Quaternary glacier-dammed lakes in the mountains of Siberia

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QUATERNARY GLACIER-DAMMED LAKES IN THE MOUNTAINS OF SIBERIA

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Abstract: The authors investigate the phenomenon of lakes dammed by glacier ice in Southern Siberia, and more specifically groups of such lakes in the Altay and Sayan-Tuvian Upland. Hundreds of cubic kilometers of meltwater have accumulated in the largest lakes—Chuya-Kuray, Uymon, Darkhat, and others—at elevations ranging from 1,500 to 2,200 m. The breaching of their ice dams (jökulhlaups) in many cases has resulted in large-scale natural catastrophes, with millions of cubic meters of floodwaters reaching velocities of 20-40 m/s. The paper investigates the frequency and spatial patterns of Siberian jökulhlaups, which are among the most powerful on Earth, and their role in the development of relief, paleohydrology, and the landscapes of Siberia.

INTRODUCTION

Glacier-dammed (periglacial, proglacial) lakes are a characteristic feature of landscapes adjacent to glaciers and icecaps. At the edges of large glacier systems—in Greenland, Central Asia, and Patagonia—there are many hundreds of such lakes (Embleton and King, 1969); in southeastern Alaska alone there are 750 (Post and Mayo, 1971). In the formation of periglacial lakes the principal role is played by ice dams: such dams block access to downstream portions of the valleys and intermontane basins, creating “containers” that are filled by meltwater.

Several morphological types of glacier-dammed lakes can be identified: supra-glacier, sub- or intraglacier, and strictly periglacial. The latter, in turn, are divided into several subtypes that include lakes situated: (a) at the edges of ice sheets; (b) in the principal valleys dammed by glaciers penetrating from side valleys;

1M. G. Grosswald, one of the authors of this paper, recently celebrated his 75th birthday. Grosswald has devoted a considerable part of his creative life to the study of Pleistocene glaciation. He participated in investigations of Cisbaykalia, Sayan, and Tuva; Tien Shan, Taymyr, Kola, and Chukchi peninsulas; northern Yakutia; and Novosibirskiy Islands and has worked in national and foreign expeditions to Franz Josef Land, Spitsbergen, Antarctica, Greenland, and the Canadian Arctic. During the 1960s-1970s Grosswald advanced the idea of a covering glaciation of the continental shelves and the past existence of a gigantic Panarctic glacial cover. He continues to develop this idea, working in different parts of the Arctic.
The principal feature of all the glacier-dammed lakes is their periodic outbursts, so-called jökulhlaups, leading to the complete or partial evacuation of water from the lake basins and flash floods in lower-lying valleys. The principal causes of the jökulhlaups are the low density of the ice in the dams, the light weight of the ice dams (relative to the water), and the low strength (resulting from fracturing of the ice) of the frontal parts of these dams. The outbursts themselves usually occur after the lake levels rise to some critical height, at which time the ice, being in contact with the lake basin, begins to float upward. As a result, the water gains access to the base of the dams, to deep glacier cavities and fractures. This is followed by the onset of seepage, which as the walls of the fractures thaw and are transformed into broader tunnels changes into powerful flows of lake water moving at an exponentially increasing speed (Nye, 1976).

Such outbursts occur quite rapidly: they rarely last more than 15-20 days. But usually no more than 10% of this time is accounted for by periods of maximum discharge. On the other hand, the discharges during the short periods of maximum flow are extremely high, in many cases enormous. For example, during jökulhlaups of the glacier-dammed Lake Mertsbacher in the Tien Shan (volume 0.20 km$^3$) the maximum discharge attains 1,000 m$^3$/s; in dumpings of Lake Tulsequa in British Columbia (0.23 km$^3$), the maximum discharge is almost 1,600 m$^3$/s; in outbursts of Lake Graenalón in Iceland (1.5 km$^3$) it attains up to 5,000 m$^3$/s; and for Lake George in Alaska (1.7 km$^3$) even exceeds 10,000 m$^3$/s (Embleton and King, 1969; Post and Mayo, 1971; Grosswald, 1987). Thus, there is a clear pattern: the larger the lake, the more powerful the jökulhlaup. Large lakes typically not only have greater floodstream discharges, but also great flow velocities, which may exceed 10-15 m/s.

Cases have been observed when, after the onset of seepage of water through the ice dam, the water discharge does not increase smoothly, but suddenly. The entire ice dam is in many cases catastrophically destroyed. In such cases water dumping occurs even more rapidly and discharges of water and its velocities are especially high (Baker et al., 1993).

Outbursts of glacier-dammed lakes located in valleys occur annually and only in exceptional cases once every two to three years. However, the outbursts of lakes associated with large intermontane basins, whose filling requires more time, usually occur less frequently. A general pattern is that with an intensification of glaciation, when glacial dams become thicker, the jökulhlaups become relatively rare, but powerful, but with a decrease in glaciation and a thinning of glaciers they become more frequent, but also weaker. The frequency of jökulhlaups is evidently increasing in the modern era. In Iceland, for example, the intervals between the outbursts of Lake Grims Vöttn during recent years have been reduced from 10 to 5 years; outbursts of another lake, Graenalón, only recently recurring every 4 years, now occur twice as frequently. But the dates of outbursts of lakes emptying annually, with the weakening of glacial dams, are displaced to earlier times: from September to August, from August to July, etc. (Embleton and King, 1969; Nye, 1976).

