches 80 m. Width of the valley vary from 50 (central part) to 100 – 125 km on the distal part. Taking into account length of the valley about 200 km we can estimate volume of eroded material as 1120 km^3. During recession phase of the cycle the flood deposit complex was formed. Researches of the valley believe that plane erosion prevail on vertical erosion (Ber, 1971). Apparently, after the deposition event the plateau had tectonic uprise amplitude about 100 m.
- Quaternary erosion cycle formed relatively shallow valley in the central part of the depression incutted into consolidated metamorphic rocks. Direction of the flow was from north to the south. Slope of the bottom of the valley is about $3.5 \cdot 10^{-4}$. Total vertical interval of erosion reaches 60 m. Average width of the valley is 50 km. Taking into account length of the valley about 200 km we can estimate volume of eroded material as 600 km^3.

4.2. Erosion of Kijim valley.

The research of geomorphology and sediments of Kijim valley reveals two phases of erosion activity. The first erosion cycle was concerning to Oligocene tectonic activation. It resulted to forming of initial valley that was filled with sediments during a pause followed the first tectonic activation (apparently, Miocene). Buried Oligocene valley we can see on the zone B and D and on uplifted terrace (zone C).

Second erosion cycle assigned to Quarter result to formation of present day river channel in mountain block (zone A) and high piedmont (zone C). The flow eroded both alluvial sediments of previous cycle and bedrock. In the zone A Miocene sediments are eroded completely.

This investigation allows calculating volume of eroded material. We can approximate cross-section profile of the valley in zones A – C by triangle and by trapezium in zone D. Rough volumes of zones A –D are 0.2, 0.9, 1.5 and 3.4 km^3. Total volume is about 6 cubic kilometres.

4.3. Quaternary areal erosion of West Siberia.

Dimension of the boulders in the bedrock of Quaternary sequence reaches 15 cm, so according to the data of Lebedev (1959), velocity of the flow was not less than 4.5 m/s.

Orientation of the dips of the cross beds is mostly meridian that is evidence of the flows direction parallel to Ural from north to the south.

Because of amplitude of the relief of erosion surface is about 50 m, therefore we can suppose that the thickness of eroded Oligocene strata exceeds 50 m. We can conditionally take into account the thickness as 100 m. Whereas it is difficult to estimate real width and extension of eroded Oligocene sediments, we shall make the calculation of duration of erosion time interval not through the volume of eroded material, but with specific erosion discharge.

5. Reconstruction of hydraulic parameters of paleoflows and calculation of the time of erosion

For determination of hydraulic parameters of paleoflows and rough calculation of the time necessary for erosion of the valleys we need to estimate the next hydraulic parameters:

C_s – coefficient of resistance of the sediment particles to the uniform flow with velocity w;

C_v – volume concentration of solid phase (sedimentary material) in flow;

d – average diameter of the particles of eroded soil or blocks of consolidated rock,m;

d_{max} – maximum diameter of the particles of eroded soil or blocks of consolidated rock, m;

f – average frequency of pulsating of the flow, s^{-1};

fr – *f*riction factor;

g – acceleration of gravity, m/s^2;

h – average depth of the flow;

H – vertical interval of erosion;

S – inclination of the bottom of paleoflow;

T_e – time necessary for erosion of the valleys;

V – average velocity of the flow, m/s;

$V_{n\,max}$ - maximum non-erosive permissible velocity, m/s;

w – hydraulic size (fall velocity), m/s;

ρ_w – density of water, kg/m^3;

ρ_s – density of sediment particles, kg/m^3;

τ_c – critical shear stress (Pa, N/m^2);

τ_* – dimensionless shear stress;

γ_s – specific gravity of sediment particles, N/m^3;

γ_f – specific gravity of the fluid, N/m^3;

These parameters are necessary for determination of P_p - erosive ability of the flow (volume of the soil that could be eroded by given flow from unit of the flow bottom), m/s.

