Quaternary paleolake formation and cataclysmic flooding along the upper Yenisei River

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ABSTRACT

A suite of geomorphological and sedimentological features in the catchment of the upper Yenisei River in the Sayan mountains of southern Siberia testifies to the occurrence of cataclysmic floods that flowed down the river. Evidence of large-scale high-energy flood events includes: 1) gravel dunes, up to a few meters high and spaced 50 to 80 m apart, in the Kyzyl Basin 2) landforms such as hanging valleys and paleochannels and 3) flood sediments in a tributary valley. The origins of the Yenisei floods were likely diverse due to complex hydrological processes operating in the Sayan mountains. The possibilities include failures of multiple, variably impounded (ice, sedimentary, tectonic scarp, and lava flow dams) paleolakes in the two large intermontane basins of Darkhadyn Khotgor and Todza, and other minor basins, in the upper Yenisei River catchment. Dating techniques applied to the paleolakes in the Darkhadyn Khotgor and Todza basins revealed their formation during various periods in the middle–late Pleistocene and Holocene. Flooding from the Darkhadyn Khotgor appears to explain many of the inferred flood features, although contributions by flooding from other paleolake basins cannot be ruled out. Computer simulation of the flooding caused by a Darkhadyn Khotgor paleolake ice-dam failure indicates a probable peak discharge of ~3.5×10⁶ m³ s⁻¹, approximately one-fifth that of the floods that formed the Channeled Scabland in the U.S.A. Many of the outburst events probably occurred in the late Quaternary, but earlier floods could also have occurred.

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1. Introduction

Cataclysmic floods drastically alter landscapes on geologically instantaneous time scales of hours to weeks. The best-known example may be the floods that created the Channeled Scabland (e.g., Bretz, 1928; Baker, 1973) in eastern Washington State, U.S.A. It has been proposed that the Channeled Scabland, characterized by a variety of gigantic erosional and depositional landforms over a loess–basalt complex, was formed by repeated outbursts of glacier-dammed Lake Missoula at the end of the Pleistocene (e.g., Baker and Bunker, 1985), although more recently a sub-ice reservoir has been suggested as an additional source (Shaw et al., 1999). Such events are not limited to North America and evidence for late-Pleistocene cataclysmic floods in Northern Eurasia has been discovered or proposed, including floods following the failures of ice-dammed lakes in the Altai mountains (Table 1) (Baker et al., 1993; Rudy and Baker, 1993; Carling et al., 2002; Reuther et al., 2006). Cataclysmic floods may have occurred also down some of the spillways connecting ice-dammed Lake Mansi and the paleo-Aral, Caspian and Black seas (Komatsu and Baker, 2007), and

Table 1

Explanation of some geographic terms used in this paper

<table>
<thead>
<tr>
<th>Geographical terms</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>aimag</td>
<td>“province” in Mongolia</td>
</tr>
<tr>
<td>Altai</td>
<td>“mountains of gold” in the Mongolian language</td>
</tr>
<tr>
<td>gol</td>
<td>“river” in the Mongolian language</td>
</tr>
<tr>
<td>khem</td>
<td>“river” in the modern Tuvan language, but means also “Yenisei”</td>
</tr>
<tr>
<td>khotgor</td>
<td>“basin” in the Mongolian language</td>
</tr>
<tr>
<td>kol</td>
<td>Turkic word meaning “river” or “valley”</td>
</tr>
<tr>
<td>nuur</td>
<td>“lake” in the Mongolian language</td>
</tr>
<tr>
<td>Sayan</td>
<td>mountain range on the Russia–Mongolia border</td>
</tr>
<tr>
<td>urotchischche</td>
<td>an area with atypical relief and/or soils” in the Russian language</td>
</tr>
</tbody>
</table>

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down the English Channel (Gupta et al., 2007). These flood events comprise an important component of a major river reorganization that operated over Northern Eurasia during the greatly fluctuating Quaternary climatic regimes.

Geomorphological indicators characteristic of cataclysmic floods in intermontane settings comprise features formed by both erosional and depositional processes, including spillover valleys, erosional scarps, giant levees, terraces, and diluvial dunes and antidunes (Rudoy, 2002). The presence of such features was noted by previous investigators along the upper Yenisei River (Figs. 1 and 2) in the Sayan mountains (Table 1) of southern Siberia (Grosswald and Rudoy, 1996a,b; Rudoy, 1998; Grosswald, 1999), but their details have been essentially unknown. In this paper, we present new remote-sensing and field observations of a wide range of geomorphological and sedimentological features that provide important keys for understanding the consequences of powerful floods (herein named the Yenisei floods) in this remote region. Such floods require large reservoirs of water at their sources, and there must have been mechanisms for the very rapid release of that water.

A number of intermontane basins in the upper Yenisei River catchment have held paleolakes. In particular, the Darkhadyn Khotgor (Darhad Basin) of northern Mongolia (Table 1), and the

Fig. 1. Positions of great rivers and large lakes near the Russia–Mongolia border. The upper Yenisei River catchment is the focus of the study. Solid line: Russia–Mongolia border. Dashed line: border of the Tuva Republic.

