Glacier-dammed lakes and geological work of glacial superfloods in the Late Pleistocene, Southern Siberia, Altai Mountains

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Abstract

Quaternary glacier-dammed lakes of Southern Siberia produced cataclysmic superfloods-floodstreams at the initial and final glacial stages, when the ice dams were unstable. Consequently, the initial surface was greatly and geologically instantly transformed. Morphologic associations of mountainous scablands developed, similar to the diluvial complexes of the Channeled Scabland in North America: giant diluvial ramparts and terraces-bars, diluvial berms and giant current ripple relief. Diluvial-erosional and erosional forms, including spillways, outburst and oversplash gorges, and “dry waterfalls” are also present. The discharges of the glacial superfloods, which have been calculated by independent methods, were hundreds of cubic meters per second at the locations where the giant current ripple marks were formed, up to millions of cubic meters per second within the gorges. Maximum discharges of $18 \times 10^6 \text{m}^3 \text{s}^{-1}$ were characteristic of the diluvial floods in the runoff channel from the Chuya–Kuray system of the glacier-dammed lakes below the mouth of the Kuray depression as far as the settlement of Chibit. The power of those floods reached $10^6 \text{Wm}^{-2}$. These values exceed the hydraulic parameters of the jökulhlaups from Late Quaternary Lake Missoula in North America, the floods of which previously were considered the most powerful freshwater streams in Earth history.

The last phenomenal glacial superflood with discharges in excess of $1 \times 10^6 \text{m}^3 \text{s}^{-1}$ occurred in the Chuya and Katun valleys no later than 13 000 years ago. Afterwards, the glacier-dammed lakes degraded simultaneously with the degradation of the glaciers. The glacier-dammed lakes of the intermontane basins in Southern Siberia disappeared completely at some time after 5000 years ago. Calculations of the hydraulics and the estimates of the geological activity of the Quaternary jökulhlaups mean that the diluvial processes of relief formation can now be viewed as the most powerful exogenous process.

1. Introduction

All of the mountains from Eastern Kazakhstan (Tien Shan, Kazakh Altai) to the mountains in the Baikal region belong to the mountains of Southern Siberia, which also includes those of Altai and Tuva. This grand mountainous chain forms a part of the Russian State boundary in the south.

The Altai is located near the centre of Asia (Fig. 1) and is the highest of all mountain ranges in Siberia (some of the maximum measured elevations are over 4000 m). The Altai Mountains consist of vast intermontane basins, which were occupied by near-glacial lakes in the Pleistocene, and of high mountain ranges that carry the grandest of modern Siberian glaciers. Numerous climatic zones, which are also peculiar to a certain extent to the neighbouring mountainous countries, are present. The nival-glacial zone changes downwards into the taiga and tundra, into the steppes and the deserts of high-mountain basins, which in turn are adjacent to the mixed woods zone and the zone of South-Siberian steppes. That is why, from the viewpoint of physical geography, the Altai may be considered representative of the whole huge mountainous region of Southern Siberia. From the palaeogeographical and geomorphologic aspects, the Altai is typical of the whole of Central Asia.

It is in the Altai that a number of great scientific discoveries have been made during the last decades, which are important for Russian and world-wide Geomorphology, Palaeoglaciology and Quaternary Geology in the 20th century. The chief ones are:

(1) Discovery and identification of geological-geomorphologic traces of giant Late-Quaternary glacier-dammed lakes whose regular outbursts resulted in generation of glacial superfloods. Those floods left...
behind exotic relief forms and deposits (in the first place, giant current ripple marks and diluvial swells and terraces—“bars” according to Bretz, 1923), similar to the diluvial morpholithologic associations of the Channeled Scabland in North America; and

(2) Discovery of the geological phenomenon of Quaternary Ledoyoms—huge amounts of ice in the intermontane basins. Those ice bodies have a very complicated paragenetic relationship with glacier-dammed lakes (Rudoy, 1991, 1998).

The present article deals with the problem of geological and geomorphological effects of the Quaternary jökulhlaups, and that of palaeohydrology and hydraulics of the glacier-dammed lakes and glacial superfloods.

2. Terminology problems

The term “cataclysm” is associated with something terrible in the minds of most people. Such a notion has no physical sense, although, in reference to those processes, which take place when geologically momentary failures of huge near-glacial lakes occur, it is true with respect to that emotional and physical effect which all natural cataclysms produce on the human beings in general.

To characterise the outbursting glacial superfloods and their influence on the Earth’s surface the author accepts a short and well-turned, in his opinion, definition given by Arnold (1990, p. 8): “Cataclysms are spasmodic alterations which occur as an abrupt reaction of the system to smooth changes of the environment”. Though the definition also contains some indeterminate terms (“spasmodic, abrupt, smooth”), it seems quite correct and convenient for the objectives of Quaternary Glaciohydrology and Geology.

The term “intermontane basin” as interpreted by Timofeev et al. (1977) is a tectonically conditioned depression located between mountainous ranges or mountainous range systems. An “intramontane basin” is a relatively small trough located within a mountainous area. Both definitions imply the sense of the words “basin”, “depression” and “hollow”. From the geological-geomorphological viewpoint all these terms are also identified in the English-language literature. The definitions “intermontane” and “intramontane” are synonyms as well. In the geographical literature these definitions are employed for the same basins nearly everywhere. Thus, by an intermontane basin I mean, regardless of their origin, all relatively large intra- (inter-) montane degradations (depressions, basins, hollows) surrounded by mountainous ranges or their systems.

Introducing new terms to describe cataclysmic failures of the near-glacial lakes and their consequences, we use in most cases the phonetic type of importation of terms that have already been adopted in western literature, into the Russian scientific vocabulary. Thus, the term “scabland” was used by Bretz, the discoverer of the floods from Lake Missoula, with the literary meaning of the English word “scab”. Since the word “valley” did not express the morphologic peculiarities of the thick net of dry riverbeds that cut into the Columbian scabland, Bretz used the more precise word “channels”, after which the whole territory gained the name the “Channeled Scabland” (Bretz, 1923). Thus, erosional- and evorsional-diluvial forms of scabland served as the main argument for giving such a name, i.e. coulee nets (from the names of the settlements of Grand Coulee and Lind Coulee) and “dry waterfalls”, which were discovered by Bretz at the beginning of the 20th century. Erosion is destruction of rock caused by the rotation of water that falls subvertically.

One of the most characteristic elements known nowadays, the relief of the giant current ripple marks, was correctly interpreted much later (Pardee, 1942). In the mountains of Southern Siberia the largest run-off channels mainly inherited river valleys (with exception of outburst and oversplash gorges) (Rudoy, 1995; Grosswald and Rudoy, 1996a, b). They were not the first to witness and prove the diluvial origin of the Asian scabland, though it is namely they that chiefly described its appearance. That is why I offered the name “scabland” in the definition given below (also in Rudoy, 1995, 1997, 1998; Rudoy and Baker, 1996) for the general indication of the territories that have suffered the influence of cataclysmic glacial superfloods.

The term “spillway” simply means “water drainage”, and some additional clarification is required to specify origin. In the Russian scientific literature the term “spillway” has already been firmly adopted to denote the routes of water drainage from ice-dammed lakes over low watersheds and mountain pass saddles-open
valleys into neighbouring basins. One of the world’s greatest spillways, for example, is the Turgay run-off channel of the Great Siberian near-glacial seas into the Atlantic basin (Arkhipov et al., 1995; Grosswald, 1998).

The term “bar” according to Bretz refers to rampart-shaped or terrace-shaped thicknesses of detrital material, which are excessively thick for a “normal” alluvial valley and have distinctive lithology. The “bar” sediments were deposited by the superfloods at suitable spots on the way of the lake water drainage. Because of the obvious inconvenience of the term caused by the presence of a widely known notion “bar” in the Russian marine geomorphology, I use the term “diluvial-accumulative terrace, rampart” to denote such thicknesses and relief forms, proceeding from the common name of the exogenic processes which resulted in the development of the terraces and ramps.

The popular (in the West) term “giant current ripples” is inconvenient, because unlike the English word “ripple” the Russian equivalent does not have the plural–singular form differentiation. When describing the relief of the giant current ripples, I employ more convenient and precise expressions and terms like “diluvial (flood) ridges, dunes and antidunes” alongside with the traditional translated form in accordance with the morphology and development mechanisms of concrete forms and deposits.