Using equation of Donenberg (Veksler, Donenberg, 2006) for P_p for incohesive soils (1) we can estimate sought parameter for upper eroded horizon of Turgay debacle, erosion of Kijim valley in zones C and D, and areal erosion in Zauralie (West Siberian piedmont).

$$P_p = A\left(\frac{V^2}{g\,d}\right)^m (V - V_n) \qquad (1)$$

where:

$$A = C_s \cdot 10^{-9} \qquad (2)$$

$$m = 1.5 + \frac{5}{C_s + 1} \qquad (3)$$

$$C_s = \frac{4}{3}\,\frac{\rho_s - \rho_w}{\rho_w}\,\frac{gd}{w^2} \qquad (4)$$

The equation (1) is applicable for the case of $1 < V/V_n < 3$. Beyond the condition correctness of using of the equation is uncertain or less precise.

Equation (5) of Mirtskhoulava (1988) is applicable for erosion of consolidated soils.

$$P_p = 6.4 \cdot 10^{-6} f\, d\, (V^2 / V_n^2 - 1) \qquad (5)$$

where f is average frequency of pulsating of the flow. Roughly it could be calculated as $f = 0{,}73V/h$; d – average diameter of separate blocks of the soil.

Fall velocity for particles more than 2.5 mm in turbulent regime could be calculated as:

$$w = \sqrt{\frac{\rho_s - \rho_w}{0.9\rho_w} gd} \qquad (6)$$

Features of the deposits filled the channels suggest that hydrodynamic parameters of the flows can most precisely be reconstructed based on the model of transportation in media with properties of the Newtonian liquid, where:

$$\boldsymbol{\tau = \mu\,(dVx/dZ\,)} \qquad (7)$$

Concentration of solid phase in the flow with properties of the Newtonian liquid is equal to 5% ($C_v = 0.05$).

We estimated the critical shear stress needed for the entrapment of particles (τ_c) for a flow with properties of the Newtonian liquid based on the Shields equation. This parameter is most conservative of any other estimations (Lalomov, 2007). The Shields equation used to describe the parameters of turbulent flow has the following form:

$$\tau_c = \tau_* (\gamma_s - \gamma_f)\, d_{max} \qquad (8)$$

If the floor is rough and large particles rise above the flow surface, the dimensionless shear stress (τ_*) varies within a range of 0.02 – 0.1 (Church, 1978) depending on the floor configuration. According to the more precise estimate given by Julien (1995), τ_* = 0.050 for sediment of small-pebble size (d 32 – 64 mm) and 0.047 for coarse gravel (d 16 – 32 mm). Specific gravity of solid phase γ_s is 26 000 N/m^3. Specific gravity of mixture (fluid) at $C_v = 0.05$ is 10 619 N/m^3.

The flow depth (h) was computed with the help of the DuBoys equation, which can be presented in the following form (Julien, 1995):

$$h = \tau / (\gamma_f S) \qquad (9)$$

If the density of rock-forming particles is 2.65 x 10^3 kg/m^3, the specific gravity of fluid containing 5 % of solid phase (i.e., $C_v = 0.05$) will be = 1.07 x 10^4 N/m^3.

The possible slope of the paleoflow was estimated using geomorphological data on the bottom of paleochannels.

Different methods are used for the estimation of flow velocity. The Chezy, Manning, and other equations are applied to flows in open channels. They provide minimum value of the velocity.

The sphere of application of these equations depends on the index of specific roughness of flow floor, which is expressed as the ratio of flow depth (h) and the average size of sediment (d) on the floor. The Chezy equation provides the most reliable results for deep flows with relatively fine material, when h/d tends to infinity. The Manning equation is applicable to flows with h/d > 100, whereas the logarithmic form of the equation is more preferable for shallow flows with the coarse-clastic material (h/d < 100) (Julien, 1995).

5.1 Turgay's Debacle

Oligocene valley. Study of the cross-bedded sand using observation of Rubin and McCulloch (1980) allows conclusion that on the recession stage of the flow the velocity was about 1.0 – 1.6 m/s. Taking into account size of the boulders (10 cm) and based on the data of Lischtvan – Lebedev (Berthault, 2002) we can conclude that during erosive stage the velocity of the flow (*V*) exceeds 3 – 4 m/s.