Fig. 2. Geography of the study area. Radarsat mosaic image (SCAN SAR R120050130 and R108331129). The Big Yenisei and the Little Yenisei rivers, and the section downstream of their confluence are highlighted. The boxes show locations of other figures in this paper.
Investigated using four main approaches: (1) chronology of study. The relationship between the Khotgor to the Mongolia drainage is called the Shishkhid Gol (Table 1) from the Darkhadyn – Altai (e.g., Komatsu et al., 2001). We present geomorphological, sedimentological, and also chronological data of paleolakes in the Darkhadyn – Altai (e.g., Gillespie et al., 2008). These paleolakes did not form primarily from the interplay of precipitation and evaporation, which are the two main processes that maintain climate-dominated paleolakes such as those in the Gobi–Altai (e.g., Komatsu et al., 2001). The Yenisei and Altai great rivers, originating in the highlands of the Mongolian plateau, a large-scale tectonomagmatic complex (e.g., Komatsu et al., 2004). This study is a reconnaissance intended to provide an introduction to the complex cataclysmic flood and paleolake stories of the upper Yenisei River.

2. Geography of the upper Yenisei River catchment

The 4000-km-long Yenisei River in Siberia is one of the world’s great rivers, originating in the highlands of the Mongolian plateau (Fig. 1). Water drains west into Tuva and then north as the upper Yenisei River. The Yenisei River flows into the Arctic Ocean after a long journey along the eastern margin of the West Siberian Plain.

We focused our paleohydrological investigations on the upper reaches of the Yenisei River (Fig. 2), where two large intermontane basins, Darkhadyn Khotgor in northern Mongolia and Todza in the Tuva Republic of the Russian Federation, and numerous smaller intermontane basins in the Sayan mountains are the drainage collectors. The upper Yenisei River has two main tributaries – the Little Yenisei and the Big Yenisei rivers (Fig. 1). The Little Yenisei River drainage is called the Shishkhid Gol (Table 1) from the Darkhadyn Khotgor to the Mongolia–Tuva border along the Busin–Gol basin, where its name changes to the Kyzyl Khem (Table 1). It merges with the Kaa Khem and flows to the Tuvan capital, Kyzyl, within the Kyzyl Basin. The Big Yenisei River drainage is also called the Bii Khem, and it flows from the Todza Basin to the Kyzyl Basin. Downstream from the confluence of the Kaa Khem and Bii Khem, the river is called the Ulug Khem.

3. Methodology

3.1. Remote sensing and field study

Investigations of flood features and paleolakes along the upper Yenisei River were conducted by remote sensing and fieldwork. The range of scales covered in the paper is wide, from outcrops to large-scale landforms (tens of meters to kilometers), and drainage paths up to hundreds of kilometers long, but crucial in understanding the phenomenon of cataclysmic floods and paleolakes. Satellite images were essential in order to deal with the large, remote area that required assessment. The images we used were from Radarsat SAR (Synthetic Aperture Radar), JERS-1 (Japanese Earth Resource Satellite) SAR, Terra ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), Landsat MSS (Multi-Spectral Scanner), Landsat TM (Thematic Mapper) and Google Earth Pro. The digital elevation models used in this study were derived from the SRTM (Shuttle Radar Topography Mission) data set. Fieldwork was conducted over several seasons at key sites where working conditions including access and logistics were greatly variable. The visited sites were photographed and documented, and excavation and sample collection were conducted for detailed analysis where the conditions were permissible. The collected samples were treated and analyzed at laboratories for 14C, IRSL/OSL, and cosmic-ray exposure-age dating.

3.2. Computer simulation

In order to investigate flood behavior, we conducted computer simulations employing the depth-averaged form of the Saint-Venant type equations and the Manning’s empirical friction equation as basic equations for the calculations of flood flows. These equations are

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solved with the finite-difference scheme with the fully implicit expansion of one point upstream accommodated by the Newton–Raphson iterative scheme. The calculation can be performed two-dimensionally with boundary conditions that include topographic information obtained directly from digital elevation models (DEMs). Therefore the code is capable of calculating time-slices of flow distribution over topography and depth, and also flow characteristics such as velocity and discharge rate. The combination of DEMs and fluid physics provides important advantages over theoretical analyses or one-dimensional simulations, including: (1) complicated water paths, including bifurcations and reconvergences of flows can be naturally reproduced; (2) relationships of individual continuous flow paths can be reconstructed; and (3) calculated areal coverages and water depths can be directly compared with geological and geomorphological observations.

4. Evidence for cataclysmic floods along the upper Yenisei River

4.1. Flood bedforms in the Kyzyl Basin

Fluvial bedforms of cataclysmic flood origin have been identified in the Kyzyl Basin (Figs. 2 and 3) (e.g., Grosswald, 1987; Yamskikh, 2001), in the form of “giant current ripples.” Giant current ripples (Bretz et al., 1956) are widely known in the Channeled Scabland (Baker, 1973, 1982) and Altai (Baker et al., 1993) provinces, where they are also called “gravel dunes” (Carling, 1996a) or “diluvial dunes and antidunes.”

![Figure 4](image-url)

Fig. 4. Dune morphology of gravel dune fields near Kyzyl. a) Gravel dune field #1 in Fig. 3b. b) Gravel dunes field #2 in Fig. 3b. c) Gravel dune field #4 in Fig. 3b. d) Gravel dunes field #5 in Fig. 3b. e) Image showing gravel dune fields commonly positioned at the lower end of alluvial fans emanating from nearby massifs. All the images from Google Earth Pro. No vertical exaggeration.

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They are widely regarded as diagnostic of cataclysmic floods. In this paper, we use the term “gravel dunes” although the features may also include antidune forms. Since gravel dunes are strongly linked with flow hydraulics (Carling, 1996b; Carling et al., 2002), they provide information on parameters such as shear stresses, mean velocities, and stream powers even though their exact formation mechanism is poorly understood due to a lack of experimental data. Nonetheless, the stream power required to transport gravels and boulders is extremely high. Some researchers oppose the cataclysmic flood origin of the dune forms in the Kyzyl Basin (e.g., Borisov and Minina, 2001), preferring a glacial origin as a type of deformation till.