Boulder-block natural levees, spits and related features are called in the Western scientific literature “Boulder Berms” (e.g. Carling, 1989). I also employ the term “diluvial berm” for the common indication of such forms, at least, as long as the morphologic and genetic classification of these forms is not developed any further from the diluvial theory viewpoint.

Scientific day-to-day existence, especially during personal discussions, broadens very often the primary meaning of many terms. Folk words and notions that describe a certain natural phenomenon have gained more general senses for whole groups of natural phenomena and processes without being properly translated. Probably, such was the metamorphosis of the Icelandic term “jökullhlaup” which was (and is) used to denote cataclysmic floods occurring when ice and snow melt as a result of a volcanic eruption in the glacial zone. Nearly immediately after the first works which dealt with Icelandic jökullhaups, foreign scientists began to employ the term to denote cataclysmic failures of any ice-dammed lakes (e.g. Clague and Mathews, 1973; Nye, 1976). It certainly cannot be considered terminologically correct. Nevertheless, the term “jökullhlaup” in its broad sense is used worldwide, Russia included. The future will show if the more convenient term “floodstream” which was recently proposed by Grosswald and Rudoy (1996a) will gain popularity with the investigators. Grosswald called a cataclysmic flood occurring as a result of a jökullhlaup a “floodstream”.

The term “diluvium” is an anachronism. It was proposed by Buckland in 1823 and denoted literally “the flood”—the Deluge from the Bible. Later on, the Biblical content was lost and it was employed in its precise meaning. In some countries, e.g. Germany, the term “diluvial” had been used until the 1950s as a synonym of the Quaternary period. This meaning of the term has been preserved in some dictionaries up to our time, noted as “obsolete”. Applying the obsolete term to new contexts, we assume that the word “diluvium” as an anachronism is well known to specialists, and the precise translation of the term corresponds to the new contexts enclosed in it. The term is convenient to use, and by its sound correlates perfectly with the names of many other genetic types of unconsolidated sediments and relief forms, such as alluvium, proluvium, and colluvium.

The criticism of some opponents of the term concerning easy phonetic confusion of the “diluvium” with “deluvium” is certainly worth attention. However, it should be no more than that paid to the criticism of the opponents of Pavlov, who more than a century ago proposed the latter term (to denote processes and products of the surface wash). It was the time when all naturalists in the world associated the notion of “diluvium” by no means with the Bible, but with glaciation and huge amounts of water. Pavlov put forward a strict requirement to the geological terminology, indicating that each term should define the formative processes of the given group of sediments (Pavlov, 1888, p. 5).

Taking into consideration the definition of “diluvium” given above, the geological activity of glacial mud-streams can also be framed within the complex of diluvial processes. Mud-streams of glacial origin are a particular case of the diluvial processes. Glacial mud-streams are also temporary floods with similar run-off hydrographs. However, in their geological effect the outbursting glacial mud-streams are as far from the diluvial superfloods as small forms of glaciation, for example, cirque or slope glaciers, are far from glacial ice sheets.

Description and study of all the aspects of the diluvial process generally cause much terminological complication. The solving of the latter, I believe, lies in broad inter-subject science cooperation and, generally speaking, is a question of time.

3. Late Pleistocene glacier-dammed lakes of the Altai and geological effects of the floodstreams

3.1. Research review

In 1980s the first traces of cataclysmic outbursts of huge basaline glacier-dammed lakes were discovered in Central Asia, in the Altai Mountains, in the river valleys
of the Chuya, the Katun, the Chulyshman, and the Bashkaus (Rudoy, 1981, 1984; Butvilovskij, 1982; Butvilovskiy, 1985). By the end of the decade all the largest locations of diluvial terraces, giant current ripple marks, spillways, outburst and oversplash gorges, dry waterfalls, etc. had been described. There have also appeared data about a wide spread of giant current ripple marks and diluvial terraces-bars in the upper reaches of the Yenisei (Grosswald and Rudoy, 1996a, b). Calculated and analytic materials also showed the possibility of immense Quaternary glacial floods—floodstreams—in the Baikal region (Rudoy, 1987; Grosswald and Rudoy, 1996a, b).

In the early 1990s, the first international expeditions to study the consequence of the Pleistocene cataclysmic superfloods were organized under the author’s leadership to the Altai Mountains. The participants of those expeditions were geologists and geomorphologists from Russia (Rudoy, M.R. Kirianova), the United States (Baker), Great Britain (Carling) and Switzerland (C. Siegenthaler). As a result of those expeditions it was ascertained, in particular, that the Altai assortment of geological traces of the cataclysmic outbursts of the glacier-dammed lakes is basically identical to that of North America (Rudoy and Baker, 1993). Structural differences of form may be explained by the fact that the initial relief of the regions under study in North America and Southern Siberia was also different. The mountains of Southern Siberia and the volcanogenic plains of America carried different types of glaciers. That is why the ancient dammed lakes were near-glacial, i.e. proglacial, while the ice-dammed lakes of the Siberian mountains were inner-glacial (intraglacial). That circumstance caused some individual interesting peculiarities in the history of those lakes at all the stages of their evolution. The highly contrasting relief determined the high potential energy even of small dammed lakes in Siberia, caused by the steep slopes of the main run-off valleys.

One of the scientific results of the international fieldwork was the conclusion that the term “scabland” has chiefly a genetic interpretation and also a broader one than had been previously adopted in America. The name “scabland” should be given to all the territories of glacial and pro-glacial zones, which undergo or underwent previously a repeated influence of cataclysmic floods from outburst ice-dammed lakes. The latter left behind original natural forms according to which it is possible to define the hydraulic parameters of the outburst water streams.

Studies of the cyclic regimes of the Quaternary glacier-dammed lakes in the mountainous countries, which began in the former Soviet Union over 20 years ago, were conducted at first using traditional methods of geological-geomorphological research on qualitative grounds. By the late 1980s two scientific approaches had evolved—lithological-geomorphological and palaeoglaciological. Each of the two approaches, having its own specific methods, is useful in the solution of the same problems. The main goal is to establish the fundamentals of the theory of diluvial morpholithogenesis.

3.2. Glacier-dammed lakes and the theory of diluvial morpholithogenesis

The concept of diluvial morpholithogenesis, formulated in the second half of the 1980s (Rudoy, 1991), may be briefly summarized as follows.

Pleistocene glaciation of dry land and continental shelves was accompanied by the rise and growth of giant near-glacier water bodies whose dimensions were many times greater than modern ones (Table 1). Discharges of outburst superfloods from these often exceeded $1 \times 10^6$ m$^3$ s$^{-1}$. Water velocities were dozens metres per second, and depths of some floods exceeded 100 m (Table 2).

The initial land surfaces underwent immense transformations during very short (minutes, hours, days) time intervals as a result of the geological work of these glacial outburst superfloods. The scales of those transformations might be compared with other known natural disasters—earthquakes, tsunami, and volcanic eruptions.

The widespread occurrence of glacier-dammed lakes of different types during glacier periods, their systematic failures caused by unstable ice dams owing to low ice density, their immense, sometimes cardinal, consequences of these failures, all led the author to identify a specific complex of diluvial exogenic processes. Diluvial processes of relief formation cause Earth surface transformation by cataclysmic water streams from outbursting ice-dammed lakes.

The very first classification of the morpholithological complex of the mountainous scablands was offered 15 years ago (Rudoy, 1987). Since then, the classification has been changed. Firstly, some formations of a different genesis, which had been falsely interpreted according to the diluvial approach, were removed from the classification. Secondly, some newly discovered and investigated diluvial forms enriched the table. Both the diluvial forms which were preserved in the table and those discovered during recent years have been investigated thoroughly in the Altai and Tuva from the morpholithological and palaeohydrological viewpoints. Owing to some new field research of the author, as well as the works of Grosswald and Butvilovskij, the knowledge of the geography of the diluvial relief and sediment forms has been considerably broadened.