Quarter valley. According to Rossinsky and Terent'ev (1973), maximum permissible (non-erosion) velocity for consolidated soils vary from 0.5 to more than 15 m/s (table 1). Whereas low structural floor of Turgay plateau consist mostly of medium consolidated sandstones, limestones and shales, we can suppose that velocity of the flow eroded the valley was more than 2 – 9 m/s.

The calculation results that for Oligocene erosion channel with d_{max}= 0.1m τ_c = 80 N/m^2. For Quarter channel with d_{max}= 0.2m τ_c = 166 N/m^2.

Using DuBoys equation the flow depth (*h*) could be estimated as 18.8 m for Oligocene flow and 39.1 m for Quarter flow. Whereas h/d is about 10000 - 20000 (close to infinity) it is suitable to use here Chezy equation for *V*.

The Chezy equation has the following form:

$$V = (8ghS \,/\, fr)^{0.5} \qquad (10)$$

Friction factor (*fr*) can be computed from the Keulegan equation (Church, 1978):

$$fr = (2.03 \log (12.2h/d))^{-2} \qquad (11)$$

Taking relative height of the highest and lowest points of the channel's bottom (40 m) and length of the valley 100 km, the slope of the paleoflow is 0.0004. Friction factor is 0.021 for both valleys. Thus, from Chezy equation the minimum flow velocity (V_{min}) were 5.2 and 7.6 m/s for Oligocene and Quarter deposits respectively (table 1).

Table 1.

Minimum flow velocity (V_{min}) for Turgay's Debacle from Chezy equation

Valley	d_{max}	τ_c	*d,*	*S*	γ_f	*h,*	*h/d*	*fr*	V_{min},

	m		*m*		N/m^3	*m*			*m/s*
Oligocene	0.1	80	0.001	0.0004	10619	18.8	18834	0.021	5.2
Quarter	0.2	166	0.004	0.0004	10619	39.1	9770	0.021	7.6

For Oligocene deposits that consist mostly of heterortanular sands maximum permissible velocity $V_{n\ max}$ from Hjulstrom diagram is about 0.5 – 0.7 m/s.

Maximum permissible velocity for consolidated soils is of a different estimation. Julien (1995, tabl.7.3) estimates maximum permissible velocity for hard rocks as 3 – 4.5 m. Rossinsky and Terent'ev (1973) suppose that it vary from 0.5 to more than 15 m/s in dependence of the type of the soil and the flow depth (table 2).

Table 2.

Maximum permissible velocity $V_{n\ max}$ for consolidated soils after (Rossinsky, Terent'ev, 1973).

Type of the soil	Average flow velocity $V_{n\ max}$, m/s with the flow depth h, m					
	1 m	3 m	5 m	10 m	15 m	20 m
Siltstone (weak)	0.50	0.60	0.70	0.80	0.85	0.90
Siltstone (medium consolidated)	1.00	1.25	1.40	1.60	1.70	1.80
Siltstone (strong)	1.50	1.90	2.05	2.40	2.60	2.70
Marl	2.50	3.00	3.45	3.95	4.30	4.55
Limestone (porous, laminated)	3.50	4.40	4.85	5.50	6.00	6.35
Limestone (solid, siliceous)	5.00	6.25	6.90	7.90	8.60	9.10
Sandstone (calcareous)	3.50	4.40	4.85	5.50	6.00	6.35
Sandstone (dolomitic)	5.00	6.25	6.90	7.90	8.60	9.10
Granite and other igneous rocks	>15	>15	>15	>15	>15	>15

For receiving of conservative estimation we take 0.5 m/s for Oligocene flow and 5 m/s for Quarter. Using equations (1) – (4), (6) for Oligocene flow and (5) for Quarter, taking into account vertical interval of erosion (H), we can estimate the time (T_e) necessary for erosion of the valleys (table 3). We believe real flow velocity as 1.5 of minimal one.

