

Reconstruction of Paleohydrodynamic Conditions during the Formation of Upper Jurassic Conglomerates of the Crimean Peninsula

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Abstract—Conglomerates and sandstones related to Upper Jurassic division of Mesozoic rocks make up the Main Range of the Crimean Mountains. Grain size and structural features testify to active hydrodynamic regime of depositional environments. Conglomerates contain a small quantity of exotic granite–granodiorite pebbles and boulders probably transported from the Ukrainian Crystalline Shield situated 400 km north of the Crimean Peninsula. Paleohydrodynamic parameters and transportation mechanisms of debris were modeled with the help of different methods used in geoenvironmental computations. The results obtained demonstrated satisfactory convergence of the data. The calculations showed that the rocks under investigation were formed during a short (from geological standpoint) but very intense episode of sedimentation related to active tectonic processes that were responsible for the activation of hydrodynamic and sedimentation processes in the paleobasin.

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Upper Jurassic conglomerates and sandstones (UJCS) of the Main Range of the Crimean Mountains are extremely informative for the reconstruction of paleohydrodynamic conditions. Their structure and composition allow us to calculate dynamic parameters of flows in the course of transportation and deposition of sediments.

Conglomerates and sandstones (primarily, the upper part Callovian, Oxfordian, and lower Kimmeridgian) make up the second structural stage of the Crimean orogen (Khain, 2001). In general, they unconformably overlie the flysch sequence of the Triassic Taurus Formation (first structural stage). The erosion surface between these complexes suggests intense mechanical washout.

These rocks are discontinuous along the strike and traced in the form of lenses at the base of the Upper Jurassic sequence of the Crimean Mountains over a distance of 150 km from Theodosia in the east to Fiolent Cape in the west. The thickness of UJCS reaches 700–800 m in some places. The rock sequence is most complete in the Mt. South Demerdji area (Fig.1).

Upward the sequence, conglomerates and sandstones are overlain by limestones. The boundary between conglomerates and limestones is often vague: in some places, one can observe a gradual transition related to decrease in the content of pebble material and increase in the content of calcareous material in sandstones up to the point of their transition into sandy limestones.

LITHOLOGICAL FEATURES OF UPPER JURASSIC CONGLOMERATES AND SANDSTONES

The UJCS sequence can be divided into three horizons with different mineral compositions, grain size patterns, and structural features of rocks. Discrimination of these horizons is a matter of convention, because transition between them is gradual. Lenses and interlayers from the adjacent horizons can exist within a single lithological variety.

The grain size composition of rocks was studied by measuring sizes of coarse gravels, pebbles, and boulders. We also measured the extent of spaces occupied by matrix (particles less than 5 mm) across the strike of the rock section. The results averaged for horizons are shown in Table 1.

The section can be divided into the following horizons (from bottom to top):

UJCS-1. The lower horizon is represented by boulder-pebble conglomerate with sandy–clayey matrix. The cement of conglomerate is basal: coarse material (pebbles and boulders) are “hung up” in poorly sorted hosting mass, which accounts for ~37% of the horizon. The matrix consists of variegated sand with siltstone and montmorillonite–hydromica clay (*Geologiya...*, 1969). Silty–clayey material accounts for not more than 20% of the matrix. Boulders and pebbles are predominantly medium- and poorly-rounded materials. Medium- to fine-grained silicified sandstones, siltstones, and shales prevail in terms of

RECONSTRUCTION OF PALEOHYDRODYNAMIC CONDITIONS



Fig. 1. Exposure of Upper Jurassic conglomerates on the southwestern slope of Mt. Demerdji

petrographic composition. The content of quartz pebbles is not more than 10–15%.

The coarse-grained material lacks predominant orientation. The size of some sandstone boulders is as much as 0.8 m (Fig. 2). Graded bedding is obscure. In some places, lenses of coarse-grained cross-bedded sand (thickness 0.3–0.6 m, length 3–8 m) are observed in the upper part of the horizon. The maximum thickness of this horizon attains 300 m.

UJCS-2. The middle horizon includes medium- to well-rounded boulder-pebble conglomerate with medium-sorted sand matrix (~30%). Rocks of this horizon are generally well stratified. Layers and lenses of medium- to coarse-grained sand (up to 0.5 m thick) with the flow-type cross-bedding (Logvinenko, 1974) account for not more than 20–30% of the sequence and alternate with layers of boulder-pebble material up to 2–3 m thick. The layers are discontinuous along the strike. One can often see their pinchout and change in lithological composition over a distance of 100 m.

Flattened pebbles are commonly oriented parallel to bedding plane. Long axes of pebbles are usually oriented from the west-northwest to east-southeast. Graded bedding is expressed in the upsection diminution of clastic material within each layer and the thickening of sand layers in the upper part of the horizon. Cross-bedded series dip toward south-southeast at an angle of 20°–25°. The thickness of the series reaches 1–1.2 m.

In conglomerates of the Demerdji and Chatyrdag mountains, local rocks are sometimes supplemented with well-rounded boulders and pebbles of biotite–hornblende granites, granite porphyres, and granodiorites (Fig. 3). Data obtained in the Absolute Dating Laboratory (Institute of Geological Sciences, Ukrainian Academy of Sciences) suggest that these granitoids have Late Proterozoic age. Hence, clastic material was transported not only from the adjacent land, but also from distant crystalline massifs (*Geologiya...*, 1969). Since the material was mainly delivered from the north, the source of these rocks