Nevertheless, the classification contains only those formations discovered, studied and identified by the author (Table 3). My own experience has shown that generalization of the literature data given by other
### Table 1
Discharges of modern glacial-dammed lakes

<table>
<thead>
<tr>
<th>Lake, region</th>
<th>Year</th>
<th>Volume, (10^3 m³)</th>
<th>Discharge, (m³ s⁻¹)</th>
<th>Emptying mode and notes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merzbacher, Tien Shan</td>
<td>Annually</td>
<td>200000</td>
<td>Up to 2000</td>
<td>Along inner-glacial slopes</td>
<td>Vinogradov, 1977</td>
</tr>
<tr>
<td>Tulsequah, British Columbia</td>
<td>1942; 1958</td>
<td>230000</td>
<td>1600</td>
<td>Along a subglacial channel 7 km long</td>
<td>Post and Mayo, 1971</td>
</tr>
<tr>
<td>Summit, British Columbia</td>
<td>1965</td>
<td>251000</td>
<td>3200</td>
<td>Along a subglacial tunnel 13 km long</td>
<td>Mathews, 1973</td>
</tr>
<tr>
<td>Abdukagor, Mountainous Badakhshan</td>
<td>1967</td>
<td>145000</td>
<td>1000</td>
<td>Along the inner-glacial slopes without damage to ice dams</td>
<td>Dolgushin and Osipova, 1982</td>
</tr>
<tr>
<td>Grimsvötn, Iceland</td>
<td>1934</td>
<td>100300</td>
<td>960</td>
<td>Along a subglacial tunnel</td>
<td>Thorarinsson, 1953</td>
</tr>
<tr>
<td>Lake George, Alaska</td>
<td>1958</td>
<td>173000</td>
<td>10000</td>
<td>Along the glacier surface by the edges of the glacial dam</td>
<td>Vinogradov, 1977</td>
</tr>
<tr>
<td>Rasselfjord, Alaska</td>
<td>1986</td>
<td>540000</td>
<td>105000</td>
<td>Ice dam failure</td>
<td>Mayo, 1988</td>
</tr>
<tr>
<td>Issyk (moraine dammed, upper reach of Little Almaatinka R)</td>
<td>1973</td>
<td>260 up to 10000</td>
<td>15 m deep appeared in the bottom of the valley during first 10 min after the lake failure</td>
<td>Vinogradov, 1977</td>
<td></td>
</tr>
</tbody>
</table>

*For comparison, the mean discharges at the river mouths of the largest world’s rivers are: Volga—7710, Ob—12700, (maximum—42800, minimum—1650), Yenisei—19800 (maximum—154000), Amazon—220000, Mississippi—19000 m³ s⁻¹.*

### Table 2
Hydraulic characteristics of largest Quaternary ice-dammed lakes

<table>
<thead>
<tr>
<th>Name of a lake or lake system</th>
<th>Area, (10^3 km²)</th>
<th>H_e, (m)</th>
<th>V_max, (km³)</th>
<th>H_j, (m)</th>
<th>Discharge, (10^5 m³ s⁻¹)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stolper, North Germany</td>
<td>5</td>
<td>0.037</td>
<td>0.10</td>
<td>Thorson, 1989</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kan Lakes, Altai</td>
<td>0.26 (?)</td>
<td>0.10</td>
<td>Rudoy et al., 1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porcupine, Alaska</td>
<td>1.34</td>
<td></td>
<td>Rudoy, 1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulagan Lakes, Altai</td>
<td>0.12</td>
<td>10–20</td>
<td>Rudoy, 1985</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abay, Altai</td>
<td>0.32 (?)</td>
<td>0.14</td>
<td>Rudoy et al., 1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uymon Lakes, Altai</td>
<td>1.2 (?)</td>
<td>1.9</td>
<td>Rudoy et al., 1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yaloman Lakes, Altai</td>
<td>0.017–0.04</td>
<td>2.0</td>
<td>Rudoy et al., 1989</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jassater Lakes, Altai</td>
<td>0.6</td>
<td>2.0</td>
<td>Rudoy, 1995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Darkhat Lakes, Mongolia</td>
<td>2.6</td>
<td>4.0</td>
<td>Grosswald, 1987</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missoula, North America</td>
<td>7.5</td>
<td>170</td>
<td>O’Connor and Baker, 1992</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chuya-Kuray Lakes, Altai</td>
<td>12</td>
<td>180</td>
<td>Rudoy and Baker, 1993</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*For comparison—the mean annual run-off of the Amazon is 7000 km³ (about 15% of the world annual runoff). H_e is the depth of the lake near the dam; V_max the lake volume; H_j the ice dam thickness calculated according to the formula by Nye (1976) and geomorphologically reconstructed.*

### Table 3
Classification of the types and forms of the diluvial morpholithological complex (diluvial morpholithological associations of mountain scablands)

<table>
<thead>
<tr>
<th>Relief type</th>
<th>Relief forms</th>
<th>Genetic type of deposits</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diluvial-erosional</td>
<td>Coulees, spillways (open valleys), outburst and oversplash gorges, diluvial-erosional ledges, relics</td>
<td>Diluvium (glacial mud-stream facies)</td>
<td>Obliquely bedded pebble gravels, unrolled rhythmically bedded coarse-grained sands, break-stone, debris, erratic boulders, blocks</td>
</tr>
<tr>
<td>Diluvial-evorsional</td>
<td>Water-forced hollows, niches, drillpots (“giant vessels”); “dry waterfalls”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diluvial-accumulative</td>
<td>Diluvial-accumulative terraces and ramparts, giant current ripple marks (flood ridges, dune and antidunes), diluvial berms</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
investigators may lead to mistakes in the diluvium diagnosis in cases when no qualitative photographs of the corresponding relief and sections are given, even if a detailed description exists.

Where glaciers dam river valleys and impound lakes, the lakes break the glacial dams, and wash away or completely destroy glacial traces in the main runoff valleys out of Lake Basins. Diluvial processes are genetically connected with glacial processes of relief formation, but they act at lower hypsometric levels, where in most cases their influence exceeds that of the glaciers that gave rise to these processes. This is the essence of the theory of diluvial morpholithogenesis.

The concept of the cause–consequence connections of glacial and diluvial processes in the Altai Mountains has been tested in all great river valleys of Southern Siberia during the last decade. Presently it can be extrapolated theoretically to all the regions of the Earth having a similar palaeoglaciohydrological situation for a given time. The theory of diluvial morpholithogenesis objectively affords considering the probability of diluvial floods within the river valleys of such mountain countries whose morphostructural appearance is similar to that of the Altai, and where Quaternary glaciation was able to block the river outflow from intermountain basins. The mountains and uplands of the Baikal region belong to this category. Here, the whole mountainous diluvial morpholithologic complex can be found. Moreover, judging by the size of dammed reservoirs, it is much larger than in the Altai-Sayany mountain district.

On the other hand, the diluvial morpholithogenesis concept lets us solve another problem: to first assume

![Fig. 2. Palaeoglaciohydrologic sketch of the Altai (Rudoy, 1995, 1998). Chronological section about 14 000 yr BP. Legends: 1—boundaries of glacier-complex; 2—probable limit of ice spread at the stage of the last glacial maximum; 3—glacier-dammed lakes; 4—spillways; 5—giant current ripples; 6—directions of diluvial floods; 7—maximum lake boundaries; 8—locations of the largest diluvial terraces and ramparts; 9—modern glaciers; 10—“dry” waterfalls. Figures on the map are names of reconstructed lakes (named after the corresponding basins): 1—Chuya Lake; 2—Kuray Lake; 3—Uymon Lakes; 4—Yaloman Lake; 5—Ulagan Lake; 6—Teletskoye Lake; 7—Jukul Lake; 8—Jassater Lake; 9—Tarkhat Lake; 10—Bertek Lake; 11—Abay Lake; 12—Kan Lakes. Lake dimensions are reconstructed according to lake terraces and deposits and also according to the marks of the glaciers that dammed lake depressions. Maximum dimensions of glacier-dammed lakes are reconstructed according to the absolute marks of spillways, outburst valleys and diluvial ramparts on watersheds. Boundaries of glacial complexes are drawn according to the position of the snowline, which was 1200 and 800 m lower 18 000–20 000 and 14 000 years ago than the modern one.](image-url)
the presence of large pro-glacial lakes at the upper reaches of the rivers containing evidence of diluvial floods within these valleys, and consequently to reconstruct the dimensions of the glaciers. Geological ages of diluvial-accumulative deposits indicate both the age of the corresponding ice-dammed lakes and the age of glaciers blocking them. Such direct extrapolations are true for lowland regions as well (Rudoy, 1998).