Table 3.

Time of erosion for Turgay's Debacle

Valley	*d, m*	*w, m/s*	C_s	*A*	*m*	*V, m/s*	V_n *m/s*	*f*	P_p *m/s*	*H, m*	T_e
Oligocene	0.001	0.13	1.2	$1.2 \cdot 10^{-9}$	3.8	1.5*	0.5		$2.7 \cdot 10^{6}$	80	< 1 day
Quarter	0.004**					11.4	5	0.24	$3.4 \cdot 10^{-8}$	60	83 years

Notes: ρ_s= 2650 kg/m^3, ρ_w = 1000 kg/m^3, g = 9.81 m/s^2.
* The value of 1.5 m/s is taken instead of calculated velocity of 5.2 m/s because of limits of using of the equation (1) $1 < V / V_n < 3$.
**In the case of absence of special research of dimension of fracture fragments of the consolidated soil, Mirtskhoulava (1988) proposed d = 0.004 m.

We should take into account that the solution for Oligocene valley is very rough: taken equation (1) is applicable for the case of $1 < V / V_n < 3$. Beyond the condition correctness of using of the equation is uncertain or less precise. In our case we have V/V_n = 16, therefore for receiving more precise and also more conservative estimation of the duration of erosion we conditionally take the value of $V = 3V_n$. Even in this case of very conservative estimation the time of erosion of Oligocene valley is less than one day.

The value of T_e for Quarter valley is about 83 years. One more conclusion of the situation is that in the case of the complex structure of eroded geological strata (consolidated and incohesive) time of erosion for solid rocks is much more than for friable sediments, therefore it is possible do not take into account time of erosion of sedimentary cover.

5.2 Kijim valley

Whereas the valley of Kijim has not uniform geomorphology and lithodynamic condition, we should make the estimation for every different part of the valley. Minimum flow velocities for different zones were calculated by different methods. For zone A (erosive source of the valley) ratio of *h/d* is certainly less than 100, so logarithmic form of the equation is suitable here.

The logarithmic form of equation defining the flow velocity is as follows:

$$\mathbf{V = 5.75\ (ghS)^{0.5}\ log\ (12.2h / k_s)} \quad (12)$$

where $k_s = 3d_{90}$ for channel beds consisting of rudaceous gravel-pebble rocks (Bray, 1982).

For zones B – D the ratio is more than 100 but far from infinity, so Manning equation is the best for the estimation of the velocity:

$$\boldsymbol{V = S^{1/2}\ h^{2/3}\ n^{-1}} \quad (10)$$

The value of roughness coefficient (n) was calculated with the help of the Limerinos equation (Limerinos, 1969):

$$n = 0.113\, h^{1/6} / (1.16 + 2 \log (h / d_{84})) \qquad (11)$$

Calculation of minimum flows velocities is shown in the table 4.

Table 4.

Minimum flow velocity (V_{min}) for Kijim valley from Manning and logarithmic equations.

Zone	d_{max} m	τ_c	d_{84} m	d m	S	h, m	h/d	*Eq.*	n	V_{min}, m/s
A	0.50	415	0.22	0.091	0.0200	2.0	21	Logarithmic	-	5.5
B	0.15	125	0.08	0.012	0.0025	4.7	392	Manning	0.031	4.5
C	0.30	249	0.15	0.032	0.0060	3.9	122	Manning	0.036	5.4
D	0.10	80	0.04	0.006	0.0025	3.0	502	Manning	0.028	3.8

*γ_f = 10619 N/m^3.

In the zones B and D (and partly C) the erosion processes affect on both consolidated and friable rocks. Bedrock erosion profile was formed during past erosion episode. Present-day erosion ability in the zones B and D is not enough for erosion of available sediment cover. Therefore we should calculate time of erosion on the base of hydraulic parameters of the paleoflows determined with lithological features of the sediments. Velocities of paleoflows (V) were taken as 1.5 V_{min}, ; V_n is approximated from table 2.