Well-developed gravel dune fields have been noted along the banks of the Kaa Khem and Ulug Khem (Figs. 2–6) by our field and remote-sensing studies. Additional gravel dunes may lie along the upper Yenisei upstream of the Kaa Khem and downstream of the Ulug Khem. However, no obvious gravel dunes are observed along the Bii Khem, within the resolution limits of the remote-sensing data (75 m for Radarsat SCAN SAR and 30 m Landsat TM).

The gravel dunes near Kyzyl (Figs. 3–6) are rich in gravels, but large particles such as boulders up to meter scale are also observed. They lie on terraces 20–30 m above the modern river (Yamskikh, 2001), which are 3–10 km long and 0.5–1.5 km wide. The gravel dune crests are hundreds of meters long, and individual dunes are tens of meters wide. The dune heights are in general a few meters or less, but higher dunes exist. The average crest-to-crest distances vary from 50 to 80 m. The dunes are equally spaced or exhibit somewhat chaotic appearances (Fig. 4a–d). Where it is possible to identify slipfaces, they point toward downstream of the Kaa Khem and Ulug Khem rivers. The long-axis orientations of the gravel dune fields are consistent with the present-day course of the Kaa Khem and Ulug Khem. The examined gravel dune fields are located downstream of topographic obstacles that form constrictions (Fig. 3b), often at the lower end of alluvial fans emanating from nearby massifs (Fig. 4e).

We measured the average chord length (assumed to be equivalent to the crest-to-crest distance in the measurements) for four gravel fields (Rudoy, 2002). The average chord lengths vary from 50 to 80 m.

Fig. 5. Ground photographs of gravel dunes near Kyzyl. a) Oblique view. Gravel dune field #5 in Fig. 3b. b) Gravel dunes. Gravel dunes field #4 in Fig. 3b. c) Gravel dune field #5 in Fig. 3b. Gravel dunes are rich in gravels, but large particles such as boulders up to meter scale are also observed. Photographs by G. Komatsu.

Fig. 6. Ground photographs of gravel dune field #1 (Fig. 3b). a) Side view of gravel dunes. The height of the highest dune crest measured from the foreground is approximately 30 m. b) Intra-dune sediments observed in the gravel dunes of a). They show deformation of gravel beds ejected into the overlying loess layer, evidence for cryoturbation during an extremely cold period. The thickness of the dark top soil is about 20 cm. Photographs by S.G. Arzhannikov.

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dune fields (Fig. 3b; Table 2) and compared with an empirical function relating chord length to the maximum stream power (Baker, 1982).

The range of stream power responsible for the Tuvan gravel dunes is calculated to be $9.27 \times 10^3$ W m$^{-2}$ ($9.27 \times 10^6$ erg cm$^{-2}$ s$^{-1}$), similar to the values found in the Channeled Scabland (7–40 $\times 10^3$ W m$^{-2}$; Baker, 1982). The relationship derived by Baker (1982) does not necessarily describe the hydraulic condition at the time of dune emplacement since the dunes may not form at the time of the maximum flood flux. Nonetheless the presence of gravel dunes along the Yenisei River provides strong evidence for the catastrophic nature of the floods.

The Tuvan dune lengths are within the range observed for gravel dunes in the Altai (Carling, 1996a), but dune heights are generally lower than those of the Altai dunes. The Altai dunes are up to about 10 m high, but higher dunes also exist (Carling, 1996a). The lower Tuvan dunes may be attributed to three possible causes: (1) post-flood modification that subdued dunes; (2) limited supply of sediments for the dune growth; or (3) scour of dunes during waning stages of an individual flood event (Baker, 1973). The locations of gravel dune fields downstream of topographic obstacles imply that deposition occurred when the floodwater conditions changed after passing by the obstacles. The observation that gravel dune fields are commonly located at the lower end of alluvial fans emanating from nearby massifs suggests that the floods at least partially utilized local fan sediments.

The intra-dune sediments on the gravel dunes (Fig. 6a, gravel dune field #1 in Fig. 3b) revealed a stratigraphic sequence of light-colored loess underlain by gravel beds deformed by cryoturbation (Fig. 6b). The sequence is characteristic of periglacial conditions, implying formation prior to 10 ka. The most recent, and likely, candidate for the cold period is the Sartan glaciation (11–24 ka; marine oxygen isotope stage 2, or OIS 2).

Another geomorphologic indicator of great flood flows could be the hanging valleys observed along the Ulug Khem which lack or exhibit only small alluvial fans at their mouths (Figs. 3a and 7). Fans predating the floods were either completely or partly eroded and truncated likely by the floods along straight valley reaches (Rudoy, 2002). A flood with great stream power is also capable of eroding even hard bedrock, resulting in deep incision of the trunk valley floor. If tributary streams have not had enough time to adjust to this newly established condition, side valleys will remain high above the main valley floors. Although with the level of current knowledge about the tectonic and glacial history of this area we cannot rule out alternative origins for these features, it seems reasonable to attribute them provisionally to flooding.

Northwest-trending linear features are observed in the Kyzyl Basin south and southeast of Kyzyl town (Fig. 3a). High-resolution imagery reveals patches of sandy deposits with occasional dune forms within the features. The origin of these features is debatable and no convincing hypothesis has been proposed: one possibility is that they represent flood sediments reworked by eolian processes. Similar sands produced and transported by cataclysmic floods are known, for example, in the Quincy Basin dune fields (Bretz et al., 1956; Nummedal, 1978). Two plausible flood sources exist: the Kaa Khem and Bii Khem rivers.