In eras of global coolings of the past, when the Earth's glaciation expanded, there also was a sharp increase in the total number and size of the periglacial lakes. This is confirmed by factual data for Scandinavia, the Alps, and North and South
America. In particular, gigantic runoff systems linking the Great Lakes, Lakes Agassiz and McConnell, and the valleys of the Mississippi, Hudson, and St. Lawrence developed in the territory of Canada and the United States. Here it was possible to determine the water discharge in flows, their intensification, and reductions associated with diversions of runoff from valley to valley; in addition, the global climatic role of these diversions was assessed (Teller, 1987). It also became clear that the restructurings of the lake systems in many cases assumed the nature of catastrophic outbursts and “floods” (Teller and Thorleifson, 1988).

An extensive literature has been devoted to the Pleistocene-glacier-dammed Lake Missoula. This lake was dammed by a large glacier descending from the cordilleras into the Clark Fork valley of Montana; its level rose to 1,280 m and its volume attained 2,500 km$^3$ (Bretz, 1923; Baker and Bunker, 1985). During the last glacial era Lake Missoula experienced no less than 40 catastrophic outbursts during which its waters were dumped westward into the Spokane-Columbia valley and from there onto the Columbia (basalt) Plateau (Waitt, 1985). Within the latter it is possible to see a complex of forms created by these outbursts: deep canyons with traces of waterfalls and whirlpools, exposed surfaces of basalts from which the cover of unconsolidated deposits has been washed away, boulder-block concentrations in the upper reaches of the valleys (the Columbia River’s tributaries), concentrations of boulders and rubble associated with valley broadenings, and terrain believed to have been created by a gigantic current ripple or pebble dunes characteristic of such broadenings (Bretz, 1923; Baker and Bunker, 1985; Baker et al., 1993; Rudoy and Baker, 1993).

The entire geomorphological complex associated with the Missoula outbursts, since the time when Bretz (1923) first discovered them, has been called the “channeled scabland” or simply “scabland,” which means an area dissected by canyons and covered by erosional “scars.” A special analysis of the morphometry of the complex led to the conclusion that the depths of the floodstreams here were hundreds of meters, their velocities exceeded 20 m/s, and the water discharges in them attained 2-3, and sometimes even 10-15 million m$^3$/s, that is, by many tens of times exceeded the maximum discharges of the Amazon (Baker and Bunker, 1985).

Nothing similar is known to have occurred in Northern Eurasia. Up to the mid-1970s we knew nothing either about the gigantic fresh-water basins arising at the southern edge of the Eurasian ice sheet or about the glacier-dammed lakes of the mountainous belt of Central Asia and southern and eastern Siberia. Suffice it to mention that even in the three-volume monograph entitled The Quaternary, published in the 1960s by K. K. Markov et al., all the information on the periglacial lakes of Eurasia was presented on a single page and applied only to a Baltic glacial lake.

Now the situation has changed. After the studies of D. D. Kvasov, S. A. Arkhipov, I. A. Volkov, and others it has become clear that the glaciations of the plains of Eurasia were accompanied by major restructurings of the hydrographic network, in particular by the formation of numerous lake basins and meltwater runoff systems. Information on the glacier-dammed lakes of mountainous regions also is multiplying. This article is devoted precisely to their description.

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2See the review in Grosswald (1989).
The Altay and Sayan became the first mountain region in Northern Eurasia in which it was possible to detect traces of glacier-dammed lakes and to assess their hydrologic parameters (Rudoy, 1984, 1990; Butvilovskiy, 1985; Grosswald, 1987). The geography of the ancient lakes was clarified (Fig. 1) and their areas and volumes were ascertained; an idea was obtained concerning the paths taken by water masses during outbursts, on probable discharges and velocities of the floodstreams, and on their geomorphological effect. In a more general way, it was possible to show that glaciations of mountainous regions having, like the Altay and Sayan, a basin and range topography, were inevitably accompanied by the formation of large ice-dammed basins. Being situated at great elevations, these basins have enormous energy reserves and their outbreaks must play an appreciable role in relief formation, especially with respect to the valley network of the mountains and foothills of southern Siberia.

Altay Mountains

In the Gornyy Altay, in the valleys of the Katun, Chuya, Biya, Bashkaus, and Chulyshman rivers, traces of catastrophic outbursts of ancient lakes became evident only in the 1980s. It is true that G. F. Lungershausen, O. A. Rakovets, and L. N. Ivanovskiy even earlier had indicated the probable relationship between individual valley forms of the Altay and especially powerful flows (Rudoy, 1995), but they did not go beyond this. Specific data could be obtained much later when special investigations of Quaternary glacier-dammed lakes and their outbursts were initiated. In the initial stage of this research, the results of which are presented in the works of Butvilovskiy (1985, 1993) and Rudoy (1984, 1989, 1990), the geography of such lakes and paths of dumping of lake waters were explained, geological traces of the outbursts were detected, and the first calculations of the discharges of floodstreams were made. In the second stage of research, beginning in the 1990s, emphasis was on study of the paleohydrology of jökulhlaups. Participating in this work were specialists from the United States and Great Britain, especially V. Baker and P. Carling, having experience in the analysis of such phenomena in other regions of the world and having at their command special methods for determining the hydraulic parameters of the floodstreams (Rudoy, 1993, 1995; Baker et al., 1993).