Table 5.

Time of erosion for Kijim valley calculated with equation (6) from Mirtskhoulava (1988)

Zone	d, m	V, m/s	V_n m/s	f	P_p m/s	H, m	T_e years
A	0.004	8.3	5.0	3.1	$3.2 \cdot 10^{-6}$	80	0.8
B	0.004	6.8	5.0	1.0	$6.7 \cdot 10^{-8}$	100	47.3
C	0.004	8.1	5.0	1.5	$5.1 \cdot 10^{-7}$	120	7.5
D	0.004	5.7	5.0	1.4	$1.5 \cdot 10^{-8}$	150	320.1

Notes: ρ_s= 2650 kg/m^3, ρ_w = 1000 kg/m^3, g = 9.81 m/s^2.

Analysis of obtained values of the time of erosion shows that erosion ability for zones A and C (erosion relief) is one – two orders of magnitude more than for zones B and D with accumulative relief. Present-day intensively eroded material from A and B accumulates in B and D because of decreasing of the erosion ability of the flow. Nevertheless, bedrock of B and D was eroded in the past, so accumulative condition of the zones is temporary and real erosion time was much less. Apparently, it was comparable with time of erosion of A and C.

5.3. Quaternary areal erosion of West Siberia

Quaternary erosion surface of West Siberia has areal character. It has not obvious river valleys with typical alluvial deposits, but system of elongated depressions and ridges. Size of boulders in the basal horizon of Quarter strata directly above the erosion surface about 0.1 m in diameter and average dimension of allows calculate *h/d* ratio. It is 5022 that is much more than 100, so we should using Chezy equation for calculation of velocity of the flow (table 6).

Table 6.

Minimum flow velocity (V_{min}) for Quaternary areal erosion of West Siberia from Chezy equation

Valley	d_{max} m	τ_c	*d*, m	*S*	γ_f N/m^3	*h*, m	*h/d*	*fr*	V_{min}, m/s
Quaternary areal erosion	0.1	80	0.003	0.0005*	10619**	15.1	5022	0.023	5.1

* value of the slope is calculated as assumed vertical interval of erosion (100 m) divided on the distance from Ural Mountains (200 km).
** specific gravity of the fluid for concentration of solid phase (sedimentary material) in flow 5%.

Donenberg equations (1) – (4) (Veksler, Donenberg, 2006) are suitable for calculation of erosive ability of the flow in incohesive soils. Inasmuch as obtained value of V is about 10 times more than maximum non-erosive permissible velocity from Hjulstrom diagram (limit of the equation is $1 < V / V_n < 3$), we conditionally take for calculation $V = 3V_n$. It will increase reliability of final result displayed in table 7.

Table 7.

Time of Quaternary areal erosion of West Siberia

Valley	d, m	w, m/s	C_s	A	m	V, m/s	V_n m/s	P_p m/s	H, m	T_e days
Quaternary areal erosion	0.003	0.23	1.2	$1.2 \cdot 10^{-9}$	3.8	1.5*	0.5	0.015	100**	< 1

Notes: ρ_s= 2650 kg/m^3, ρ_w = 1000 kg/m^3, g = 9.81 m/s^2.
* The value of 1.5 m/s is taken instead of calculated velocity of 5.6 m/s because of limits of using of the equation (1) $1 < V / V_n < 3$.
** Vertical interval of erosion is conditionally taken as twice difference of highest and lowest elevation of erosion relief.

This conservative calculation shows that incohesive Oligocene sands could be eroded by Quarter areal flow very quickly. Taking into account rough character of initial data of the calculation we could estimate the time interval as less than 1 day. Even if the value is overestimated, we can affirm that the erosion process has catastrophic character.

6. Interpretation of Cenozoic geological history of Ural region from the point of view of erosion events

Study of Cenozoic erosion events of Ural region provides new data that allows looking at geological history of Ural and surrounding areas from new point of view.