4.2. Paleochannel complex in the Minusa Basin and possible flood sediments in the West Sayan mountains

The upper Yenisei River cuts through narrow gorges in the West Sayan mountains downstream from the Kyzyl Basin (Fig. 2). The area where the river opens into the Minusa Basin (Fig. 8) has been studied in great detail due to the presence of many Upper Paleolithic archaeological sites, referred to as the Maina group (Yamskikh et al., 2001; Vasilev et al., 2001). The geomorphology near the West Sayan–Minusa transition provides possible evidence for ancient cataclysmic floods. A wide swath of braided and/or anastomosing paleochannels emanating from the mouth of the Yenisei River into the Minusa Basin is clearly visible in satellite imagery (Fig. 8). The modern channel path is diverted east. The paleochannels may have been formed by normal stream migration or by high-energy floods. The Oya River valley (Fig. 8), downstream and to the east, was a site of both intensive erosion and deposition as inferred from destroyed terrace strata, although dating of these processes is inconclusive (Yamskikh and Yamskikh, 2001).

Of particular interest for the paleohydrology of this region is the presence of sediments comprising high terraces. For example, the high

![Image](https://example.com/image.png)
sandy terrace deposit along the Golubaya tributary river is cross-beded (Figs. 8 and 9) with sand layers alternating with horizons of coarser subangular pebbles. Yamskikh et al. (2001) interpreted this deposit as alluvial–lacustrine, formed in the basin when it was dammed by a glacier. However, an alternative interpretation derives from the similarity of this sedimentary sequence to ones observed on giant bars (“diluvial-accumulative terraces”) along the Katun and Chuya river valleys in the Altai (Carling et al., 2002; Rudoy, 2002). The Altai giant bars consist of sediments accumulated during an abrupt decrease in stream energy, or under conditions of reversed flow in the

Fig. 8. The Yenisei River cuts through the West Sayan mountains via narrow gorges and opens into the Minusa Basin. Note paleochannels in the Minusa Basin. Radarsat image SCAN SAR R108331220. Inset is a sketch map based on Landsat TM GeoCover data, of the area indicated by the framework.

Fig. 9. Deposit interpreted to be related to high-energy flooding in the West Sayan mountains. a) Golubaya deposit. b) Close-up of the Golubaya deposit. The pen in the foreground is about 10 cm long. Photograph by G. Komatsu.

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erosional shadows below bed ledges, bends of the main valleys, or within vast expansions of the valleys (Rudoy, 2002). The Golubaya deposit may also be sediments related to high-energy flooding, as their deposition may be explained by movement and stagnation of floodwater in the tributary valley.

4.3. Flood indicators interpreted from remote-sensing data in the upper section of the Little Yenisei River

The upper reaches of the Little Yenisei River consist of a series of deep, narrow canyons (Figs. 2 and 10a), characterized by steep longitudinal gradients. A “diluvial,” i.e., cataclysmic flood, origin has been argued for the deep canyons of the Kyzyl Khem (Grosswald and Rudoy, 1996a,b). Along such deep, narrow, steep, and meandering gorges, cataclysmic floods tend to leave a set of geomorphic features that can be used to infer the nature of the floods (Rudoy, 2002).

For example, we note a lack or near absence of tributary fans in these reaches during our photointerpretation of JERS-1 SAR images. Tributary valleys along the reach downstream of the Busiin-Gol basin commonly are hanging valleys with their mouths raised above the main valley floor (Fig. 10a). As in the case of the Kyzyl Basin, high-energy floods could have removed pre-existing tributary fans as well as deeply incised the main valley.

Downstream of the Busiin-Gol basin (Figs. 2 and 10a), Pleistocene volcanism (Grosswald, 1965; Litasov et al., 2001a) has created a series of high terraces composed of thick basalt flow sequences (Fig. 10b–e), although some may be giant bars. These high terraces are deeply incised, sometimes by as much as a few hundred meters. Data on the gorges, cataclysmic floods tend to leave a set of geomorphic features that can be used to infer the nature of the floods (Rudoy, 2002).

Fig. 10. Fluvial landforms along the section of the Yenisei River near the confluence of the Kyzyl Khem and Kaa Khem rivers. a) JERS-1 image S151–214. Note hanging valleys and terraces. b–e) Up to 200–300-m-high basaltic terraces observed along the Kyzyl Khem. Photographed by A. Genik and reproduced with permission from him.

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lesser amounts of granite in the mountains surrounding the basin, by the Sayan, on the southeast by the Khoridolyn Saridag, and on the mechanisms seem to have varied widely and rehydrological conditions during the Quaternary. Their damming (Table 1) of northern Mongolia and is the Mongolia. 5.1. Paleolakes and glacial chronology, Darkhadyn Khotgor

The basin is one of the sources for the Yenisei River, collecting a large quantity of water and discharging it through before the Pliocene. The basin is one of the sources for the Yenisei River and near the gorge of the Shishkhid Gol. According to Spirkin (1970) the Little Yenisei River catchment (Table 3) are examples of drastic changes in Little Yenisei River catchment and the Todza Basin in the Big Yenisei River catchment (Table 3) is shown in Fig. 14c."

"...incision rate of the Yenisei River in this area is lacking, so it is unknown if the incision was a result of high-energy floods or background downcutting. We hypothesize that cataclysmic floods also contributed to the incision."