All of the largest Late Pleistocene glacier-dammed lakes of the Gornyy Altay (Fig. 2) belonged to the basin type. Such lakes as the Chuya, Kuray, Uymon, Yaloman, Abay, and Dzhasaterskoye, and groups of lakes—the Ulagan, Kansk, and Teletskoye groups—were located in the Chuya, Kuray, Uymon, etc., intermontane basins. The valleys of the Biya, Katun’, Chuya, Chulyshman, and certain other rivers played the role of troughs along which the lake waters were emptied.

For most basins the existence of ancient lakes was established from the presence of such indisputable traces as terraces, wave-cut notches, canyonlike channels through which lake waters were dumped, and silt to fine-sand sediments with a horizontal, sometimes varved, stratification. In some cases from the horizontal
Fig. 1. The Altay-Sayan mountain region and southern parts of the Ob' and Yenisey basins. The rectangles correspond to the regions depicted in Figures 2 and 3.

pattern and the heights of the shorelines it was possible to ascertain the areas and levels of ancient lakes and to calculate their volumes. For example, judging from the position of the upper terrace, the level of Lake Tuzharskoye, included in the group of the Ulagan lakes, reached 1,475 m. The total volume of the lakes of this group, arising as a result of the damming of the Kubadra and Bol'shoy Ulagan rivers by the ice of the Bashkaus Glacier, was 20 km$^3$ (Butvilovskiy, 1985). The water level of Lake Chuya rose to 2,200 m (Rudoy et al., 1989), the area of the lakes of the entire Chuya-Kuray system reached up to 10,000 km$^2$, and the water volume attained up to 1,000 km$^3$ or more.

The total area of the lakes shown in Figure 2 attained 25,000 km$^2$ and their water volume attained 5,000-6,000 km$^3$ (if it is assumed that the maximum lake levels coincided with the highest shorelines of the basins). However, judging from the elevations of the discharge channels emanating from the basins and cutting the passes, these levels were 100-200 m higher. For example, the channels leading from the Chuya and Kuray basins into the Chagan-Uzun and Bashkaus basins lie at absolute elevations greater than 2,400 m; it therefore follows that the volumes of the Chuya-Kuray lake system could attain 3,500 km$^3$. They therefore considerably exceeded the maximum volume of the glacier-dammed Lake Missoula, which, as already mentioned, was no greater than 2,500 km$^3$ (Baker and Bunker, 1985).

The limits of the glaciation, depicted in Figure 2, do not reflect the conditions prevailing at the glacial maximum, but during one of the deglaciation stages. It was established, for example, that the Kuray and Chuya ice-dammed lakes arose...
and attained their highest levels only after the onset of deterioration of glaciation (Rudoy et al., 1989). The glacial dams of this stage, reconstructed from the corresponding moraines, were relatively small, so that their further lowering meant a rapid degradation of the lakes: first the sharp reduction in their water volume, and then also complete elimination. The absolute age of the lake stages can be judged by $^{14}$C datings. The last outburst of the Chuya-Kuray lake system, after which the ice dam was no longer restored, occurred about 13,000 years B.P. (Baryshnikov, 1992). Later, 12,000-13,000 years B.P., the remaining glacier lake systems of the Altay also must have been degraded. Thus, the lake stage depicted in Figure 2 dates back no more than 14,000 years.

It is difficult to judge the size and levels of the more ancient lakes because the shores were for the most part of ice and most of the shore forms disappeared together with the ice. If one judges from the elevations of the already mentioned dis-
charge channels, the glacier lakes of the earlier deglaciation stages had higher levels. And still earlier, about 20,000 years B.P., the Altay glaciers attained their last maximum, forming a virtually continuous cover. Thus, conditions arose under which the intermontane depressions were entirely filled with ice, leaving no room for water basins.

In actuality, the lowering of the boundary of glacier alimentation here attained 1,200-1,300 m (Vardanyants, 1938), so that the northern edge of the Altay glacier complex reached the boundary that is shown in Figure 2; it follows from this figure than 14,000 years ago this edge shifted southward by 50-150 km. Such an estimate of the scales of the last Altay glaciation follows from a comparison of the elevation of the peaks of its ranges and the elevations of the ancient alimentation boundary. Some geologists—V. P. Nekhoroshev, A. I. Moskvitin, and others—also wrote about the same subject much earlier. According to their concepts, based on geological-geomorphological data, the Altay glaciation was semicovering and the intermontane basins were replaced by the appearance of “ice bodies,” that is, especially thick ice concentrations, becoming independent centers of ice outflow. Among the probable ice basins were the Chuya, Kuray, Uymon, Dzhulukul’, and most other basins.