Table 1. Grain size composition of Upper Jurassic conglomerates and sandstones

Horizonts	Grain size class, %							Diameter of coarsegrained particles, mm		Standard deviation
	<5 mm (matrix)	5-10 mm	10-20 mm	20-40 mm	40-80 mm	80-160 mm	>160 mm	maximum	average	
UJCS-1	$\frac{37.0}{37.0}$	$\frac{3.0}{40.0}$	$\frac{4.9}{44.9}$	$\frac{13.3}{58.2}$	$\frac{11.4}{69.6}$	$\frac{22.8}{92.4}$	$\frac{7.6}{100}$	780	91	42.8
UJCS-2	$\frac{28.6}{28.6}$	$\frac{5.4}{34.0}$	$\frac{3.0}{37.0}$	$\frac{19.2}{56.2}$	$\frac{24.2}{80.4}$	$\frac{19.6}{100}$	$\frac{0.0}{100}$	370	62	33.9
UJCS-3	$\frac{69.0}{69.0}$	$\frac{7.3}{76.3}$	$\frac{9.2}{85.5}$	$\frac{9.8}{95.3}$	$\frac{2.0}{97.3}$	$\frac{2.7}{100}$	$\frac{0.0}{100}$	200	30	18.1

Note: Numerator and denominator show the content of grain size class and cumulative contents, respectively.



Fig. 2. Boulders (diameter up to 0.8 m).



Fig. 3. Exotic granite pebble presumably transported from the Ukrainian Shield.

was more likely represented by the Ukrainian crystalline massif situated at a distance of ~400 km (Dobrovolskaya, 1966). In the Mt. South Demerdji area, the thickness of this horizon is approximately 250 m. The indistinct upper boundary is distinguished based on the significant decrease in the content and size of pebbles and the thickening of sand layers.

UJCS-3. The upper horizon is dominated by varigrained sandstones with gravel and small pebbles. The rudaceous gravel-pebble constituent varies from 30–40% in the lower part of the horizon to 10–15% in the upper part. Sandstones, usually with clearly expressed bedding, are massive in some places (mostly in the upper part of the horizon). The bedding is emphasized by small gravel interlayers with a thickness of up to several centimeters. The flow-type unidirectional cross bedding is encountered in the sand layers. The thickness of cross-bedded series is 0.6–1 m. The layers dip mostly south-

ward (140° – 200°) at an angle of 15° – 20° . Pebbles are commonly well rounded and small. Individual boulders, up to 15–20 cm across, are encountered.

The thickness of the horizon is ~200 m. The upper boundary grades into the overlying limestones over a distance of no more than 3–5 m. The lower part of limestones contains sand (up to 10%) and small wellrounded pebbles (not more than 5–10%).

In general, the prevailing dip direction of the crossbedded series indicates the direction of flow (Kutyrev, 1968). Therefore, one can conclude that clastic material in the UJCS accumulation basin was transported in the south-southeast direction. This is also indicated by the north-northwestern location of the possible provenance for granite pebbles. The entire conglomerate–sand sequence is characterized by the diminution of material along the paleoflow direction: conglomerates are replaced south-southeastward

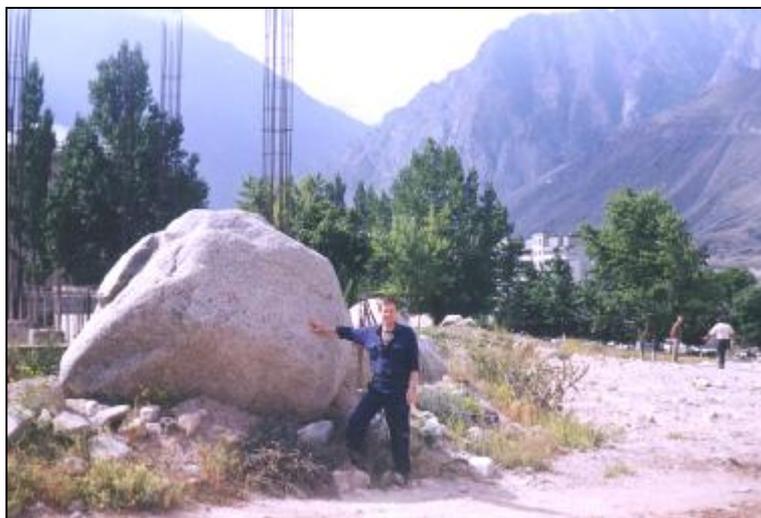


Fig. 4. Granite block transported by mudflow (Baksan Gorge).

by coeval sands and sandy sandstones (*Geologiya...*, 1969, Fig. 24.3). The most complete UJCS section (750–800 m) is observed in the Mt. Demerdji area. In some areas (e.g., the Nikita mountain pasture), conglomerates and sandstones are missing at the base of the Upper Jurassic section (*Geologiya...*, 1969, Fig. 23).

The degree of sediment sorting increases from the base to the top of the sequence. Data on the grain size composition and structural features suggest that the studied section has a single transgressive sequence reflecting the significant drop of hydrodynamic activity in the basin at the final stage of sedimentation.

MECHANISM OF SEDIMENT TRANSPORTATION

Sediments are transported as the result of the combination of several mechanisms of transport and retention of particles in flow. Therefore, the most reliable determination of transportation mode is based on the analysis of maximum quantity of relevant factors. Moreover, the relationship of different processes can change in the course of sedimentation. Therefore, various stratigraphic levels can be formed as the result of different sedimentation mechanisms even within a single sedimentary body. For example, sediments are transported simultaneously within a river channel by dragging and saltation. They can also be transported as suspension. The relationship of volumes of sediments transported by these mechanisms depends on velocity, velocity gradient, and flow depth. However, dilution with water can provoke rapid changes of rheological properties, i.e., “flow transformation” (Pierson and Costa, 1987). In connection with these features, the detailed division of clastic sediments based on the mode of their transportation and the establishment of clear boundaries between different horizons is not always possible.

Therefore, researchers are compelled to enlarge classification units based on the mode of clastic particle transportation.