5. Paleolakes in the upper Yenisei River catchment

The formation of paleolakes in the Darkhadyn Khotgor in the Little Yenisei River catchment and the Todza Basin in the Big Yenisei River catchment (Table 3) are examples of drastic changes in hydrological conditions during the Quaternary. Their damming mechanisms seem to have varied widely and reflect various unique conditions characterizing Quaternary climate and structures of the Sayan mountains.

5.1. Paleolakes and glacial chronology, Darkhadyn Khotgor

5.1.1. Evidence of paleolakes

Darkhadyn Khotgor is one of three large structural basins near the Mongolia–Russia border (Fig. 2). It is located in Khovsgol Aimag (Table 1) of northern Mongolia and is >100 km long in the north–south direction and 20–40 km east–west. It is bounded on the north by the Sayan, on the southeast by the Khoridolyn Saridag, and on the west by the Ulaan Taiga mountains. Bedrock is largely schist and lesser amounts of granite in the mountains surrounding the basin, but the Khoridolyn Saridag is carbonated. Basalt flows are found in and near the gorge of the Shishkhid Gol. According to Spirkin (1970) and Ufland et al. (1969), subsidence of the Darkhadyn Khotgor began before the Pliocene. The basin is one of the sources for the Yenisei River, collecting a large quantity of water and discharging it through the west-flowing Shishkhid Gol. Dood Tsagaan Nuur and Targan Nuur (Table 1) lakes (1538 m a.s.l.) occupy the northwestern part of the basin today, but are negligible in size compared to the basin. Paleoshorelines (Fig. 11a, Selivanov, 1967; Komatsu and Olsen, 2002; Krivonogov et al. 2005) and lake sediments (Fig. 11b) are evidence of gigantic paleolakes in the basin (Paleolake Darhad; Gillespie et al., 2008). Late Pleistocene lake surface reports are reached to have appeared 1720 m a.s.l., ~180 m above the current lake level (Grosswald, 1999), and degraded horizontal terraces on the basin walls suggest even higher earlier stands — perhaps as high as 1825 m (Gillespie et al., 2008). Lake volumes calculated for the higlthands mentioned in this discussion are shown in Table 4. According to Ufland et al. (1969) and Spirkin (1970), the highest shoreline features (1700–1720 m) are recorded on the Jarai Gol terminal moraines. Although 1720 m may be the highest late Pleistocene stand, the Jarai moraines themselves are lower. Gillespie et al. (2008) measured (GPS) the highest wave-cut bench on the Jarai moraines at 1679 m, and considered the top of the moraine to have been risen above all highstands subsequent to its formation.

Grosswald (1987, 1999) suggested the Darkhadyn Khotgor as the source of the cataclysmic floods for which evidence is observed downstream in the Tuva Republic, and he estimated the discharge rate to have been 0.4 × 10^6 m^3 s^-1. Gravel dunes with 1–20 m wave-lengths are found at several locations in the basin. In addition, dipping benches on bedrock slopes near Högiyn Gol (Fig. 11a) mark spillways where hydraulic dams were established during draining events. These benches testify to the strong, erosive currents during these events.

Glaciation has certainly affected the hydrology of the basin, most notably by blocking the Shishkhid Gol outlet valley with glaciers descending the tributary Tengis Gol from the north (Figs. 12–14, e.g., Krivonogov et al., 2005). The uppermost section of the Yenesey River valley, from the Darkhadyn Khotgor to where the Kaa Khem enters the Kyzyl Basin, is crossed by many NNE–SSW-trending structurally controlled side valleys, one of which contains the Tengis Gol. Inspection of ASTER stereo satellite images suggests that the Shishkhid Gol was dammed at one time or another by glaciers from at least four south-draining side valleys (Fig. 14c) and probably by accumulations of glacial/alluvial fan deposits also (Fig. 13). The Tengis glacier was ~250 m thick near Öshig Nuur, and ~200 m thick just north of the confluence with the Shishkhid Gol near its terminus. It left remnants of end moraines, not eroded by the outburst floods, in the side canyons south of the Shishkhid Gol (Merle, 2001). Other blocking mechanisms such as landslides and lava flows may have created lakes in the Darkhadyn Khotgor, but no compelling evidence exists for them.

A series of terraces up to 125 m above the modern Shishkhid Gol and downstream from the Tengis glacier dam are observed (Fig. 13b). Some of these lower terraces have numerous east-west channels and levees, characteristic of large floods. Upstream from the site of the Tengis dam, the Shishkhid Gol is also flanked by a pair of gently westward-rising terraces composed or covered by lake sediments (Fig. 13). This was the floor of the Darkhadyn Khotgor paleolake before its incision during and following the last floods. Rounded basalt boulders up to ~1 m in diameter lie on the terraces, some transported >1 km from their source area during the floods. Although lake sediments are widespread upriver from the Tengis confluence, they are missing from the terraces downstream for at least 10 km (J. Cady, pers. comm., 2000; Merle, 2001). Krivonogov et al. (2005) regard these terraces as supported by eroded intracanyon basalt flows, but they are capped by fluvial gravels. Terrace remnants are found up to 20 km west of the Tengis Gol, near the site of another paleoglacier dam ("ice dam #2," Fig. 14c).

Grosswald and Rudoy (1996b) suggested that the ice fields of the Ulaan Taiga and Sayan mountains themselves grew enough to join and dam the Shishkhid Gol. This idea does not appear to have been widely accepted, but photo interpretive evidence suggests an older generation of eroded stepped-terrace nunataks in the Ulaan Taiga that may have protruded from an ice field that was large and low enough to have dammed the river by itself, ~7 km west of the Tengis Gol (Fig. 15). A cross section of the valley of the Shishkhid Gol there is shown in Fig. 14b.