The ice-bodies hypothesis appears plausible, although it is still regarded as debatable. By no means in every one of the basins mentioned above is it possible to detect traces of filling with ice; in some cases they contain no glacial deposits, i.e., moraines, eskers, or kames. However, this does not mean that they remained ice-free. Instead it is rather a matter of the special features of their paleohydrology. The fact is that the ice bodies did not arise in “dry” basins, but in places where there had been lakes that should have existed here in the early glaciation stages. This means that the ice, spreading and filling the basins, first was held afloat and then formed an ice “roof” over the lakes, transforming them into closed water lenses similar to Lake Vostok beneath the ice in Antarctica. In this regard, one of the authors deemed it possible to assign the ice bodies of the Altay to a special type, proposing the name “encrustation” for them (Rudoy, 1990). These were complex systems consisting of under-ice lakes and overlying strata of lacustrine, encrustation, and glacier ice. The lake sediments, lying on the basin floors, sometimes served as the bases of eskers; in other cases they bear distinct evidence of post-sedimentation compaction.

Thus, during the period of the glacial maximum, strictly ice-dammed lakes could exist only in the marginal parts of the Altay glacial complex. However, at that time only lakes of the under-ice type could develop in the internal basins. Therefore, the lakes indicated in Figure 2 were confined only to one of the late glacial stages, when the intermontane basins were freed of ice, giving rise to conditions for the transformation of ice bodies into water bodies.

**Sayan-Tuvian Upland**

In the Sayan and Tuva ranges, the glaciation was also accompanied by the formation of large glacier-dammed lakes. For the time being most remain unstudied. Only the Quaternary Darkhat Lake, periodically forming in the
Darkhat Basin of northern Mongolia (Fig. 3A), can be considered “known” to any extent.

The Darkhat Basin is a narrow intermontane depression in the southern part of the Sayan-Tuvan Upland. On the west, north, and east it is bounded by ranges with elevations of approximately 3,000 m, but on the south is separated from the Selenga-Muren basin by an interfluve ridge with minimum elevations of roughly 2,000 m. The average elevations of the basin floor are close to 1,570 m.

According to data published by A. I. Spirkin (1970), the basin contains clear traces of an extensive water body: systems of abrasional terraces and shorelines, lake sediments, and relict lakes. Terraces and shorelines were worked in the lower parts of the basin slopes—they form staircases of horizontal steps, whose number attains 25, and the uppermost lies at an elevation of 1,720 m. The surfaces of the terraces are from 30 to 60 m in width and are tilted toward the center of the basin at angles of 5 to 10°; their cliffs have heights of 3 to 4 m and slopes of 10 to 30°. Lake deposits are rarely encountered here; they are represented by horizontally layered sandy loams and fine sands, less frequently by gravel. The bottom of the Basin was formed by two terraces: lower, at an absolute elevation of 1,550 m, consisting of
varved sandy loams, and higher (sandy), having elevations from 1,560 to 1,600 m. The area of Lake Darkhat at the 1,720-m level was 2,600 km² and its water volume exceeded 250 km³, that is, was approximately equal to the mean annual runoff of the Volga.

Lake Darkhat was glacier dammed: the valley of the Shishkhid-Göl River, flowing from the basin, was blocked by concentrations of moraine whose thickness sometimes amounts to 200 m. The good preservation of glacial forms in the valley indicates that they are associated with the last glaciation. This conclusion also was drawn by Spirkin; he cites the morphological freshness of the moraines and lake shorelines, the finding of the bones and teeth of Late Quaternary rodents in their sediments, as well as the fact that the lake shorelines have not been affected by neotectonic movements. In addition, according to his observations, these deposits have been replaced in facies by fluvial-glacial pebble beds associated with the last glaciation of the surrounding mountains.

The Shishkhid Glacier can be seen on the paleoglaciological map and profile (Fig. 3). In this glacier there is a concentration of ice moving from the south and north, following the trough of the Busin-Göl and ten other meridional valleys. One end of the glacier moved westward, downward along the Shishkhid-Göl–Kyzyl–Khem, and the other, eastward, damming the Darkhat Basin. Its greatest thickness, where the lake attained the 1,720-m level (thereby retaining a capacity for periodic outbursts), was computed using the formula of Nye (1976) and was 430 m. Judging from the profile, the difference in elevation between Lakes Darkhat and Kyzyl (distance 350 km) was no less than 1,100 m. Hence the average slope of the channel was 3/1,000, but in the upper half of the profile was 5/1,000.

Lake growth in the basin must have continued, with interruptions, throughout the Pleistocene, as is confirmed by the stratigraphy of its bottom sediments. The interruptions must have occurred during the interglacial period, and also, possibly, in eras of glacial maxima. For example, according to the data of Osadchiy (pers. comm.), during the most recent such maxima, the Darkhat Basin was entirely filled with ice. At this time, as in the Chuya and Kuray basins, all the lake terraces formed on the basin slopes could only be late glacial.