According to (Polyakov, 2001), high-density turbidity (suspension) currents, as well as debris and grain flows distinguished by different authors have the common mechanism of transportation and maintenance of sediments in flow. They differ only by the composition of initial material and conditions of their transportation and deposition. Thus, it is possible to distinguish three principally different modes of sediment transportation that are reflected in the structure of sedimentary accumulations.

(1) **Landslides and slumps** produce sediments without stratification, sorting, and roundness of material. Intrastratal sedimentary structures (cross- or trough-bedding, ripple marks) are not observed. Only structures of the crumpling of clayey sediments related to the sliding of beds are encountered. The coarsegrained material is included in sandy–clayey matrix (basal matrix). One can often see the downflow coarsening of clastic particles. The content of liquid phase is insufficient for any significant influence on the pattern of material movement.

(2) **Debris flows** unite several types of mass movement defined by different authors as grain flows, liquefied and fluid flows, high-density turbidity currents, and debris flows. Despite certain differences in properties of these flows and structural-textural features of their sequences, one can recognize several common properties. Two mechanisms participate in the maintenance of particles in flow: (i) floatability of fragments in the sandy–clayey matrix and (ii) nonelastic collision of particles provoked by the external kinetic energy.

In terms of rheological properties, debris flows correspond to properties of non-Newtonian liquids,

Table 2. Lithological characteristics of sediments formed by different transportation processes

Transportation process	ST	GS	SO	CB	RO	PM	BM	VGS	References
Aquatic transportation by dragging and in suspension		N						D	N D Znamenskaya, 1976 Rossinskii and Debol'skii, 1980
Low-density turbidites		N/R							Mulder, Alexander, 2001 Sohn et al, 1999
High-density turbidites		N/R						D	Mulder, Alexander, 2001 Sohn et al, 1999
Debris flows									Mulder, Alexander, 2001 Sohn et al, 1999
Landslides and slumps								D	Esenov and Degovets, 1982
Upper Jurassic conglomerates and sandstones of the Crimea									
UJCS-1 (lower horizon)								?	
UJCS-2 (middle horizon)		N						D	
UJCS-3 (upper horizon)		N						D	

Note: (ST) stratification; (GB) graded bedding; (N) normal, (R) reverse; (SO) sorting; (CB) cross-bedding; (RO) roundness; (PM) pore matrix (boulder-pebble particles are contiguous to each other, matrix fills up porous space); (BM) basal matrix (boulder-pebble particles are rarely contiguous to each other and are mainly suspended in matrix); (VGS) downflow variation of the grain size of material: (D) decrease, (I) increase.

Which have yield stress $\tau_o > 0$. The structure of sediments is dominated by basal matrix, although one cannot also rule out the development of pore matrix between large fragments. Particles are predominantly medium rounded, and their orientation is poorly expressed. Sand interlayers with cross- and trough-bedding are sometimes found in the sequence. Graded bedding of both normal and reverse types is encountered. Debris flows are characterized by the high content of clastic material (more than 9%), which promotes the collision of particles. Flow of this type can be considered granulated medium (Polyakov, 2002).

(3) **Low-density flows** with transportation of sediments by dragging and in suspension. They are characterized by the low content of debris (<9%). In terms of rheological properties, these flows match the Newtonian liquid with the linear dependence of shear coefficient on the external impact and yield stress $\tau_o = 0$. Fine fractions of clastic material are transported in suspension, whereas coarse fractions are transported by dragging and saltation due to the tangential influence of water flow on separate particles (Grishin, 1982). The matrix of flows is porous. Gravel-pebble and boulder materials are marked by the medium or high degree of roundness, with elongated particles oriented along the flow. The bedding of sediments is well expressed. The section includes layers of well-sorted sand with unidirectional cross bedding of the flow type. In some cases, one can see the normal graded bedding manifested as decrease in the grain size of material from the base to

top of the layer. The grain size of material diminishes along the flow direction.

Table 2 shows lithological features of sediments related to different modes of transportation. Properties typical of the particular flow are shaded. The partial shading denotes sporadic characteristics depending on specific conditions.

Comparison of sedimentary structures and textures of the Upper Jurassic conglomerates and sandstones indicates that they represent a heterogeneous sedimentary body. According to lithological features shown in Table 2, the lower horizon (UJCS-1, conglomerate with basal matrix) significantly differs from the overlying sediments. Despite the differences in some characteristics (average grain size, sorting, type of matrix, and roundness of fragments), the two upper horizons more likely formed as the result of a common mechanism, parameters of which quantitatively changed with time.

The complex analysis of all lithological characteristics of the sediments (stratification, graded bedding, sorting, crisscross bedding, roundness, grain size distribution, and structure variation along the flow) allowed us to establish the most probable mechanism of their transportation.

Recognition of sediments of debris flows during the reconstruction of formational conditions of ancient sequences is hampered by difficulty of the reliable estimation of flow properties, such as concentration of sedimentary material therein and fluidity of the

medium. Therefore, conclusions concerning the participation of debris flows in sedimentation process should be drawn based on indirect data.

Such flows are characterized by the saturation of liquid phase with clay fraction and the consequent significant increase of viscosity of medium. Numerous investigations of debris flows showed that we commonly deal with two-phase or multiphase media, in which the coarse-grained material (gravel and pebble) and matrix (fluid consisting of sandy-clayey particles and water) have different styles of behavior (Smith, 1986; Pierson and Costa, 1987). This phenomenon leads to the density stratification of flow and the formation of its twolayer structure. The lower (denser) part contains coarsegrained material. The upper (diluted) part of the flow transports fine particles of material (Postma et al., 1999). In addition, debris flows have a longitudinal zonality (Sohn et al., 1999). Thus, the displacement of these zones with the development of debris flows leads to vertical stratification of sediments.