If the Ulaan Taiga icefield did dam the Shishkhid Gol, the dam could have been high enough to impound the 1825-m highstand. It seems unlikely that later ice fields that left the fresh-appearing nunataks above ~2350 m were extensive enough to have dammed the Shishkhid Gol. This is consistent with the preliminary K/Ar dating of subglacial volcanoes in the Azas Plateau, which suggested that the latest Pleistocene glaciers (OIS 2 and perhaps OIS 3) were much smaller than earlier ones (Komatsu et al., 2007a,b). On the basis of OSL dating in the Russian Altai, Krivonogov et al. (2005) also regarded OIS-

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2 glaciers in all of southern Siberia as smaller than earlier ones of the last glacial cycle.

Downriver from the Tengis confluence, another large dam ("ice dam #4," Fig. 14c), also from an outlet glacier of the Sayan icefield, dammed the river to a depth of 200 m, producing a deep but small-volume lake. Fig. 16 shows the area of ice dam #4. Some of the terraces close to the confluence are probably moraines or till terraces, and others are probably fluvial, possibly from outburst floods originating at any one of the dams upstream. The prominent intermittent notch in the southeast valley wall shown in transect E–E' in Fig. 16 is probably an old channel of the Shishkhid Gol. Because the floors of the notches are ~200 m above the modern river, roughly the same elevation as the top of the glacier, the notches may have been an ice-marginal stream at that time. The existence of deep lakes in the Shishkhid valley below the Tengis confluence, albeit of low volume, illustrates the complex nature of the outburst flood history of the upper Yenisei River.

5.1.2. Chronology

Gillespie et al. (2008) established a direct chronology for the Darkhadyn glaciations by \(^{10}\)Be exposure-age analysis of till stones from the Tengis and Jarai moraines and drift (Fig. 17), augmented by \(^{14}\)C and IRSL/OSL dating of lake sediments in the Darkhadyn Khotgor. A
The Todza Basin yields evidence for considerable modification of the environment in the second half of the Quaternary (Chudinov, 1959; Grosswald, 1965; Yamskikh, 1972, 1983; Orlova, 1980; Arzhannikov Grosswald, 1965; Yamskikh, 1972, 1983; Orlova, 1980; Arzhannikov

Table 4

<table>
<thead>
<tr>
<th>Basin</th>
<th>Highstand elevation (m a.s.l.)</th>
<th>Lake volume (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darkhadyn Khotgor</td>
<td>1560</td>
<td>16</td>
</tr>
<tr>
<td>Todza Basin</td>
<td>1602</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>1679</td>
<td>276</td>
</tr>
<tr>
<td></td>
<td>1710</td>
<td>373</td>
</tr>
<tr>
<td></td>
<td>1825</td>
<td>809</td>
</tr>
<tr>
<td></td>
<td>834</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>310</td>
</tr>
</tbody>
</table>

The Darkhadyn Khotgor was filled by lakes 64–172 m deep repeatedly for brief periods during the late Pleistocene and early Holocene. Earlier lakes may have been as deep as ~290 m. The lakes were impounded by glaciers of the Tengis Gol blocking the drainage from the Darkhadyn Khotgor, although the deepest one may have been dammed by the edge of the Ulaan Taiga ice field. Smaller lakes may have intermittently filled parts of the valley of the Shishkhid Gol, impounded by other glaciers from side canyons. The rich and complex history of lakes and ephemeral dams suggests that the chronology of floods farther downstream, on the Kaa Khem or Yenisei, may be likewise complex, and hard to unravel.

5.2. Todza paleolakes

The Todza Basin is located in the eastern part of the Altai-Sayan mountain area (Fig. 2). It is bounded by the mountains of the East Sayan to the northeast, the West Sayan to the northwest, and the Academician Obruchev Ridge to the south. The basin is ellipsoidal in plan view and measures 250×70–100 km. Middle-late Pleistocene subglacial volcanoes (Litasov et al., 2001b; Komatsu et al., 2007a) in the Azas Plateau volcanic field may have produced jökulhlaup-type floods (Komatsu et al., 2007b).

Reconstruction of the paleogeographic setting of the western Todza Basin yields evidence for considerable modification of the environment in the second half of the Quaternary (Chudinov, 1959; Grosswald, 1965; Yamskikh, 1972, 1983; Orlova, 1980; Arzhannikov Grosswald, 1965; Yamskikh, 1972, 1983; Orlova, 1980; Arzhannikov

![Fig. 12. The area of the glacier dam at the Tengis/Shishkhid confluence. Photograph by V. Sheinkman.](image-url)
et al., 2000), a period marked by the formation of large paleolakes (Fig. 18, Table 4). The Taskyl Ridge at the western end of the basin, part of the Academician Obruchev Mountains, is the key locality for the damming the Todza Basin (Figs. 2, 18 and 19). The paleolakes could have been impounded by ice, debris flows/landslides, or tectonic scarps at this locality. Ice-dammed lakes formed by valley glaciers, snow avalanches and river ice, and also of high floods along the Bii Khem during the late Pleistocene and Holocene have been proposed by Yamskikh and Yamskikh (1999). Favorable localities for ice dams are shallow braided valleys with numerous floodplain islands, and narrow gorges where the river cuts through mountain ridges. However, other damming mechanisms are possible, and these will be discussed below.