For the time being it is impossible to say anything definite concerning the periglacial lakes of the Sayan. They evidently arose in the valleys of the tributaries of the Ka-Khem, where accumulations of varved clays are known, as well as in the western part of the Todzhinsk (Todzha) Depression (Eastern Tuva) and in the Upper Yenisey-Khemchik valley, directly above the Yenisey "tube." The latter—Verkhneyeniseyskoye Lake, dammed by the glaciers of the Western Sayan, was mentioned by Butvilovskiy (1993). Its existence seems possible, although for the time being it has not been confirmed by facts.

SIBERIAN JÖKULHLAUPS AND THEIR EFFECTS

Catastrophic outbursts (jökulhlaups) constitute the principal feature of the hydrological regime of glacier-dammed lakes. However, such outbursts may not occur if the ice dams are especially thick. In such cases, the increase in levels of the dammed lakes, always limited by the elevations of the surrounding passes, does not attain the critical levels necessary for an outburst. Precisely for this reason the
jökulhlaups are more typical of stages of decreasing glaciation and thinning of ice than for the periods of glacial maxima.

Reconstruction of Past Outbursts

Facts regarding past outbursts are established by two methods: (1) on the basis of water-balance calculations—from the ratio of the volumes of lake basins and the time of their filling; (2) from the geomorphological traces of jökulhlaups preserved in the lower-lying valleys. For example, comparison of the calculated volume of meltwater runoff from the Late Quaternary glaciers surrounding the Chuya and Kuray depressions (8.8 to 8.5 km$^3$/year) with the water volumes in the lakes of the same names made it possible to conclude that the filling of the former (Chuya) to the 2,200-m level required no more than 100 years, whereas the filling of the latter (Kuray) required no more than 30 to 35 years (Rudoy et al., 1989). Similar calculations for Lake Darkhat and its basin indicated that the time required for their filling to the level of 1,720 m, that is, to the level of the upper shoreline, was 100 to 130 years (Grosswald, 1987).

Thus, the filling of the dammed lakes of the Altay and Sayan occurred during time intervals that were many tens of times shorter than the last glacial epoch. Nevertheless, the rise of their levels stopped at the aforementioned levels and did not continue to the elevations of the nearest passes. It is evident that these levels were critical breaking points; after these were attained, the process of lake filling was interrupted, being replaced by the stage of their sudden emptying. The conditions for such a change in regimes are illustrated by the profile in Figure 3B.

At lake level L, the calculated depth (B) of some basin in which the entire glacier could float like an iceberg is greater than the depth of the Kyzyl-Khem, so that in the sector MN the ice laid on the bed and the lake basin remained tightly blocked. On the other hand, at level L', when the depth of this same basin was reduced to B' and the segment MN was reduced almost to a point, the hydrostatic pressure of the water was adequate for the ice to begin to float. The water began to seep through the glacier, which very rapidly experienced a catastrophic outburst—a jökulhlaup.

As already mentioned, modern jökulhlaups occur very rapidly, they rarely last more than 15 to 20 days, and the periods with maximum floodstream discharges last only hours. The gigantic Quaternary lakes also emptied very rapidly, so that the flows bursting from them had truly enormous water discharges. The latter can be calculated. One of the calculation methods was proposed by Clague and Mathews (1973); it relies on the empirical relationship between maximum discharges and the total volumes of dumped water, which was determined for modern lakes. This method was used to obtain the following discharges of the Quaternary floodstreams of the Altay and Sayan: the valley of the Bashkaus below Lake Tuzharskoye—about 100,000 m$^3$/s; of the Katun' below Kuray Lake—up to 1 million km$^3$/s; and of the Kyzyl-Khem and Ka-Khem below Darkhat Lake—up to 400,000 m$^3$/s (Rudoy, 1984, 1989; Grosswald, 1987). The current velocities of the floodstreams must have attained, and in some cases exceeded, 15 to 20 m/s. Later, it is true, it was clarified that for the case of flows bursting from the largest Quaternary lakes, this method yields understated values (Baker et al., 1993; Rudoy and Baker, 1993; Rudoy, 1995).
The more modern methods, elaborated by Baker and his colleagues, use data on the water surface slopes of the floodstreams, the height of the high waters, the size of the bouldery-pebbly material in the channels, and the morphometry of channel forms, in particular, of the gigantic current ripple. It is true that the first calculations of the discharges of jökulhlaups associated with the emptying of Lake Missoula were made by Baker using the Chezy and Manning formulas, which are well known in hydrology. The discharges obtained in these calculations were enormous: they varied from 2 to 10 million m$^3$/s. However, these formulas require introduction of a channel roughness coefficient that is virtually impossible to determine, so that these results seemed questionable to many. Later Baker et al. (1993) used a new method based on the empirical relationship between the depths and velocities of the outburst flows, on the one hand, and the morphometry (height of ridges and mean wavelength) of the gigantic current ripple, on the other. It was established in this way that the maximum water discharges in the flows generated by the Missoula jökulhlaups may have reached 16 to 17 million m$^3$/s.