Three types of the relief formation processes form the surface of the scabland. They determine the total assortment of the forms of the diluvial morpholithologic complex and the prevalence of one form over the others depending on the lake volumes, thickness of the ice dams, the initial relief and the energy of floodstreams. These processes are those of diluvial accumulation, diluvial erosion, and diluvial evorsion.

3.3. Generation and composition of Quaternary diluvium

3.3.1. Diluvial-accumulative ramparts and terraces

Diluvial-accumulative ramparts and terraces are present in all main runoff valleys from the glacier-dammed lakes. They are especially well expressed at the middle and lower reaches of the Katun River (Fig. 2). These forms are thick, usually about 240 m (maximum up to 340 m) above the river edge, units. They are clearly bedded, with well-washed deposits of gravel, breakstone and debris, including both sand and loamy-sand layers and lenses, as well as angular boulders and blocks of diverse lithology (Fig. 3). The units accumulated under an abrupt fall of stream energy or under conditions of reversed flow in the zones of the erosional shadow below bed ledges, bends of the main valley, or within vast expansions of the valleys.

Deposits of the natural screen zones, whose development mechanism is thoroughly described by Chistiakov (1978), were studied in large Siberian rivers by Laukhin (1971), who suggested that they should be called limno-like facies. The deposits of the upper levels of the diluvial ramparts and terraces do resemble the deposits of poorly drained lakes. They were formerly considered as such, within the Yaloman Basin. Baryshnikov (1992, p. 117) presented a map of the dammed lake boundaries in the Katun River valley, which was reconstructed according to the pebble gravels on the slopes of the tributary valleys of the Inya, the Big and Little Yalomans, the Kupchegen rivers and their tributaries. There also exist other ideas of the genesis of the units which form the high levels of the diluvial terraces, such as “kame terraces” according to Okishev (1982), or “anomalously thick alluvium units” under tectonic dipping, that served as the grounds to indicate the “Yaloman tectonic depression” in particular—the idea of all investigators who worked here in 1950–1960s.

As in the slackwater deposits from the Quaternary glacier-dammed Lake Missoula in North America (Baker and Bunker, 1985; Smith, 1993), fine-grained silt and polymictic sand layers alternate inside these units with coarser, normally break-stone and gravel horizons, which are confined with the main runoff channels—the Chuya and Katun River valleys. The texture of the deposits fines along the tributary valleys with distance from the main valleys. Foreset beds which dip at 6–8° under the edge of the Little Yaloman River indicate water oversplashes from the Chuya valley. Here, horizons of sands, break-stone and pebble-gravels, which are about 25 cm thick, alternate with silt layers about 10 cm thick. Horizons of loamy-silt and silts are present. These deposits of stagnant water are discordantly overlapped with boulder and pebble-gravel layers with some insertions of small blocks (Fig. 4). The relatively coarse-grained composition is the consequence of energetic pulsations of the flood moving upslope along the tributary valleys. These same powerful streams directed up the Little Yaloman and Inya River valleys as
the flood passed along the chief channel could also
generate the breakdown textures inside the silt horizons.

All high diluvial terrace deposits have a poorly
rounded break-stone and debris fraction, which dom-
inates in the composition of the units, and have varied
lithology. These last two facts indicate that clastic
material was mainly transported in suspension by floods
(Rudoy, 1995; Rudoy and Baker, 1996). These deposits
contain some large angular boulders, up to several
meters long in diameter, which do not deform bedding.

The surfaces of the diluvial terraces are generally
inclined towards the bedrock sides of the valley. They
are often complicated by small isometric caps, which
mark the spots of the underwater vortices. Terrace edges
are emphasized by the bank ramparts or berms.
Subsequent erosion and mass wasting processes have
shaped these units into distinct terrace forms with well-
defined edges and clearly distinguished benches. Their
dip is close to the natural slope angle (angle of repose)
for the corresponding fractures (Fig. 5). That is why
diluvial terraces and ramparts, strictly speaking, are not
terrace terraces.

Diluvial units blocked the Inya and the Yaloms
River valleys and those of some other tributaries of the
main valleys. In the Central Altai these constructions are
known as the “high terraces” of the Chuya and the
Katun. Their striking dimensions and perfect shape
excited the famous Russian geologist Petr over 150 years
ago (Chikhachev, 1973). The genesis of the “high
terraces” was formerly the subject of discussion
(Ivanovskij, 1998). In the piedmont areas, the heights
of the diluvial-accumulative terraces decrease to 100 m,
reaching 60 m at Gorno-Altaiisk (the so-called Maima
rampart). The proportion of well-washed coarse-grained
sands increases, as does gravel roundness. The develop-
ment of the “high terrace” deposits was a result of either
a single powerful floodstream, or (more probably) was
the work of several floods. Judging by the deposit
thickness, the minimum depths of the diluvial foods in

the Chuya and the Katun River valleys were at least
250 m. This correlates very well with data gained from
calculations (see below).

The deposits of lower terraces (conventionally-up to
100 m above the river edge) are normally represented by
pebble-gravel and gravel members with deltaic bedding,
which are separated by subhorizontally layered sedi-
ments of small pebble-gravels of normal river channel
streams. The thickness of these members at the location
of the Inya settlement near the old bridge over the
Katun River is 8–10 m. In the Chuya River valley, the most complete
exposures have from 7 to 9 of these members, with over
10 preserved in the Katun River valley (Fig. 6). The
upper cross-bedded series overlying most exposures of
the low terraces are overlapped by “boulder pave-
ments”. They are formed by the channel facies of
alluvium, and may indicate incision of the post-flood
streams into the thick diluvial unit.

The accumulative mechanism of the diluvial sedi-
ments, which make up the terraces of the Central Altai,
is the subject of the current investigations. On the whole,
those regularities which are true for the channel processes in modern streams producing polyfractional mountain alluvium cannot be an instrument to interpret the lithological peculiarities of the diluvial-accumulative forms. These deposits represent a completely different physical process, which exceeds in scale the hydraulic parameters of most powerful modern waterstreams by several orders.

3.3.2. Diluvial berms

Diluvial berms are a genetic macro-analogue of boulder-block ramparts and spits (“cobblestone pavements” of the big modern rivers). The most well-known location in the Altai is a long rampart, which begins at the foot of the “high” terrace of the left side of the Katun River below the settlement of Inya. This rampart is armoured by angular blocks of various (but not local) lithologies. The rampart crosses the Katun River valley at an acute angle (Figs. 3 and 5). At its proximal part the rampart is 110 m wide and its maximum height above the terrace surface is 4 m. Further down the valley its height decreases, as does the size of the fragments that armour the rampart.

The biggest blocks lying on the surface of the rampart have long axes of 14 m, and blocks 2–3 m long are common. The blocks are imbedded in the surface. The rampart itself is separated along a clear oblong narrow gully at its head from the rear junction of the terrace. As the rampart becomes wider in the shape of a train down the Katun River, its surface has developed several smaller ridges aligned parallel to the trend of the rampart. The hollow boundary to the “high terrace” periodically is a swamp covered with gooseberry and barberry bushes.

As this accumulation of coarse-rock material is located in one of the most often visited places in the Altai (the block and boulder field crosses the Chuya Highway), all of the investigators of the Altai tried to explain its origin. Different interpretations include a large mud-stream discharge, perluvium on the end moraine, and perluvium on the sediments of the “high terraces”.

Meanwhile, papers dedicated to channel processes have studied and described in detail the mechanism of the development of the coastal coarse-rock ramparts and terraces, as well as shallow water fords (works by Chistiakov, Chalov, Makaveev, and others). According to Lodina and Chalov (1994), the instantaneous velocities under condition of turbulent streams considerably exceed the mean values (up to 40%). Under such velocity impulses, the streams acquire an ability to carry much coarse material, which forms the deposits of stretched ramparts within the expansions of the valleys or below their bends as lateral forms. The observations made by these authors along the large rivers of Siberia within semi-mountainous regimes showed high velocities of movement of coastal boulder ridges downstream 3–4 m/y.

Vortex hollows develop in the channel (Petkevich, 1973). Lodina and Chalov indicated that the velocities of the floods, which produced these forms, might exceed the velocities of the diluvial floods along the axis the channel by almost 1.5 times.