Lithological characteristics of sediments (Table 2) suggest that hydrodynamic parameters of the formation of sediments of the lower horizon can most precisely be reconstructed based on the model of debris flow, which corresponds to the non-Newtonian (Bingham) liquid in terms of its rheological properties. Comparison of the lithological characteristics of sediments from different types of flows and the UJCS horizons (Table 2) suggests the following conclusion. Among eight characteristics analyzed in the table, sediments of debris flows and the lower horizon (UJCS-1) are identical with respect to seven characteristics. The presence of pore matrix is common for 94% of sediments.

Parameters of sediments of the middle and upper horizons are closest to conditions of transportation in media with properties of the Newtonian liquid. It is evident that sediments were transported during the accumulation of these horizons by various mechanisms for different grain size fractions: (i) dragging over river bed and saltation for boulder-pebble and coarse- to medium-grained sand fractions and (ii) in suspension for particles of fine sand and silt fractions. This is indicated by results of the calculation of maximum diameter of floatable suspended particles in the flow with parameters typical of UJCS-2 and UJCS-3 (Julien, 1995).

RECONSTRUCTION OF HYDRODYNAMIC PARAMETERS OF THE PALEOFLOW

In some cases, the common engineering computations of flow parameters cannot be applied to paleohydrodynamic reconstructions, because the data available for the study of recent flows are mostly inapplicable for paleoflows. Laboratory and field investigations reveal interrelations between flow

capacity, velocity, depth and other hydrodynamic parameters. Along with the data on sedimentary formations, they provide an opportunity to reconstruct the hydrodynamic parameters of paleoflows.

In some cases, one can calculate only minimum parameters. Lebedev (1959) cites the relationship of sediment grain size and minimum erosion rates. For example, if the fluvial stream is 5 m deep, boulders 400 mm in diameter start their movement at a flow velocity of 6 m/s. Consequently, the presence of such boulders in flow indicates that the transporting flow had a velocity of more than 6 m/s. Accordingly, calculations based on the maximum size of particles in a rock yield the minimum parameters of flow at the sedimentation phase.

Several methods are used to reconstruct the parameters of paleoflows. Characteristics, such as energy gradient, channel depth, fluid density, maximum size of transported particles, channel floor roughness, and sedimentary structures are most frequently used. Structural differences between the lower (UJCS-1) and overlying (UJCS-2, UJCS-3) horizons (mainly the matrix/rudaceous material interrelation, sorting, and presence of significant clay component in the lower horizon) indicate the dissimilarity of transporting flows. Therefore, application of different methods of paleohydrodynamic reconstructions is essential for the study of such flows.

The following properties are used in the present paper for the calculation of hydrodynamic parameters:

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

D is the distance of clastic material transportation (m);

d_{av} is the average size of rudaceous material (boulders, pebbles, gravel);

d_{max} is the size of the largest boulders along long axis b (mm);

$d_{50}, d_{84}, \dots, d_n$ are the size of particles, relative to which 50, 84, ..., n % of particles have lesser size (mm);

f is the friction factor;

g is the acceleration of gravity (m/s²);

ΔH is the height gradient of flow (m);

h is the flow depth (m);

k_z is the coefficient of vertical inhomogeneity of the clastic material distribution in flow;

n is the roughness coefficient;

q is the specific discharge of clastic material (m³/s/m, i.e., cubic meter per second per 1 m of flow width = m²/s);

S is the paleoflow grade;

V is the flow velocity averaged over depth and time (m/s);

x, y, z are components of parameter along axes in the rectangular coordinate system;

τ_c is the critical shear stress (Pa, N/m²);
 τ_o is the yield stress (Pa, N/m²);
 τ_* is the dimensionless shear stress;
 ρ_s is the density of solid phase (kg/m³);
 ρ_f is the density of mixture or fluid (kg/m³);
 γ_s is the specific gravity of solid phase (ρ_g , N/m³);
 γ_f is the specific gravity of mixture or fluid (ρ_g , N/m³);
 μ is the coefficient of dynamic viscosity of pure liquid (Pa s);
 μ_f is the coefficient of dynamic viscosity of fluid (Pa s)

CALCULATION OF SHEAR STRESS FOR DIFFERENT RHEOLOGICAL TYPES OF FLOW

(1) **Debris flow** (non-Newtonian liquid). Data presented in Table 2 suggest that the lower horizon of UJCS was formed with the participation of debris flow with properties of the non-Newtonian liquid, which is characterized by the following specific property: this medium behaves as a solid body below a certain load known as yield stress (τ_o) and acquires properties of liquid only when the load exceeds this limit. According to (Mulder and Alexander, 2001), the lower limit of the content of solid phase in fluid, at which the flow acquires properties of the non-Newtonian liquid, varies from 10 to 40%. At that the same time, the significant share (20 vol % or more of the of solid phase) of clay component sufficiently increases the viscosity and changes rheological characteristics of the flow.

Properties of the non-Newtonian liquid are described by the Bingham–Shvedov equation:

$$\tau = \tau_o + \mu_m (dV_x/dZ), \quad (1)$$

where dV_x/dZ is the rate of flow velocity deformation along Z axis.

Yield stress of the Bingham liquid is defined by equation obtained in laboratory experiments with different mixtures of liquid and solid phases (Julien, 1995). In the case of high content of clay fraction in the solid phase (up to 20–30%), the equation takes the form

$$\tau_o = 0.1 e^{23(C_v - 0.05)}. \quad (2)$$

Coefficient of dynamic viscosity of the fluid containing mud–clay fractions (∞_f) is defined by equation:

$$\mu_f = \mu (1 + 2.5 C_v + e^{23(C_v - 0.05)}), \quad (3)$$

where μ is the coefficient of dynamic viscosity of pure water.