Applying this method to an investigation of the Quaternary jökulhlaups of the Altay, A. N. Rudoy (1984) demonstrated that in the Platovo area, located where the Katun' emerges onto the northern piedmont, the floodstream velocities reached 14 m/s, the water depth 40 m, and discharges up to 560,000 m$^3$/s or more. However, Platovo is almost 300 km distant from the ice-dammed lakes; the flow here was spread out and its depths and velocities fell. Higher in the mountains these quantities increased. For example, at the exit from from Lake Yaloman the depths of the flow were greater than 400 m; its velocities reached 30 m/s, and water discharges exceeded 1 million m$^3$/s. In the Kuray Depression, gigantic ripple indicators were formed at a depth of 80 to 100 m (although its greatest values were 400 m greater) with a water current velocity of 12 m/s and flow discharges from 0.2 to 1.8 million m$^3$/s (pers. comm., P. Carling, 1994).

Judging from the data obtained by the Russian-American expedition of 1991, the greatest velocities and discharges were observed in the Chuya valley during catastrophic outbursts of the entire Chuya-Kuray lake system. Using the HEC-2 computer program (Feldman, 1981) for ascertaining the energy of the floodstreams from the Bernoulli equation for a stable gradually changing current, it was possible to obtain the profiles and velocities of the Chuya floodstream. Judging from modeling data, this floodstream consisted of two sectors with different hydraulics — upper, where the flow was relatively broad and its flow was subcritical, and lower, coinciding with a narrow canyon in which the flow acquired supercritical velocities. In the latter the flow depth was 400 m and its peak discharges attained 18 million m$^3$/s (Baker et al., 1993). This quantity exceeds the maximum discharges of the Missoula “floods,” which until recently were considered to be the most powerful floodstreams on the Earth.

We emphasize that the peak parameters cited above were not characteristic for any outburst of the Missolula or the Chuya-Kuray lake system, but only for those that followed the sudden destruction of ice dams. Precisely such catastrophes were accompanied by superpowerful jökulhlaups, accompanied by record flow velocities and discharges. In the Altay, these records included flow depths as great as 400-500 m, velocities from 20 m/s in subcritical sectors to 45 m/s in supercritical sectors, shear at the bottom ranging from 5,000 n/m$^2$ in subcritical sectors to
20,000 n/m² in supercritical ones, and flow intensities varying from hundreds of thousands of W/m² in the former to millions of W/m² in the latter (Baker et al., 1993). It can scarcely be doubted that in the event that sudden collapses also befell the Shishkhid Glacier, the discharges of Sayan floodstreams also increased to quantities exceeding 1 million m³/s.

Another, more common mechanism for the emptying of glacier-dammed lakes is the tunnel mechanism (Nye, 1976), which is not as rapid or catastrophic. In the Altay, the floodstream discharges associated with the tunnel mechanism did not exceed 1 million m³/s, and their velocities remained subcritical; in the Sayan such discharges probably were lower still. In some cases, the different outburst mechanisms alternated in the “biographies” of the very same lakes, whereas in other cases the lakes gravitated to one of the two groups: either to those characterized by the predominance of catastrophic outbursts, or to those with a predominance of calmer discharges of water through gradually expanding intra-ice tunnels.

The great discharges and velocities of the floodstreams determine their capacity for performing enormous erosional and transport work. This follows from known formulas, according to which solid runoff and the intensity of erosion are proportional to the square of the discharge of channel flows and the cube of their velocity. This is indicated by the geomorphology of valleys experiencing the impacts of jökulhlaups. Since the scales of the catastrophic floods associated with the celebrated Lake Missoula and with the glacier-dammed lakes of southern Siberia are so close, their geomorphological effects undoubtedly also were commensurable. Since the Missoula floodstreams gave rise to enormous complexes of erosional and accumulative scabland forms (Bretz, 1923; Embleton and King, 1969; Rudoy and Baker, 1993), we had reason to expect that geomorphological landscapes of this same type also would be discovered in Siberia (Grosswald, 1989).

Types of Scabland Landscapes

Now scabland landscapes are already known in southern Siberia. They were studied in the Altay by one of the authors where he discriminated a special “diluvial” type of morpholithogenesis (Rudoy, 1995). According to Rudoy, all the landforms of the Siberian scablands can be grouped into several subtypes, the most important of which are diluvial-erosional, diluvial-evorsional (pothole erosion), and diluvial-accumulative.

Diluvial-erosional subtype. The first subtype, diluvial-erosional, is represented by complexes of deep canyons, splash valleys, canyonlike spillways, erosional scarps and remainants. In North America, in the Columbia Basin, these are primarily small canyons incised 100-150 m into the basaltic plateau. In the Altay, such canyons for the time being are known only in the central part of the Chagan River Basin, serving as a channel for discharge of waters of the adjacent Lake Ak-Kol’. Here a system of branching channels, bent in the horizontal plane, which are incised 50-70 m into the bedrock, was discovered. In the Eastern Sayan,
the deep Kyzyl-Khem canyon, cutting through a thick stratum of Quaternary basalts in addition to granites and metamorphic rocks, is assigned to this subtype (Fig. 4). In the Altay and Sayan we assign to this subtype the main valleys, worked by floodstreams, which are here overdeepened, are virtually devoid of clastic material, and which have been straightened because of the truncation of lateral spurs and alluvial fans. This type includes “blind” canyons—spillways abutting onto mountain passes, as well as “splash canyons.” The latter arose in those sectors of floodstreams where their water mass did not fit within their own valleys and the water was thrust into adjacent valleys, forming turbulent currents eroding the interfluves between adjacent valleys. In addition to hanging canyons, specific depositional forms also developed. Their position (high on the slopes and interfluves) and composition (erratic boulders, in many cases extremely large and weighing tens or hundreds of tons) are almost beyond belief.