5.2.1. Middle to late Pleistocene lake formation

A middle–late Pleistocene paleolake (~2000 km² in area and up to 250 m deep) occupying the western part of the Todza Basin was reported by Chudinov (1959) (Fig. 18). The sediments of this lake consist of gray yellowish sandy loams and yellowish-brown loams that cover various geomorphic levels at elevations up to 1000 m, and were deposited with a sharp contact in tributary valleys and on slopes and watershed divides. The thickness of the deposits on slopes and divides is 2 m or greater, and unknown in valleys. The maximum level of deposits is about 250 m above the modern level of the Bii Khem. Age control is from fossils (Chudinov, 1959). No evidence for significant lake level fluctuation has been found. High water levels are also indicated by eroded cliffs and fragments of terraces at relative heights of 250 m and 50–100 m above the Bii Khem (Chudinov, 1959).

According to Grosswald (1965), middle–late Pleistocene glaciers descending from the Taskyl Ridge were too short to reach the Bii Khem valley, making a 250-m-high ice dam unlikely. The homogeneity of the lacustrine sediments indicates that deposition occurred over a long period of time, rather than through a series of short fillings and drainings of the lake. This is inconsistent with glacier or ice dams, which apparently fail and reform.

Fig. 13. Maps of the lower Tengis Gol and the Shishkhid Gol below the confluence showing a) extent of the late Pleistocene glaciers and other deposits, after Gillespie et al. (2008), and b) terraces, with spot elevations from SRTM.
provide a stationary condition for an extended period, which is consistent with the nature of the lacustrine deposits.

The final significant decline of the water level in the paleolake was no later than 23,900–25,310 cal yr B.P. according to \(^{14}C\) dating (Yamskikh, 1993b, Table 5). This is supported by a high concentration of mammal bones at the base of the 18–20-m terrace section (latitude 815 m) in Urotchishche (Table 1) Merzly Yar (Yamskikh, 1993a).

5.2.2. Late Pleistocene to Holocene lake formation
At the end of the late Pleistocene, damming of the Bii Khem at the Academician Obruchev Ridge likely resulted in paleolake formation. The maximum depth of the late Pleistocene–Holocene paleolake was about 60 m, and its surface area was much smaller than the area of the middle–late Pleistocene paleolake (Figs. 18 and 20). The paleolake began about 2 km below the Khut River mouth (latitude 774 m) and came to an end in the area of the Systyg Khem mouth (latitude 834 m).

Lacustrine sediments associated with that lake crop out in the Bii Khem valley in sections of an 18–20-m-high terrace (Urotchishche Merzly Yar), located on the left bank of the Bii Khem 13 km downstream from the mouth of the Systyg Khem (and the paleomouth of the Bii Khem that was running into the paleolake), and a 4–6-m-high terrace at the mouth of the Siberiachka River, a tributary of the Bii Khem, which is located 40 km from the paleomouth of the Bii Khem (Figs. 18 and 20).

Urotchishche Merzly Yar consists of a 700-m-long and c. 2-km-wide terrace 18–20 m above the river (Fig. 21a,b), and is composed of lake sediments rhythmically alternating with buried soil horizons (Fig. 21a–c) and woody remains that are often in-situ. The terrace is completely frozen and has repeated ice wedges that considerably deform the deposits in places (Alexeev et al., 2007). The estimated age range of the 18–20-m terrace sections based on \(^{14}C\) dating is 13,480–13,800 and 3350–3560 cal yr B.P. (Fig. 21c; Table 5; Arzhannikov et al., 2000). Thus, formation of the late Pleistocene–Holocene paleolake began at about 13,480–13,800 cal yr B.P. (Fig. 22; Table 5). This date shows that about this time the paleolake level had gone down considerably, and peat had started to form. The sandy and clay sediments were deposited probably because of seasonal fluctuations of the Bii Khem.

The non-uniform distribution of deposits depends on the dynamics of flow in the paleolake (Fig. 20). The most rapid deposition occurred near the paleomouth of the Bii Khem. Further away from the paleomouth, deposition occurred very slowly in a lower energy environment. That explains the significant difference in the thickness of the deposits in Urotchishche Merzly Yar (~15 m) and in the area of the Siberiachka River (~3.5 m).

Water level changes are strongly reflected in the sedimentation pattern in the area of Urotchishche Merzly Yar (18–20-m terrace), where the sedimentary sequence is interrupted by paleosol horizons, and, to a lesser degree, in a correlated sedimentary sequence in the area of the Siberiachka River mouth where accumulation was continuous (4–6-m terrace, Fig. 22). Shallowing of the paleolake is represented by the formation of soil horizons in the 18–20-m terrace and by coarsening (up to sand) of the 4–6-m terrace. In contrast, deepening resulted in burial of soil horizons in the 18–20-m terrace and reduction of grain sizes down to sandy loams, loams and clays in the cross section of the 4–6-m terrace. Fluctuations of the water level are also evidenced by the repeated root growth of trees located near the shoreline of the paleolake.

The late Pleistocene–Holocene fluctuations in paleolake level could be related to three factors: mass-wasting, tectonics, and climate. The debris-flow deposit and landslide block in the vicinity of the Krasnaya River mouth (Fig. 19) may have been the damming obstructions for the late Pleistocene–Holocene paleolake. However, the sedimentation episodically (Wohl and Cenderelli, 1998). A large debris-flow deposit (Fig. 19), several square kilometers in area near the Krasnaya River mouth (Yamskikh, 1993a) may have been a factor in the middle to late Pleistocene lake formation. The maximum altitude of the surface of the eroded remnant of this debris flow is about 900 m.