According to data based on the examination of natural objects (Julien, 1995), the degree of flow velocity deformation along Z axis rarely exceeds 100 s⁻¹.

Thus, the available data allow us to calculate the shear stress for the debris flow involved in

accumulation of the lower horizon of UJCS. The content of solid phase in the flow is taken as 40% ($C_v = 0.4$), coefficient of dynamic viscosity of water (μ) at 20°C is $1.0 \cdot 10^{-3}$, and the degree of flow velocity deformation $dV_x/dZ = 80$, because it is evident that this paleoflow had increased clay content (viscosity) and high intensity. The calculated value of τ_o is equal to 313 Pa and $\mu_f = 3.14$. From Eq. (1), one can obtain the value of shear stress equal to 564 N/m². The high share of the τ_o value (56%) in the total value of τ confirms the non-Newtonian nature of the fluid.

Values of shear stress of the same order (from 200 to 1000 N/m²) were obtained by Lord and Kehew (1987) during calculations of parameters of the hyperconcentrated flow formed after breakthrough of the Regina Glacial Lake in the southeast of Saskatchewan.

(2) Rheological parameters of the **low-density water flow** are described by Newton's equation: $\tau = \mu (dV_x/dZ)$. The medium without the yield stress is called the *Newtonian liquid*, which is characterized by depletion in the solid phase (relative to the debris flow) and, what is most important, by the insignificant content of clay fraction. The upper limit of clastic material concentration, at which the flow maintains properties of the Newtonian liquid, is differently estimated by researchers. For example, Middleton (1993) draws the boundary of low-density flows at 25% concentration of the solid phase. According to Kuenen (1966), the concentration of solid phase is up to 5% in low-density flows. Polyakov (2002) analyzed data of R.A. Bagnold and pointed out that, starting with the concentration of 9%, interaction between particles affects significantly the flow properties. Therefore, he takes this concentration as the upper boundary of low-density flows. Based on all of these data, we assume that the 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 (UJCS-2 and UJCS-3) based on the Shields equation and empirical diagram of the American Highway Research Board.

The Shields equation used to describe the parameters of turbulent flow has the following form:

$$\tau_c = \tau_* (\gamma_s - \gamma_f) d_{\max}. \quad (4)$$

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), $\tau_* = 0.050$ for sediment of small-pebble size (d 32–64 mm) and 0.047 for coarse gravel (d 16–32 mm). Specific

Table 3. Calculation of critical shear stress (τ_c , N/m²) based on the measured maximum size of particles

Horizons	d_{\max} (m)	Debris flow	Newtonian liquid flow	
		Bingham–Shvedov equation	Shield equation	diagram of the Highway Research Board (Julien, 1995; Fig. 7.7)
UJCS-1	0.78	564	-	-
UJCS-2	0.37	-	284	323
UJCS-3	0.20	-	145	175

gravity of solid phase ($\gamma_s = \rho g$) is 26 000 N/m³. Specific gravity of mixture (fluid) at $C_v = 0.05$ is 10619 N/m³.

In addition to the calculation by the Shields formula, we used the empirical diagram of the Highway Research Board given in (Julien, 1995) to estimate the shear stress. The diagram estimates the critical shear stress for rudaceous sand-gravel and boulderpebble rocks. Both methods yielded comparable results (Table 3).

For further calculations, we used values of shear stress based on the Bingham–Shvedov and Shields equations.

CALCULATION OF SPECIFIC DISCHARGE OF THE TRANSPORTED CLASTIC MATERIAL

To calculate the specific discharge of solid phase q (quantity of solid sediments transported by flow in 1 s over 1 m of flow width), we used the following scheme based on methods applied for the solution of engineering tasks.

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

$$h = \tau / (\gamma_f S). \quad (5)$$

If the density of rock-forming particles is $2.65 \cdot 10^3$ kg/m³, the specific gravity of fluid containing 40% of solid phase (i.e., $C_v = 0.4$) will be $\gamma_{f 0.4} = 1.63 \cdot 10^4$ N/m³. If $C_v = 0.05$, then $\gamma_{f 0.05} = 1.07 \cdot 10^4$ N/m³.

The possible slope of the paleoflow was estimated using data on the UJCS thickness and the distance from the possible provenance.

We can only estimate indirectly and approximately the height gradient between areas of erosion and sedimentation. Since the UJCS thickness is 800 m and the erosion zone at any case must be higher than the sedimentation zone, one can state that $\Delta H > 800$ m.

On the other hand, the rudaceous composition of material and the absence of interlayers of deep-water

sediments (except for the uppermost part of the sequence) testify to shallow-water conditions and active hydrodynamic regime of the sedimentary basin. The accumulation of UJCS could be compensated by basin floor subsidence.

Hence, the real height gradient could be less than 800 m. Since the adopted value can deviate toward both sides, the average possible value of height gradient between the eroded provenance and sedimentation zone was adopted for calculations. This value is comparable with the thickness of accumulated conglomerates (800 m).

According to the data presented in (Dobrovolskaya, 1966), pebbles of metamorphosed slates could be derived from outcrops of probably Paleozoic rocks that exposed 100 km north of the sedimentation basin are now overlain by the Meso–Cenozoic sedimentary cover. The biotite–hornblende granites, granodiorites, and granite porphyres could be delivered from the Precambrian Ukrainian crystalline massif situated 400 km north of the Upper Jurassic basin (*Geologiya...*, 1969). This assumption is indirectly confirmed by the high degree of roundness of the exotic granitoid pebble. Slopes of the paleoflow (S) for the proximal and distal sources are 0.008 and 0.002, respectively.