Diluvial-evorsional subtype. The second subtype, diluvial-evorsional, is closely related to the first. It includes enormous (with a diameter of hundreds and a depth of tens of meters) water-cut depressions, sinkholes, and potholes. Formed by evorsional or boring processes, these forms are traces of waterfalls and whirlpools. Judging from experimental laboratory data, the evorsion of bedrocks by floodstreams, especially in sectors with supercritical current velocities, could occur unusually rapidly. The reason for this is connected with the cavitational destruction of rocks, occurring at the contact between the bed and the water flow, most likely with an “explosive” air-water mixture. The Ayskiye Lakes of the Katun’ valley serve as examples of diluvial-evorsional depressions, now filled with water. However, most such forms presently are devoid of water. An example
forms created by diluvial accumulation. High 240-m terraces of the Katun' River at the village of Inya in the Gornyy Altay. In the foreground is a field of erratic blocks transported by floodstreams (figure prepared by M. Grosswald, based on a photograph taken by A. Rudoy).

Of these are the picturesque "dry waterfalls" of the Chulyshman valley, especially the Katuyaryk area, into which water from the Ulagan Lakes was discharged.

Diluvial-accumulative subtype. Forms belonging to the third (diluvial-accumulative) subtype are of special interest. These, in particular, include diluvial terraces and the gigantic current ripples that are present in all the main runoff valleys from the glacier dammed lakes. It is relatively easy to use them to calculate the hydraulic parameters of the ancient floodstreams. In the Altay these forms are beautifully expressed in the lower course of the Chuya, in the middle and lower courses of the Katun' (Fig. 5), and in Eastern Tuva—in the lower course of the Kakhem River and on the floor of the Tuva Basin. In both places they consist of thick strata of layered, well-washed pebbly to gravelly deposits, which include thin intercalations of sands and sandy loams, as well as angular fragments of rocks of mixed composition, including their blocks. Such strata accumulated in places of the reduction of the energy of the floodstreams, e.g., in valley broadenings and in sectors of return flow after valley inversions or on the sheltered side of buttresses (large obstructions). The clastic material was transported here primarily in a suspended state and therefore was virtually not rounded or otherwise smoothed by the running water.

In most cases diluvial terraces are morphologically fresh forms with clearly defined brows and distinctly expressed scarps. The terrace surfaces in general are tilted toward the bedrock edges of the valleys, complicated by isometric swales that mark the places of former whirlpools or buried ice blocks; the terrace brows in many cases are highlighted by levees. The accumulative bodies of the terraces block the valleys of the tributaries, which entering into them, are rapidly wedged out. The terraces attain their maximum elevations, close to 240 m, in the middle course of the Katun' at the village of Inya (see Fig. 5), where they have been known for over 150 years. The height of the terraces decreases in the direction of the foothills; their elevations at first decline to ~100 m, and then, at Gorno-Altaysk, to 60 m.
Gigantic current ripples are quite typical for the surfaces of such terraces. They can be likened to the sand ripple of river bars if all of the elements of the latter were increased by two to three orders of magnitude and the sand was replaced by a boulder-pebble mass. Like a river ripple, current ripples form long asymmetric ridges with a cross-valley orientation. The average heights of these ridges are 7 to 10 m and the lengths of the “waves” are 80 to 100 m (Embleton and King, 1969; Baker and Bunker, 1985).

In Russia the first region where relief of this type was discovered was the Altay. This discovery, associated with the names of G. F. Lungershausen and O. A. Rakovets, was made in the late 1950s. Later, in the 1980s, the fields of gigantic current ripples attracted the attention of V. V. Butvilovskiy, A. N. Rudoy, and others; these forms, in fact, became the first evidence in support of the possibility of Quaternary jökulhlaups of the Altay and their possible role in the formation of Altay valleys. Here, as in the Sayan, the individual ripple indicators are similar to bakhans and are joined into slightly sinuous ridges; the interridge troughs in many cases are separated by partitions, so that the ridged relief undergoes a transition into a reticular-cellular pattern, similar to fish scales (Fig. 6). The ridges have an asymmetric profile: their convex slopes, turned downstream, dip at angles of 15 to 20°, whereas the steepness of the opposite slopes rarely exceeds 3 to 5°. The length of the ridges varies from 100 m to 3 km, with a width ranging from 3-5 to 100 m and a relative elevation of 1-10 m. Along the right bank of the Tete River (Kuray Basin), the lengths of the waves reach 200 m and the elevations of the ridges locally exceed 15 m, which are of record size.