3.3.3. Giant current ripple marks

Giant current ripple marks are active channel relief forms, which develop within near-thalweg areas of the pre-axis parts of the main valleys of the diluvial outflow. Giant current ripple marks are morphologic and genetic macro-analogues of small sand ripples (Rudoy, 1984, 1995). Lungershausen and Rakovets (1958) were the first to correctly interpret a “mysterious” ridge-and-padding relief in the Kuray intermontane depression (Fig. 8). The giant current ripple marks indicate powerful Pleistocene floods in the east towards Mongolia. Although this paper suggested a neotectonic origin of those floods, the correct genetic interpretation of the ridge relief was undoubtedly significant for Russian Quaternary geology. The discovery of giant ripple marks in the Altai was immediately called into question by Deviatkin, who referred to an oral conclusion made by E.V. Shantser and wrote that the ridges in the Kuray depression were the result of heavy erosional modification of a huge fluvo-glacial fan (Deviatkin, 1965). Petkevich (1973) expressed a similar opinion, and believed that the ridged relief on the right bank of the Tetio River in the Kuray depression were the remains of a washed proluvial fan. Borisov and Minina (1980), who were consistent opponents to the fluvial origin of the giant ripples not only in Siberia, but also in the Pamirs, thought that the ridges shown in Fig. 8 were ribbed moraine. Okishev “closed” the discovery completely, when he asserted that the Kuray relief under discussion is (1) an “inversion” relief of the marginal water-glacial accumulation; (2) “bedded, small-ridged, poly ridged”
moraines (p. 36). Position 1 was defended Okishev in 1984, although publications which supported the initial hypothesis of the geologists of the All-Union aerogeological trust had already appeared (e.g. Butvilovskij, 1982; Rudoy, 1984). Earlier, the Russian translation of Richmond (1965) mentioned geological traces of the cataclysmic glacial floods. That paper also failed to draw scientific attention in Russia, as did the work of Reineck and Singh (1981) with its short section about giant current ripple marks. Had the Russian investigators been persistent, and the examiners more critical and erudite, there would have been a far greater sum of knowledge about the palaeogeography of the mountain regions in Russia in the early 1980s.

Giant current ripples in plan are a system of elongated poorly sinuous ridges, or chains of cuspatc dunes, which are oriented sub-perpendicularly to the valley trend (Figs. 7–9). The inter-ridge hollows are usually elongated troughs and are separated by small bulkheads. Horns of the ridges face the direction of the palaeoflood. The length of the ridges correlates with their height and may reach kilometers (e.g. those on a very effective field of the giant current ripple marks in the Kuray intermontane depression in the Altai, Fig. 8). The smallest (30–60 m) is the flood dunes in the Central Altai (Fig. 9) and those in the depression of Kara-Kol Lake (western part of the Kuray depression). Both the height and the length of the ripple marks also vary and reflect the dynamics of the floods. The maximum wavelength was registered on the right bank of the Tetio River—about 200 m with relief over the inter-ridge hollow of a minimum of 15 m (Fig. 8). The slope angles vary from 3° to 11° for proximal slopes and from 5° to 20° for distal ones.

The composition of the giant ripple marks is practically the same for different sites (the depression of Kara-Kol Lake excepted). The covering loamy-soils and loamy-sands are from 10 cm (on the crest) up to 150 cm and more (in the inter-ridge hollows) thick. The characteristic cross-bedded texture generally agrees with the distal slope dip. This is also characteristic of the giant ripple marks in North America.
The bedding is conditioned by various granulometric compositions of the horizons, which are 10–70 cm thick. The relatively coarse layers (fractions of pebbles and small boulders) are on average twice as thick as the fine-grained ones. The concentration of boulders and coarse pebbles is greatest in the lower parts of the sections. The alternation of the granulometrically different layers may be explained by the combination of mechanisms of periodic sliding of the coarse-grained material that accumulates on the crest of the distal slope, by flood fluctuation and by periodic change in the granulometry of the bed-load. Carling (1996) believes that as the bedding dip angle in the flood dunes is close to the repose condition, the ridges in the channel should move mainly due to rolling of the mobile layers over the bend at the crest tops and due to the sedimentation on the distal slope, rather than by collapsing and sliding.

The coarse rock material is well and moderately rounded at nearly all the locations of the giant ripple relief. The lithologic composition of the biggest fragments is rather varied and is normally similar to the composition of the channel alluvium of a corresponding modern river. In the Kuray depression the composition of the biggest fragments (fractions exceeding 0.3 m) is represented by chlorite-epidote-quartz metosomatites, quartz porphyries, basalts, microdiorites, and meta-morphic slates. V.P. Parnachev made field determinations of lithology inside the giant current ripples in the Kuray depression in August 1990. This composition is different from the lithological assemblage of the dropstones lying in the depression, including those on the flood dunes. The biggest dropstones, which are over 1 m along the long axes, are angular blocks of various granitoids.

In contrast, the ridged relief of the Kara-Kol Urochishtshe includes coarse material of the local rock. All fragments are angular, although the bedding inside the ripple marks is similar to that at the other locations. This suggests that the relief of the giant current ripple marks developed very rapidly, and local rocks dominated in its formation, as they were incorporated from the underlying surface.

The Kara Kol Urochishtshe is adjacent to the right slope of the Maashey River trough (Fig. 10). Here the two fields of the giant current ripples, which are situated close to each other, are oriented in opposite directions. The outer field, lying close to a small watershed ridge between the Chuya River valley and the Kara-Kol Basin, is strictly related to the diluvial-erosional oversplash gorges of the palaeoflood from the Chuya River valley onto Yeshtikkol Plateau. The gorges thalwegs and the ripples are studded with large angular fragments of erratic rocks (granodiorites and dolerites), which are not found in the bedrock of the North-Chuya Mountain Range, and with blocks of Devonian deposits. The crest height relative to the inter-ridge hollows is 120–130 cm. The prominent parts of the ridges are oriented westward, where in a high rocky bulkhead between Kara-Kol and the Jangyskol lake depression narrow outburst valleys correspond to the ridged relief.

The inner ripple field, which is situated between Kara-Kol and an elevated pediment of the North-Chuya Range, has an opposite orientation, towards the Maashey River. The oversplash valleys and the spillways functioned many times, while the spatial interrelation between the diluvial-erosional and diluvial-accumulative forms indicate powerful floodstreams from the Chuya–Kuray system of the ice-dammed lakes. Those floodstreams both transformed the main runoff valley and generated numerous oversplashes onto the near-watershed benches, as well as giant vortices and backwater areas (Fig. 10).

A few years ago, nearly all the investigators recognized the correct diluvial origin of the giant current ripple marks. Some perplexity remained concerning the “strange” orientation of the giant flood ridges in the Kuray intermontane depression. According to this orientation the Quaternary diluvial floods from the depression were directed opposite to the modern flow of the Chuya River.

The palaeoglaciological reconstructions of Okishev (1982) are based on his conclusion that the last glaciation in the Altai Mountains existed due to the decrease of the mean annual air temperatures relative to modern values by approximately 5°C, without any increase (relative to modern conditions) in the mean annual precipitation. Thus, the meltwater runoff from the glaciers of the Altai at that time was 10 times less than the modern value, i.e. was so much reduced that it was absorbed by the “channels”, cracks in the glacier. A glacier occupied the Chuya River valley at the glacial maximum and a lake did not develop in the Kuray depression (Okishev, 1982, p. 39).

To estimate the meltwater runoff at the maxima and postmaxima of the last glaciation in the largest basin in the Altai Chuya depression, the data of Okishev (1982) concerning the temperature gradients and snowline depression (−5°C with 800–850 m, and −3.8°C with 610–660 m correspondingly relative to the modern ones) were used. The estimated inaccuracy of the results did not, evidently, exceed the error involved in determining the limits of the Quaternary glaciers made according to the air- and space photographs and in the field. The calculations showed that the volume of the modern glacial runoff in the basin of the upper Chuya (the source range of the Chagan–Usun River) is about 0.3 km³ yr⁻¹. During the first stage of the Late Quaternary glacial it produced 8.8 km³ yr⁻¹, and during the second stage about 8.5 km³ yr⁻¹. Thus, during the glacial maximum of the Wurm, the volume of the melt runoff from the glaciers in the Altai might be nearly 30 times more than the modern one. Judging by these
estimates it is easy to calculate that to fill the Chuya Basin up to the horizon of 2200 m (the limit level of the deciphered shore lines) it would have taken only about a hundred years. The Kuray depression would have had to be filled up at least three times as rapidly. Thus, until the establishment of the levels of the Kuray and Chuya ice-dammed lakes, the runoff should have been directed eastwards, into the basin of the Chuya Lake, which was just being filled (Rudoy et al., 1989).