Different methods are used for the estimation of flow parameters. The Chezy, Manning, and other equations are applied to flows in open channels. All of these equations describe the relationship of characteristics of a stable uniform flow, but the real flows are characterized by different degrees of inhomogeneity. Nevertheless, these equations are applicable to real flows without significant errors (Costa, 1984).

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 boulder-pebble and gravel fragments (d_{av}) on the floor. The Chezy equation provides the most reliable results for deep flows with relatively fine material, when h/d_{av} tends to infinity.

Table 4. Calculation of specific discharge of debris

Horizon s	d_{\max} (m)	d_{84} (m)	d_{av} (m)	τ_c (N/m ²)	C_v	$Y_f \times 10^4$ (N/m ³)	S	h (m)	h/ d_{av}	n	f	V (m/c)	k_z	q (M ² /c)
UJCS-1	0,78	0,10	0,091	564	0,4	1,63	0,008	4,3	48	0,033	0,072	7,1*	0,89	11,0*
							0,002	17,3	190	0,032	0,041	9,3 / 8,1**	0,35	22,5 / 19,8**
UJCS-2	0,37	0,08	0,062	284	0,05	1,07	0,008	3,1	54	0,031	0,058	6,4*	0,93	1,0*
							0,002	13,4	216	0,031	0,035	8,1 / 7,8**	0,51	2,8 / 2,7**
UJCS-3	0,20	0,02	0,030	145	0,05	1,07	0,008	1,7	57	0,025	0,060	5,1*	0,98	0,4*
							0,002	6,8	227	0,025	0,035	6,4 / 5,5**	0,79	1,7 / 1,5**

* Logarithmic form of equation was used for values $h/d_{av} < 100$ ($S = 0.008$).

** Numerator shows values of flow velocity and specific discharge of debris based on the Manning equation; denominator shows the same parameters based on the Chezy equation.

The Manning equation is applicable to flows with $h/d_{av} > 100$, whereas the logarithmic form of the equation is more preferable for shallow flows with the coarse-clastic material ($h/d_{av} < 100$) (Julien, 1995). The calculations showed that the h/d_{av} value varies from 48 to 227 (Table 4). The precise boundary between the application zones of Chezy and Manning equations has not been established. Therefore, calculations based on both equations were accomplished to enhance the reliability for the flows with $h/d_{av} > 100$. For the flows with $h/d_{av} < 100$, logarithmic form of the equation was applied.

The Chezy equation has the following form:

$$V = (8ghS / f)^{0.5} \quad (6)$$

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

$$f = (2.03 \log(12.2h/d))^2 \quad (7)$$

The Manning equation has the following form:

$$V = S^{1/2} h^{2/3} n^{-1} \quad (8)$$

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

$$n = 0.113 h^{1/6} / (1.16 + 2 \log(h / d_{84})) \quad (9)$$

The value of cumulative curve d_{84} is approximately 0.1 m for the lower horizon, 0.08 m for the middle horizon, and 0.02 m for the upper horizon. Using values of h from Eq. (5), we obtain values of n for the lower, middle, and upper horizons (0.032–0.033, 0.031, and 0.025 respectively).

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

$$V = 5.75 (ghS)^{0.5} \log(12.2h / k_s), \quad (10)$$

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

From these data, we can estimate the specific discharge of solid phase in the flow during the UJCS formation:

$$q = h V C_v k_z \quad (11)$$

where h the calculated flow depth, V is the flow velocity, C_v is the volume content of solid phase in fluid, and k_z is the coefficient of vertical inhomogeneity of solid phase distribution in the flow

The irregularity of solid phase concentration in vertical section of the flow significantly increases with increase of its depth. At a depth comparable with the size of turbulent vortices, volume concentration of solid phase in the near-bottom layer is comparable with the concentration averaged over the whole thickness of the flow ($C_{vz} \approx \text{const}$), and the coefficient of vertical inhomogeneity is close to unity. When the flow depth sufficiently increases, material transportation takes the form of near-bottom stratified current (Samolyubov, 1999). The bulk of material is transported in the near-bottom layer, but the flow already cannot be considered a homogenous medium. The volume concentration of particles along the vertical axis C_{vz} already cannot be considered a constant value: it depends on distance from the bottom and grain size of transported material. This is reflected in the decrease of the coefficient of vertical inhomogeneity.

The final calculation data are shown in Table 4. Values of the specific discharge of clastic material obtained by different methods show a satisfactory convergence. Scatter of values in many instances is dictated by paleogeomorphological factors (uncertainty of the flow length and, correspondingly, slope S).

The total error of calculations is sufficient to say with convenience only about the order of the defined values. Nevertheless, the minimal values obtained clastic material, had a velocity of 5 m/s, and its maximum specific discharge could vary from n to 10 m³/(s m).

PARAMETERS OF RECENT FLOWS

For the reconstruction of paleohydrodynamic conditions of UJCS formation, let us compare the calculated parameters of the paleoflow with the data available on the specific discharge of clastic material in recent channels.

According to (Polyakov, 2001), monitoring of bottom debris of the Bzyb River near the Alakhadze Settlement (Abkhazia) showed that movements of pebblesized material ($d_{av} = 2$ cm) started at a flow velocity V equal to 1.3 m/s and a waterdepth $h = 1.1$ m. With the flow discharge of 537 m³/s, the discharge of bottom debris was 50.6 kg/s; i.e., the volume concentration in debris flow is $C_v = 3.3 \times 10^{-5}$, and the specific discharge of debris ($q = hVC_v$) is approximately 5×10^{-5} m²/s.

Julien (1995) presents the data on debris discharge of the Colorado River (United States) near Taylor Ferry, where the channel width is ~100 m, flow depth is 1.2–3.6 m, flow velocity is 0.8–1.2 m/s, and the specific flow discharge is 0.8–3.5 m²/s. The total discharge of debris (both bottom and transported in suspension) dominated by sand-sized fractions is approximately 0.1 m²/s.