The terraces, whose surfaces are complicated by a gigantic current ripple, consist of thick strata of pebbly-boulder material with a small admixture of coarse-grained sands. The material is usually rounded and has a diagonal bedding that in general is consistent with the dip of the distal (steep) ridge slopes. No glaciotectonic dislocations were detected in the terraces (Baker and Bunker, 1985; Grosswald, 1987; Rudoy and Baker, 1993; Rudoy, 1995). It is clear that both the accumulation of clastic strata and the formation of the ripple are effects of specific fluvial processes accompanying outbursts of glacier-dammed lakes. As already has been mentioned, using the morphometry of the ripple indicators it is possible to determine the hydraulic parameters of the floodstreams (Feldman, 1981; Baker et al., 1993), and on the basis of their orientation to reconstruct the directions of the former currents. In the Kuray Basin, for example, it was possible to reconstruct a cyclonic circulation with a radius of 8 km (Rudoy, 1995); together with the principal, longitudinal paleocurrent, it can serve as a (mirror-image) model of present-day circulation in the Arctic Basin.

**Effects of Jökulhlaups on Paleohydrology**

The probable effects of the considered jökulhlaups for the paleohydrology of the plains lakes of Western and Central Siberia (Grosswald, 1989) are of special interest. Already the very fact that the Quaternary lake system of northern Eurasia consists of two levels—i.e., upper (mountain) and lower (plains) subsystems—suggests the inevitability of powerful dynamic interactions among lakes at different levels. What specific hydraulic impacts did the plains lakes sustain as a result of the outbursts
of mountain lakes high in their drainage basins? What happened to the Yenisey and Mansiysk lakes, when water masses having velocities of 60 to 80 km/hour and volumes commensurable with the annual runoff of the Volga burst into them? These questions for the time being have not been addressed by specialists. However, it can scarcely be doubted that such catastrophes, repeated at intervals of several decades, had quite significant hydrological and ecological consequences. In the plains lakes they caused powerful turbulence bursts, sudden rises of levels, warping of water surfaces, and the appearance of gigantic waves similar to tsunamis. This means that there was washing and reworking of bottom sediments, destruction of shoreline
terraces, and “run up” of lakes onto the adjacent interfluves, leaving behind pile-ups of lake ice.

Thus, in the Altay and Eastern Sayan, and specifically in the valleys of the Biya, Katun', Chulyshman, Bashkau, Chuya, Kyzyl-Khem, Ka-Khem, and the lower-lying Upper Yenisey, there are indisputable traces of jökulhlaups.

CONCLUSIONS

All Siberian mountains experienced Quaternary glaciations. These glaciations were repeated and exceedingly thick; judging from the maps compiled for the Atlas of Snow and Ice Resources of the World, they had the morphology of true icecaps or large reticular systems. In combination with the mountain-basin relief of the Siberian uplands, the glaciations created ideal conditions for the appearance of large dammed lakes. It is evident that a direct relationship existed between the sizes of the glaciers and the dammed lakes—the larger the glacier, the more grandiose the lake associated with it, and the greater the volume of the lake, the more powerful the water flows arising during its catastrophic outbursts, and the more extensive the geomorphological and hydrological consequences.

The material presented in this paper applies to the Altay and Sayan. However, it is clear that the aforementioned processes must have been involved in the development of the relief and paleohydrography of many other regions in Siberia. Gigantic systems of dammed lakes appeared, in particular, during the glaciation of the mountains of Cisbaykalia and Transbaykalia; traces of these lakes are known to exist in the valleys of the Vitim, Selenga, Upper Angara, Chara, and Kirenga rivers (Bazarov, 1986; Osadchiy, 1995). According to our reconstructions (Grosswald and Kuhle, 1994), even the mighty Lake Baykal was periodically “blocked” by glaciers. In establishing this fact we could, for the first time without resorting to neotectonic hypotheses, also explain the sharp variations in lake level and shifts of Lake Baykal's runoff into the Lena drainage system, as well as the special morphological features of the valleys of the Angara and Lena.

Issyk-Kul', one of the world's largest mountain lakes in Kyrgyzstan, also underwent a similar metamorphosis during the glacial period. The famed “paleogeographic mystery” of the lake can be explained by an examination of the true scales of glaciation in the Issyk-Kul' region, which demonstrate that Issyk Kul' was dammed by ice. This glacier dam explains the ancient lake levels and terraces of Issyk-Kul'; the jökulhlaup outbursts associated with the lake explain the origin of the Boomskoye Canyon and the clastic strata lining the bottom of the Chuya Depression in Kyrgyzstan (Grosswald et al., 1994).

The glacier-dammed lakes and the effects of their outbursts are nevertheless little known to physical geographers, geomorphologists, and hydrologists. We hope that this article may broaden their horizons. At the same time it will provide an additional tool for geomorphological and paleoecological analysis, which in the Siberian context certainly will be useful. We take the liberty to offer the following suggestion: seek traces of ice-dammed lakes and jökulhlaups, search for gigantic current ripples, and many new insights into long-standing problems will emerge. Diluvial formations are developed far more extensively than many of us think and in order to find them only one thing is necessary—a knowledge of
precisely what must be sought. Bretz, the first to discover the Missoula "floods," did not imagine that a gigantic current ripple existed; although he spent years on the study of the scabland, he nowhere detected these forms. On the other hand, learning about them from others, he rushed into the field and discovered a current ripple, not just in one, but in 40 different locations.

LITERATURE


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