Another probable scenario of palaeohydrologic events may give a satisfactory explanation for the "strange" orientation of the giant current ripple marks in the Kuray depression (Rudoy, 1995). Changes in the plan configuration of the river channel (a bend, an expansion, etc.) will also cause some changes in the hydrodynamic regime, as well as in bottom and lateral erosion, shore and other types of accumulation. The processes are controlled by the differentiation of the stream velocities at the different parts of the stream and of the changes in the longitudinal character of the longitudinal and cross circulation. At some sites there appear zones of energetic local vortices, and even wider areas of backwaters. Here, migrating ridged channel forms develop, associated with maximum velocities and depths in the stream.

In the Kuray depression, the palaeohydrologic situation may resemble the scheme depicted in Fig. 10. The offered explanation is not a revelation for channel processes specialists, but it may appear an interesting one for the investigators in the sphere of dynamic geology and geomorphology. These two scenarios are not mutually exclusive. The cyclone turnover which has been reconstructed in the Kuray depression in the Altai, and which had a more than 10-km radius, together with the main longitudinal palaeoflood, might serve as a mirror image of the modern circulation of the Arctic Basin (Grosswald and Rudoy, 1996a, b).

Ripple growth requires a short time under flood conditions. Dinehart (1992) ascertained from rivers of the northwest USA, that for river dunes of crest height 0.2–0.4 m, their length exceeds 30 m during 24–48 h. Gustavson (1976) observed during floods along modern rivers in Texas that ripples grew up to 2 m with lengths of 100 m. Although direct physical analogies between the modern sand ripples and the giant boulder-and-pebble diluvial dunes may not be completely correct, it is
possible to assume that the development of the giant current ripples within the channels of the diluvial floods was also very rapid. The giant current ripple marks are channel forms that cannot be analysed directly according to the observations in modern rivers (Rudoy and Baker, 1993).

In addition to the diluvial-accumulative terraces, ramparts, bars and berms, the giant current ripple marks are an exclusive proof for the cataclysmic outbursts of the huge glacier-dammed lakes. The outburst and oversplash gorges, spillways and other erosional and evorsional forms of scabland (see below) may be mistakenly diagnosed according to some different genetic interpretations, but in the complex with the above-described accumulative forms they do not leave any doubt as to their only diluvial interpretation.

The diluvial-accumulative forms are more common than has occurred to many researchers before. To find them, we lack only one thing—the knowledge of what exactly we should look for. Discovery and large-scale mapping of new locations of fields of giant current ripples and other accumulative forms of scabland will give the investigator new scientific and methodological instruments to reconstruct the large systems of periglacial palaeorunoff of all of Central and Northern Asia, which are known at present only in general terms.

3.4. Forms of diluvial erosion and evorsion

3.4.1. Diluvial erosion

Diluvial supererosion leads first of all to the development of deep gorges on the route of the water outlet (outburst gorges). The largest outburst gorges in the Altai are the majority of the canyons of the Bashkaus and the Chulyshman Rivers, the upper reaches of the Katun River, and a young gorge on the site between the Yeshtikkol Urochishthes from the Maashey River mouth to the settlement of Chibit (Figs. 1 and 10). There are also outburst gorges at the mouths of many other valleys of the Chuya depression basin: the Chagan–Usun, the Chagan–Burgazy, the Tarkhaty, and others (Fig. 11). Most of the so-called epigenetic gorges, which were already described (Ivanovskij, 1967), are actually outburst valleys of diluvial origin, which were formed by powerful water streams during quite short periods.

Along the straight sites of the main runoff valleys the rock material was either partly or completely washed out, the prominent slopes were destroyed, the ancient fans were intensively cut off, and the valleys deepened. For example, the cut-off proluvial fans are a most characteristic element of the Chulyshman River valley, especially at its middle and lower reaches.

The mountain pass saddles, along which the water surplus was thrown into the neighbouring basins each time the lake depression was full, turned into the open valley-spillways. They had canyon-shaped, and less commonly narrow box-like cross profiles. Some of the spillways, for example the Kokoria spillway (the right source of the Chuya River); Kokoru (the upper left source of the Bashkaus River); Tobozhok (another right source of the Chuya); and the Karasy (a tributary of the Bashkaus River, had been prepared by the ice floods which overflowed from the Chuya aufeis ledoyom into the Bashkaus Basin (see Rudoy, 1990, 1998). The “open trough” of the Tobozhok River was described by Speranskij (1937), who wrote in particular that practically all the tributaries of the upper Chuya (the right sources included) served as runoff channels for the ice of the Chuya ledoyom into the Bashkaus river valley. Subsequently, these concepts were rejected due to the fact that the Chuya depression was never occupied by glaciers during the Quaternary (Deviatkin, 1965), as there are no moraine remnants on the depression bottom. This last fact was used as the main proof of the Quaternary ledoyoms’ existence. The ideas of Speranskij (1937) were denied and forgotten, but the open valley remained.

Study of the open valleys at the upper reaches of the Bashkauas ascertained that erosional gorges are cut into the shallow (60–100 m deep), flat-bottomed, relatively wide (1.2–1.5 km) valleys. These gorges are locally very narrow (up to 10 m wide between the upper benches), with step-like longitudinal profiles on the Bashkauas side.

When the theory of the aufeis ledoyoms appeared (Rudoy, 1981, 1990, 1998), it became clear that the mechanism of the development of some ledoyom types differs in principle from that mechanism of the intermontane depression ice filling, which had been offered

Fig. 11. The outburst gorge of the Chagan River. The Chagan Scabland, South-Eastern Altai, South-Chuya Range.
by Nekhoroshev (1930). Beside the “classical ledoyoms”, which are intermontane depressions filled with glacier ice that produced huge valley glaciers from the depressions within the outlet runoff channels, some other mechanism of ledoyom development in the depressions was indicated. Depressions were already occupied by the glacier-dammed lakes [“catch lakes” and the ledoyoms of the aufeis type (Rudoy, 1998)] when mountain glaciers reached them. Thus, it was proven that Speranskij (1937) had been right. The Chuya depression was a ledoyom, which produced glacial floods into the neighbouring basins, and the open troughs were employed at the degradation stages of the glaciers as spillways to partially move the water from the Chuya ice-dammed lake into the neighbouring basins.

Where the runoff valley was not able to contain the passing water masses, the flood splashed high over the local watersheds and produced a series of diluvial-erosional valleys and oversplash gorges. The flood transported and accumulated erratic material high on the slopes of the watersheds, some fragments of which were rather sizeable: boulders and blocks weighing hundreds of tons. Unlike the erratic boulders of the glacial origin, the diluvial erratic material is, as a rule, rather poorly rounded.

From the palaeoglaciohydrologic viewpoint, an interesting system of variously oriented outburst and oversplash valleys is located on the Yeshtikkol plateau (Fig. 10). The outburst gorges here cross a low watershed between Kara-Kol Lake and the depression of Jungyskol Lake, via a narrow, curved channel through the system of foothill diluvial bench-steps. These gorges (there are not less than five of them there) vary from 500 m to 1.5 km long. Their depth along the subvertical slopes is 120–300 m, with their width from dozens to a hundred of meters. Presently, all these gorges are dry, as their bottoms are slightly higher than both depressions. Along the extreme northern gorge there is a road connecting Kuray village to the settlement of Chibit. All these gorges are abundantly populated.

The runoff and oversplash channel from the depression of Kara-Kol Lake into the Chuya River valley is employed presently by melt water as a temporary one during the period of heavy rains and during spring snow melting. However, neither a modern stream bed nor bed alluvium is presently found in the channel along its whole length. The channel looks like a canyon 80–100 m deep and no more than 50 m wide, with steep, often nearly vertical, walls. The longitudinal profile of the channel is complicated with step-like benches, which fix the cataracts formed by outthrows of the lake water down the gradient. The height of these benches is 2–3 m. Within the thalweg of the canyon along its whole length up to Kara-Kol are poorly rounded blocks of dolerites and granodiorites (diluvial erratic boulders from the Kuray Range). Their dimensions vary from boulders up to blocks 3 m in diameter. The gradient slope of the canyon is covered with larches.