Erosion event of the west and east slopes of Ural are of different character. Common feature for Central part of Ural is Hercynian folding with followed formation of planation surface with developed weathering crusts in Mesozoic time. In the middle Paleogene (Eocene) marine basin occupied east and north-west Ural piedmonts and even had a straits through Ural. Later, after activation of tectonic movement in Oligocene and raising of Ural Mountains the erosion processes of European and Asian piedmonts became differ.

On the Western (European) slope and piedmont of Ural we see series of valleys of sub-latitudinal orientation; typical of them is Kijim Valley. Intensity of erosion processes of different geomorphological sections of the valleys was differ: it varies from $3.2 \cdot 10^{-6}$ to $6.7 \cdot 10^{-8}$ m/s. This intensity could form available valley during few years. After initial Oligocene episode the erosion became less intensive up to present-day moderate value. Some sections of the values became of accumulative character; the bedrock eroded in Oligocene is covered with Quarter alluvium deposits.

Cenozoic erosion history of the Eastern (Asian) piedmont is more complex: here we see evidences of two erosion episodes.

The first episode is assigned to Oligocene. On the central part on the border of Ural and West Siberian plain the erosion surface is revealed with geophysical data and rare drilling holes. Available data do not allow us determining Oligocene flow velocity that was directed from north – northwest to south – southeast. Main Oligocene sequence above the erosion surface consists of heterogranular sands and silt of big lake basin that occupied most of West Siberian plain.

In the zone of Turgay plateau we see sub- meridian through valley 50 – 100 km width assigned to Oligocene. Direction of the current in the valley is from north to south, the velocity exceeds 5.2 m/s. Apparently, the valley was formed in result of outburst of the waters of Oligocene West Siberian lake to Aral depression through Turgay plateau. To all appearance, elevation of the plateau above the level of surrounding plain did not exceeds 60 – 80 m. The outburst was of catastrophic character: conducted calculation shows that duration of the erosion event was in the scale of few days. The erosion affected upper part of the plateau strata which consist of weakly consolidated sedimentary rocks.

The second erosion event is assigned to Quarter. Evidences of the event are traced on extensive territory of Siberia, Aral depression and south-east Europe (Caspian – Black Sea plain). Grossvald (2005) believe that it was result of outburst of big glacial lake on the edge part of continental glacier. Whereas the flow velocity on the plain of West Siberia was about m/s (table 6), in the narrow spot of Oligocene valley of Turgay plateau the velocity of the current could be more than 8 m/s (table 1). In this case duration of erosion of inner valley incutted into solid metamorphic rocks could be less than 80 years.

It is very difficult to estimate time interval between this erosion events. According conventional Stratigraphic chart the interval was about 4 million years. It is impossible to determine it by paleohydraulic data, so we should use the results of geological observations. If the period of stagnation was very long (millions years), so fine-grained sediments with high organic content could be found on the surface on Oligocene terrace. Inasmuch as such deposits were not found, we could suppose that the period between the erosion events was much less than millions years.

Conclusion

Study of Cenozoic paleovalleys and erosion surfaces of Ural region allows collection of data necessary for paleohydraulic reconstruction. Executed calculation shows that typical Kijim Valley on West Ural was formed in result of short erosion event assigned to Oligocene. Following geological history had minor input to formation of the valley.

In the Cenozoic geological history of Eastern Ural piedmont two similar erosion events (Oligocene and Quarter) could be recognized. Whereas Quarter erosion could be connected with outburst of giant glacial lake, the reason of earlier Oligocene flood is unclear. In both case registered water movement was from north to south; velocity of the current varied moderate strong on the plain to catastrophic in the narrowness of Turgay Debacle. These intensive currents could carry out huge erosion work in a short time: days in weakly consolidated sediment and years in hard metamorphic rocks.

Reconstruction of paleohydraulic parameters and followed calculation of duration of erosion events contradict with conventional Stratigraphic Chart presupposed on slowly geological processes and long geological chronology.

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Fig.13. Cross-country vehicle “Ural” of REC “Monitoring” and research team from Moscow and Khanty-Mansiisk.

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