In terms of specific discharge of clastic material, the calculated parameters of paleoflows involved in the UJCS formation (Table 4) significantly exceed the parameters of recent alluvial channels. Data obtained for the UJCS can be compared with catastrophic mudflows, parameters of which were quantitatively estimated during hydrological observations. First, they include mudflows, which destroyed Alma-Ata in 1921 and 1977 (Esenov and Degovets, 1982).

In July 1921, mudflow with the total volume of 1×10^6 m³ provoked by prolonged heavy shower brought into the city more than $3 \cdot 10^6$ m³ of mud–rock mixture. The maximum flow discharge in the mountains was 5000 m³/s. Since the content of solid debris in the mudflow was equal to ~30% and the valley width in the mountainous area was 500 m, the specific discharge of debris was approximately 3 m²/s.

In August 1977, intense melting of glaciers and catastrophic breakthrough of the ice dam of Lake Kumbulsu along the Bol'shaya Alma-Atinka River valley provoked a series of mudflows with the total debris volume of up to 6×10^6 m³. Separate waves of mudflow in the mountainous part of the river valley reached a height of 12 m, and mudflow splashes rose to a height of 15–50 m at steep bends of the valley. The velocity of the mudflow reached 8–10 m/s, and the flow transported rock blocks up to 5–6 m across. The specific discharge of debris was approximately 6–8 m²/s.

In 2000, the fast melting of glaciers produced several catastrophic mudflows in the Baksan Gorge of the Caucasus near the Tyrnauz Settlement. The flow transported rock blocks up to 3 m in diameter (Fig. 4). Six episodes of mudflow descent were recorded, and each episode lasted approximately half an hour. According to the author's data, the mudflows produced an approximately 800-m-long fan with a width of ~1 km near the base. At the thickness of ~5 m, the total

Table 5. Comparison of paleohydrogeological parameters of the formation of Upper Jurassic conglomerates and sandstones (UJCS) with parameters of recent channels.

Object	V (m/s)	q (m ² /s)
Bzyb River	1,3	5×10^{-5} *
Colorado River	1,2	0,1
Alma-Ata, , 1921	?	3
Alma-Ata, , 1977	up to 8–10	6–8
Tyrnauz, 2000	> 6	4
UJCS	UJCS -1	7,1–9,3
	UJCS -2	6,4–8,1
	UJCS -3	5,1–6,4
		11,0–22,5
		1,0–2,8
		0,4–1,7

* Bottom debris transported by dragging

volume of the fan was approximately 2×10^6 m³. At the width of stream channel equal to 50 m, the specific discharge of debris was approximately 4 m²/s.

Comparison of the calculated hydrodynamic parameters of paleoflows involved in the UJCS formation with the cited data of natural observations (Table 5) shows that velocity and specific discharge of debris in paleoflows are significantly higher than those in recent mountainous alluvial channels and are compatible with the recorded recent catastrophic mudflows. For the upper sequence (UJCS-3) mainly represented by sandsized sediments, the minimum flow parameters are close to those for recent mountainous rivers.

CONDITIONS OF THE FORMATION OF UPPER JURASSIC CONGLOMERATES AND SANDSTONES

The data obtained show that the rocks under consideration are products of intense hydrodynamic and sedimentary processes, which are observed only during catastrophic events at present. Judging from the known volumes of the conglomerate–sandstone sequence and the calculated specific discharge of debris, one can estimate the real “pure” time of sedimentary processes of the UJCS sequence formation. Since the nature of parameters involved in the calculations is approximate, we cannot give the exact figure. However, even the most approximate estimate shows that, although the formation of the UJCS sequence is considered as a stratigraphically long-term process (several millions of years), in reality in terms of geology it can be referred to as a virtually instantaneous episode (not millions of years).

Such a relationship of sedimentation duration and stratigraphic age of rocks is characteristic of the injective sedimentogenesis (Romanovskii, 1988) when the real time of sedimentation is sufficiently less than the stratigraphic interval of the rock sequence under consideration.

Based on results of the study of grain size characteristics of rocks across the section, one can conclude that hydrodynamic parameters of the medium of debris transportation and accumulation changes relatively uniformly from the formation of boulder-pebble conglomerates at the initial stage to the deposition of gravelpebble conglomerates, sandstones, and sandy limestones at the final stage. Origination of bedding, which is observed predominantly in the middle and upper horizons of the UJCS, can be explained by processes of dynamic sorting and separation of varigrained debris (2002). Thus, the available data suggest that the UJCS structure reflects the traces of a powerful and intense hydrodynamic process that occurred against the background of transgression of the Jurassic marginal sea of the Tethys Ocean toward the East European Platform (Khain, 2001).

CAUSES OF CATASTROPHIC SEDIMENTATION

Interpretation of the causes of catastrophic sedimentation is hypothetical. We propose to discuss conditions of UJCS formation as formulation of the problem. The available data do not allow us to draw a single conclusion about the reasons of such powerful and intense geological event, but one can suggest that the answer can be found in the field of catastrophic manifestations of natural processes (in particular, tsunamis and mud-flows) caused by earthquakes, volcanic explosions, meteorite impacts, as well as breakthrough of glacial lakes or marine waters into depressions lying below the sealevel.

On the Earth's surface, 135 astroblemes with crater diameter of more than 4 km have been recorded (Fel'dman, 1990). The largest Vredeford astrobleme (South Africa) reaches 335 km in diameter and is dated at 2 Ga. The catastrophic extinction of Mesozoic fauna at the Cretaceous/Paleogene boundary is attributed to the Chiksub Crater (180 km in diameter) situated in the Yucatan Peninsula (Central America). The largest in the Russian territory Popigai astrobleme (100 km in diameter) is characterized by a huge amount of released energy (10^{23} - 10^{24} J), which corresponds to the maximal energy for catastrophes reliably recorded within continents. Since the Earth's surface is mainly occupied by water, we can suppose that the number of meteoritic craters is three times higher than the known value, the more so that the fall of a giant meteorite to the sea can be accompanied by the generation of catastrophic waves of tsunami.