Two more diluvial-erosional canyons, which are much longer, have been studied farther westward. Their structure is generally similar to the one described above. Diluvial-erratic material has been also found on the bottom of the channels. These channels must have been used by diluvial floods many times, both as outburst and oversplash gorges. The orientation of the giant current ripple marks at the Kara-Kol Urochishtshe also confirms the fact (Rudoy, 1995).

The diluvial-erosional channel-coulees, which were distinguished in North America, are rarely found in the mountains of Southern Siberia. It is possible that their existence simply has not been established. Further field studies will show if such channels really exist in the areas where Quaternary basalt covers Eastern Tuva and the basins of the Khubsugul and Darkhat intermontane depressions. Grosswald and Rudoy (1996a, b) noted the diluvial genesis of the deep canyon of the Kyzyl-Khem River. This canyon cuts both granites and metamorphic rock, and huge thicknesses of Quaternary basalts (Fig. 12). Judging by the palaeo-glaciohydrologic situation, a vast area of Putorana plateau also may contain diluvial runoff channels. It is possible that the largest Altai channels-coulees are the Chulyshman, the Bashkaus and the Argut river valleys. Morphologically they look quite similar to the diluvial canyons in North America. The palaeohydrologic situations of the Eastern and the Central Altai do not contradict this assumption.

In the Altai Mountains, the only site of undoubted scabland has been discovered where the system of branching, discontinuous, deep (50–70 m) coulees complicates the central part of the Chagan River valley.

Fig. 12. Diluvial-erosional canyon-coulee of the Kysyl-Khem River above the junction with the Ka-Khem River. Relief of the edge of the interglacial basalt terrace over the channel is about 150 m. Picture by Grosswald (Grosswald and Rudoy, 1996a, b).
(Rudoy and Kirianova, 1994). Above the confluence of the Ak-Kol and Kara-Oyuk Rivers, the valley for nearly 8 km is filled with Varved Lake sediments with an exposed thickness of about 30 m (Fig. 13). The modern outlet of Ak-Kol Lake above the Kara-Oyuk River mouth is dammed by a moraine rampart. Its outer edge is adjacent to the side of a tectonic rock bar, which flanks the Chagan River valley for nearly 10 km downstream. At the site the river runs along a narrow gorge over 50 m deep. The surface of the rock bar, Upper Devonian poorly metamorphosed slate, bears clear marks of glacial striation. Hollows are sprinkled with small boulders and well-rounded pebble gravel.

There are two systems of glacial furrows on the exposed surface of the rocks, which are oriented 25° and 50° (Fig. 14). A characteristic feature of this part of the valley is a broad spread of secondary dry channels and shallow gullies. They divide the field of roches moutonnées into separate (curved in plan) rows and columns of rocks. The shallow gullies and the channels are filled with sands, pebbles, break-stone and glacial boulders. This coulee-dissected 10 km part of the Chagan River valley is referred to in the geomorphological

Fig. 13. Map-sketch of the Chagan–Usun. Legends: 1 — varved lake-glacial deposits of various age; 2 — the “Chagan Scabland”; 3 — end moraines of the second (which was last, younger than 25 000 years) phase of the Late Quaternary glaciation; 4 — end moraines dated 58 ± 6.7 thousand years (MSU-KTL-93); 5 — modern glaciers; 6 — modern lakes; 7 — subvertical trough slopes; 8 — gorges; 9 — location of a “dry” waterfall. The inset picture shows a fragment of the “Chagan Scabland” (legend Fig. 2 on the map-sketch).
literature as the “Chagan Scabland”. The exotic landscape of the Chagan Scabland was formed no later than 3000 years ago as a result of one or several outbursts of Ak-Kol ice-dammed lake (Rudoy and Kirianova, 1994).

3.4.2. Forms of diluvial evorsion

Diluvial-evorsional forms are connected genetically and spatially with spillways and diluvial-erosional outburst and oversplash valleys. Judging by the laboratory data, the evorsion of the bedrock by the diluvial floodstreams might be very rapid, especially at the sites with supercritical current velocities. This results from cavitation, which took place at the contact point of the bed with the mixture of air and water (Grosswald and Rudoy, 1996a).

Short-lived but exceptionally energetic waterfalls very often appeared where lake water was thrown over local watersheds and mountain pass-saddles. These waterfalls produced huge (hundreds of meters in diameter and dozens of meters deep) water-forced hollows, funnels and drillpots (“giant vessels”). Some of such diluvial-evorsional depressions are occupied nowadays by picturesque lakes, while others are presently waterless.

An example of a diluvial-evorsional depression presently filled with water is the famous Altai-Aya Lake (Fig. 15). The depression of the lake, as well as the adjacent evorsional depressions “Moss Swamp” and Pionerskaya, are situated on the left bank of the Katun River, 30 km upstream away from Platovo. All these depressions were developed in the surface of a 60 m pebble terrace, and their corresponding dimensions are $1200 \times 200$, $400 \times 390$ and $200 \times 70$ m. The water was thrown via the spillways, which were sawn in a narrow, mainly gravel crest, which protrudes into the Katun River valley above the depressions. Maloletko (1980) discovered a washed denudation rock separating the depressions of Aya Lake and Pionerskaya. He also noted fields of large erratic boulders brought by the flood onto the valley slopes nearly as high as the watershed. The discovery of the evorsional origin of a system of depressions at the location of Aya Lake (the so-called Aya depressions) also belongs to Maloletko. His studies of the bathymetry of Aya Lake and the general geomorphologic situation, as well as his original way of thinking, allowed him, despite the general scepticism which was sometimes mingled with irony, to solve correctly the problem of the origin of the Aya Lake depression. Maloletko was not able to interpret properly the appearance of huge water masses that cut through the local watersheds above the Aya depressions and formed the spillways and the evorsional depressions themselves, although the outbursts of collapse-dammed lakes in the mountains, as Maloletko wrote about, are not rare.

In the Altai Mountains, in addition to the Aya depressions, “dry waterfalls” in the central part of the Chulyshman valley at Katuyaryk Urochishtshe also look very impressive. Here, the water surplus moved from Ulagan ice-dammed lake during the Wurm glacial postmaximum. Smaller, but also very effective, diluvial-evorsional forms may be observed on the south-eastern
slope of the Shapshal Range at the lower part of the Chulcha River canyon, at the lower reaches of the Shavla River valley (a tributary of the Chulyshman), and down-stream of the Chagan–Usun River on its right bank in the South-Eastern Altai (Fig. 16).

In Gorny Badakhshan (Western Pamirs) there are very beautiful stepped “dry waterfalls” on the left bank of the Vanch River. They are situated on the opposite side of the end-moraine rampart of the Russian Geography Society (RGS) glacier. Each of the steps of this cascade has a deep (up to 10 m in diameter and up to 10 m deep) round water-forced hollow, which is filled with snowfield melt water. A narrow rocky bulkhead separates each hollow from the step below, which contains the next water filled hollow. This evorsional cascade (“Kujzop depressions”) is separated from the Vanch River channel by a long narrow rocky crest, so it cannot be seen from the river. The origin of this channel and the hollows may be associated with the outburst of an ice-dammed lake at the upper reaches of the Vanch River. The lake development was caused by the shift of the RGS glacier at the beginning of the 20th century (presumably in 1911). The traces of the lake have been clearly preserved as lake terraces which are set against the left-bank edge moraine of the RGS glacier, and as varved “clay” units, which are pressed on a bench to the moraine from its proximal side. It is possible that the “dry waterfalls” of the upper reaches of the Vanch “revived” afterwards as well, when cataclysmic failures of the glacier-dammed Abdukagor Lake occurred (see Table 1).