In this sense, the situation with the Altanin asteroid is highly typical. The asteroid fell onto the South America – Antarctica shelf approximately 2.5 Ma ago in the Late Pliocene. Its remnants were recently recovered from the crater formed on the seafloor. Consequences of this asteroid fall were quite catastrophic: giant tsunamis threw marine fauna deep

into the land. Very strange burials of a mixture of marine and terrestrial fauna appeared precisely during this period on the Andian shore, and purely marine diatomaceous algae appeared in Antarctic lakes (Es'kov, 2000).

Based on a number of specific geomorphological features of territories of West Siberia and Kazakhstan, as well as the northern Caspian region and Kuma-Manych Basin, Grosval'd (1999) proposed the existence of an ancient giant water flow (megaflood) related to the breakthrough of a large glacial lake, which was located in the outer part of the continental Arctic ice shield. The existence of scablands in the northwestern United States and southwestern Canada is explained by the analogous breakthrough of a glacial lake. Highintensity flows, which existed in these areas, washed away not only loose sedimentary rocks, but also basaltic sheets. The breakthrough of oceanic waters into the Mediterranean Basin in the terminal Miocene could also be accompanied by similar catastrophic events (Rezanov, 2003).

Explosive volcanic eruptions and earthquakes are confined to certain structures of the Earth's crust and stages of their development. They are the sources of giant tsunami waves. The megatsunami, which devastated the coast of Southeast Asia on December 26, 2004, can serve as example of such catastrophic events. This event was caused by the sharp displacement of seafloor and the consequent origination of a giant wave (up to 35 m high in concave areas of the seacoast), the propagation velocity of which exceeded 10 m/s near the coast.

The tsunami in Southeast Asia was the largest one recorded over the whole period of scientific observations, but the origination of much more powerful waves is theoretically possible. According to Zimov (1989), intense catastrophic tectonic movements in the MOR zone can generate near shallow-water areas giant waves with a height of up to several hundreds of meters, propagation velocity of tens of meters per second and water discharge of millions of cubic meters. Such waves can transport huge volumes of clastic material over long distances and, thus, execute significant geological work during a short time span.

A number of indirect signs makes it possible to suppose that the formation of Crimean UJCS could be related to a catastrophic megatsunami caused by tectonic processes in the zone of collision of a southern continent (or island arc) with the southern margin of Eurasia represented by the Scythian Platform (Khain, 2001). These sediments represent the typical lower (marine) molasse, which occupies a characteristic position in the black shale–flysch–lower molasse system and is distinguished as a separate molasse formation, which terminates the sedimentary evolution cycle of oceanic deep-water trenches (Romanovskii, 1988).

The process of molasse formation is characterized by the link with orogenic epochs, which follow powerful tectonic movements, high hydrodynamic activity of sedimentation environments, great distance of clastic material transportation, and presence of exotic rocks. "Clastic material of molasse is mainly composed of the destruction product of mountain massifs with a subordinate amount of rocks transported from platform areas" (*Geologicheskii...*, 1960, p. 46).

Thus, the Crimean UJCS is not a unique or exotic material. In foldbelts, such sequences typically occupy a definite position related to the stage of intense tectonic processes. Other sources of energy are not necessarily related to the evolution of foldbelts. Therefore, one can suggest that strong earthquakes and the consequent tsunamis related to the folding and mountain building phase were the main reason of UJCS formation. Discontinuous occurrence of conglomerates along the strike within the Crimean folded system indicates that terrigenous sediments were mainly transported along a system of valleys, which extended as submarine canyons on the shelf.

Model used in the present paper for the calculation of hydrodynamic parameters of paleoflow involved in the UJCS formation is a simplified version. Therefore, we can only say about the order of defined values. Nevertheless, the data obtained indicate the catastrophic character of the lower molasse formation in the Crimean Mountains. Analogous deposits are spread in the entire Alpine–Himalayan Foldbelt and other folded systems of the world. Therefore, one can suppose that similar catastrophic sedimentation (with different degrees of intensity and periodicity) also occurred in the geological past in other regions of our planet.

The proposed interpretation is debatable and we do not reject the classical mechanism of UJCS formation (Khain, 1983). Nevertheless, catastrophic mechanisms cannot be excluded from the consideration. The frequency of their occurrence seems to be insignificant only from the point of view of human life, but they are manifested regularly at the geological time scale. In addition, geological work performed by short-term but intense hydrodynamic processes is comparable and possibly more significant than the work accomplished in "normal" conditions over a prolonged period.

CONCLUSIONS

The detailed lithological investigation, of Upper Jurassic conglomerates and sandstones in the Crimean Mountains made it possible to identify three horizons with different grain size compositions and structural specific features. We reconstructed rheological properties of the paleoflows involved in the clastic material transportation and accumulation of the UJCS sequence.

Based on a modified procedure applied for geoenvironmental computations of hydrodynamic characteristics of recent water flows, we could quantitatively estimate hydrodynamic parameters of paleoflows. The results obtained showed that the UJCS material was transported and deposited under conditions of high hydrodynamic activity of the medium.

We suppose that catastrophic megatsunamis provoked by intense tectonic movements in the Alpine–Himalayan Foldbelt were the possible source of such activity. The structural similarity of the UJCS with analogous rocks in other regions allows us to suppose that the similar mechanism was also responsible for the formation of the lower (marine) molasse sequence in other folded systems.

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