4. Calculations of the chief hydraulic parameters of the diluvial floods

It was ascertained in general for small sand ripples of river channels that the height and the length of the ridge wave increases with water depth and velocity. However, experiments show that this interconnection is very complicated, though within certain intervals of the dual parameters of the ridges and the flood it may also be a linear dependence, as $B = 4.2D$, where $B$—ridge length
floodstreams from the Late Quaternary Lake Missoula
streams (Table 4). A similar dependent relationship is also given
by Yalin (1972): \( B = 5D \). At a certain critical flood depth
this dependence may become inverse: the deeper the
flood, the lower the dunes, but, probably, the longer the wave
(Kondratiev et al., 1982). The first relationship is
often used to calculate channel processes in Russian
literature, and the second one is used in the western
scientific literature. As Dinehart (1992) notes, Yalin's
rules are quite correct for small gravel channel forms.
However, if we proceed from the given formulas, then if
the length of a flood dune reaches 100 m, the flood depth
should be 20 m. With the depths of hundreds of meters,
which were characteristic of the Quaternary diluvial
floodstreams, we should expect to see quite a different
morphometry of the channel forms of scabland. Thus,
given relationships are of little use for the mesoflows
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should be 20 m. With the depths of hundreds of meters,
dimensions are smaller by at least by two orders than those of the Quaternary lakes (Tables 1 and 2). Nevertheless, when direct measurements of the diluvial floods are impossible, the above-given dependencies give quite comparable results, which may be relied on in the absence of other alternative correct methods of palaeohydraulic calculations.

Discharges were calculated for the diluvial floods at failures of the whole Chuya–Kuray system of the Quaternary ice-dammed lakes according to the data of field and cartography works of the Russian–American expedition of 1991 (Baker et al., 1993; Rudoy and Baker, 1993a, b). The computer program HEC-2 2 (US Army Corps, 1985) was used for hydraulic calculations of the water surface profiles. The calculation procedure was based on the solution of the equation of specific energy, which had been inferred from the equation by Bernoulli for a stable, smoothly changing current. The hydraulic calculations were performed rapidly. The calculations prove that it would have taken only about 10 min at the hydrograph peak considering the figures given above for the total water volume from Chuya–Kuray lakes to pass through the analysed area. Those streams had an extremely high bed shear stress (\(\tau\)), which may be described as: \(\tau = \gamma DS (4);\) \(\omega = \gamma QS/W = \tau V (5)\); where \(\tau\) is the tension of the bed shear; \(\gamma\) the specific water weight; \(S\) the channel gradient; \(Q\) the discharge; \(V\) the mean stream velocity; \(W\) the stream width. The combination of the factors gives a tremendous pressure on a square unit (\(\omega\)).

According to formulas (4) and (5), at the jokulhlaup culminations the flood depths exceeded 400 m, and their velocities varied from 20 to 45 m s\(^{-1}\) (subcritical and supercritical values, correspondingly). The bed shear stress ranged from 5000 nm\(^2\) (subcritical) to 20 000 nm\(^2\) (supercritical), and the flood capacity was, correspondingly, from \(10^2\) to \(10^6\) W m\(^{-2}\).

The laboratory of palaeohydrologic and hydroclimatic analysis of the University of Arizona ascertained that the floodstream from Lake Missoula, with a discharge of \(17 \times 10^6\) m\(^3\) s\(^{-1}\), needed no more than 3 h to develop the main characteristic features of the Channeled Scabland relief of Columbia basin plateau in North America. To perform an adequate amount of work such river as the Mississippi during its high water regime would need at least 30 000 years (Baker et al., 1987). Comparison of the energy of the Quaternary diluvial floods of Southern Siberia with the potential work of, for example, the Ob River will give equally impressive results.

<table>
<thead>
<tr>
<th>Region</th>
<th>North Toutle River, Washington</th>
<th>Medina River, Texas</th>
<th>Columbia Plateau</th>
<th>Altai</th>
</tr>
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<tbody>
<tr>
<td>Date</td>
<td>December 1989</td>
<td>August 1978</td>
<td>Pleistocene</td>
<td></td>
</tr>
<tr>
<td>Wave length, m</td>
<td>6–15</td>
<td>80</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>Wave height, m</td>
<td>0.2</td>
<td>3</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Flood depth, m</td>
<td>1.4</td>
<td>10</td>
<td>100</td>
<td>400–500</td>
</tr>
<tr>
<td>Mean flood Velocity, m s(^{-1})</td>
<td>2.5</td>
<td>3.5</td>
<td>18</td>
<td>32.5</td>
</tr>
<tr>
<td>Bed shear, nm(^2)</td>
<td>100</td>
<td>300</td>
<td>1800</td>
<td>up to 20000</td>
</tr>
<tr>
<td>Flood capacity, W m(^{-2})</td>
<td>250</td>
<td>1000</td>
<td>32000</td>
<td>up to 1000000</td>
</tr>
<tr>
<td>Maximum discharge, m(^3) s(^{-1})</td>
<td>175</td>
<td>7000</td>
<td>10 000 000</td>
<td>over 18 000 000</td>
</tr>
</tbody>
</table>
5. Geochronology

Nowadays there are several trustworthy radiocarbon dates from various parts of the Altai Mountains, from the foothills up to the high-mountain basins. These dates show that the last phenomenal cataclysmic failure of the Chuya–Kuray system of glacier-dammed lakes left giant current ripples in the Kuray and, probably, Yaloman Basins and at the site of Platovo–Podgornoye in the Altai foothills happened not later than 13 000 years ago.

The age of vegetation remnants from lake loamy soil in frost mounds of the Yeshtikkol plateau in the western part of the Kuray Basin is $10845 \pm 80^{14}C$ yr BP (CO AH-2346). Thus, there was no water in that part of the Kuray Basin later than approximately 11 000 years ago. Marlstones and vegetation remnants within the sediments of the North Altai gave numerical dates of $13890 \pm 200$ and $12750 \pm 65^{14}C$ yr BP (CO AH-779). Maloletko (1980) associates these dates with the time of cavity-evorsional depressions of Ai and the carrying of erratic boulders over the foothills of the Altai (Fig. 15). Thus, the last cataclysmic flooding took place in the Katun river valley 13 000 years ago. After that date, the lakes would degrade simultaneously with the degradation of the glaciers that fed them. This does not, of course, exclude their cataclysmic outbursts, but the hydraulics of those failures could not be so great.

Rudoy discovered vegetation remnants in the exposure of a large frost mound (pingo) in the central part of the Chuya intermountain basin. Panishev and Orlova estimated the absolute age of the hold rock according to those remnants as $3810 \pm 105^{14}C$ yr BP (CO AH-2146). There are reasons to think that the frost mounds themselves developed even later, about 2140 years ago (Rudoy, 1988).

river valleys. The main hydraulic parameters of the diluvial floods, which were determined by independent methods for the periglacial plains of North America and Southern Siberian mountains, show that diluvial processes of relief-formation are among the most powerful known exogenous Pleistocene processes. Diluvial processes generated by glaciers transformed glacial and pre-glacial terrains of many regions on the Earth and, probably, on other planets (Rudoy, 1999), and created characteristic landscapes of plain and mountain scablands.

Despite their wide spread presence on all the continents of the Northern and, possibly, the Southern Hemispheres, diluvial-erosional and evorsional forms are still rather poorly studied. Without a complete assortment of the morpholithologic scabland associations, giant current ripple marks ranking first among them, the diagnostics of the destructive diluvial forms is always problematic. The mechanisms of the geologically momentary supererosion, which created the above-described gorges and canyons, are not quite clear. Their geography, especially on the plains, is also under discussion. This latter fact may be partly explained by the fact that the very theory of the diluvial morpholithogenesis has not yet gained its due development in Russia as a methodical palaeogeographical instrument only because some Russian geologists and palaeogeographers still support extreme antiglacial positions.

The social effect of the investigation of the diluvial processes is also obvious. Although the ecology experts and representatives of some non-governmental nature protecting organisations refer to our materials concerning the failures of the huge lakes to find analogies with the consequences of probable seismic deformations of big hydrotechnical constructions on the mountain rivers, cardinal changes in the natural environment over immense areas, which we have already studied rather well on the examples of the Pleistocene glacial superfloods, do not still strike the imagination of those institutions and governments which are responsible for the solution of constructional problems. Even the project of the construction of the Katun hydroelectric power station in the Altai, which has failed to pass the ecology examination many times, judging by the state of affairs, will be realized.

UNESCO declared the last decade of the past century as the decade of natural disaster reduction. With regard to the rapid assimilation of the mountainous territories, it is desirable to consider the role of short-term, but powerful and systematically repeated, processes in estimating the degree of natural risk. Such processes transform during geologic moments things that have been created for thousands of years. The consequences of these processes are more tragic as the disasters are more unexpected.

6. Conclusion

Glacier-dammed lakes in the mountains and on plains developed whenever glaciers grew large enough to block
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