We propose another mechanism: damming of the Bii Khem by a landslide block on the right bank of the higher Krasnaya River mouth (Fig. 19). The altitude of this block is over 1100 m, but a 1-km-wide valley at the rear of the block at an elevation of 1000–1030 m is consistent with the highstand lake level and may correspond to a semi-stable spillway which allowed the lake to remain at a stable level for a long time.

No age data exist for either the debris-flow or the landslide block deposits. Therefore, support for these damming mechanisms comes from (1) their altitudinal relationships with the lacustrine deposits (~1000 m), though the maximum altitude of the debris-flow deposit may be too low; and (2) the fact that these dams can
pattern of Urotchishche Merzly Yar most likely results from variations in the lake level, which precludes the possibility that a single large mass-wasting event impounded the lake.

Instead of a debris-flow/landslide-block dam, Arzhannikov et al. (2000) hypothesized that tectonic uplift of the Taskyl Ridge (Fig. 19) dammed the late Pleistocene–Holocene lake in the western Todza Basin at about 13,480–13,800 cal yr B.P., based on the presence of tectonic escarpments at the base of its northeastern slope, the antecedent character of the Bii Khem valley, the absence of alluvium and presence of bedrock in the Bii Khem at some sites, narrowing of the river valley down to 50 m, and a series of fluvial terraces along the Ospyur River (Fig. 19). Uplift of the Taskyl Ridge does not seem to explain the formation of the middle–late Pleistocene paleolake since the maximum level of the ridge does not reach the highest lacustrine deposit (>1000 m) of the early lake. Uplift of the Taskyl Ridge would result in an increase of base level at the basin outlet and backflooding along the Bii Khem, burying trees in lake deposits. Intervening fluvial erosion of the uplifted Taskyl Ridge would gradually reduce the level of the lake. Thus, the lake fluctuation may be explained by this cycle of uplift and erosion of the Taskyl Ridge.

It is unlikely that the late Pleistocene–Holocene shallow paleolake was glacially dammed as no trace of extensive Holocene glaciers has been detected in the vicinity. However, ice-dams caused by river ice (i.e., ice-jamming) are a possible cause: Yamskikh and Yamskikh (1999) interpreted the Merzly Yar section as an alluvial–lacustrine sequence and attributed its formation to cyclic ice-dam formation during the late Pleistocene–Holocene.

6. Computer simulation of flood flows
6.1. Numerical simulation program

Cataclysmic flood processes are better understood if we know their dynamical behavior. This can be achieved by computer simulation. We have been developing a two-dimensional numerical flood simulation program exactly for this purpose (Miyamoto et al., 2006, 2007).

The program has been tested by comparing its simulation result with that of a well-established numerical code HEC-2 (Feldman, 1981; Hydrologic Engineering Center, 1985) on the Channeled Scabland flood and the validity of the program has been confirmed (Miyamoto et al., 2006). The program also simulated the behavior of the Channeled Scabland flood in a way difficult to conduct with HEC-2, such as estimating flood coverage (Komatsu et al., 2000; Miyamoto et al., 2007), and successfully reproduced flood paths predicted from field observations. However, this simulation approach has limits when applied to paleofloods. First, pre-flood topography of the region can differ significantly from the modern topography owing to active neotectonics and also deep erosion by the floods. Second, our program is not designed to incorporate flood erosion that may alter the very topography the flood is moving over. Third, floods of cataclysmic scales may carry significant sediment load, a consideration not treated in our simulation. Despite these limitations, a first-order estimate of hydraulics and graphical presentation of flood streams is possible and very useful for the understanding of flood behavior in the Yenisei River reaches.

Fig. 15. Perspective view of the Tengis/Shishkhid confluence area, looking south to the Ulaan Taiga. Image is from ASTER 11292001043827 (November 29, 2001) and the topographic data were calculated from ASTER stereo images using SilC software (http://www.silc.co.jp/en/products.html). Note the limits of fresh and eroded step-terraced nunataks indicating the extent of the Pleistocene ice fields in the Ulaan Taiga.
Fig. 16. Moraines and terraces along the Shishkhid Gol below “ice dam #4” (Fig. 14a,c). a) Perspective view of glacier dam area, looking north. The Shishkhid Gol flows from the right edge of the image to the lower left-hand corner. b) Plan view; north is up. White lines show topographic transects. c) Topographic transects. Image data from ASTER 05182000044927 (May 18, 2000); topographic data from ASTER stereo images processed with SilcAST software (http://www.silc.co.jp/en/products.html).

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For the simulations, we used United States Geological Survey digital elevation models (DEMs) of the world (grid: 927 m N–S, 598 m E–W at the latitude of the study area). We applied the program to the case of floodwater derived from the Darkhadyn Khotgor, because this represents one of the largest cataclysmic flood events along the Upper Yenisei River, and relatively well-constrained boundary conditions exist in terms of volume of water and where the flood originated (Table 6). The lake volume at a level of 1710 m is c. 373 km$^3$, which is about one-sixth of Lake Missoula (2184 km$^3$; Clarke et al., 1984). An even higher stand at 1825 m is inferred from degraded horizontal terraces, giving a lake volume of c. 809 km$^3$ (Table 4). However, this lake stand probably required impoundment by the Ulaan Tiaga ice field (Fig. 14), which we do not model in this work. We followed the scenario of a glacial-ice dam failure by placing a topographic barrier where the Tengis Gol con verges with the Shishkhid Gol and suddenly removing the barrier. The floodwater movements are naturally and seamlessly calculated before and after the breakout of the dam by the simulation code. We assumed a Manning’s coefficient of 0.07. The low DEM resolution prevented floodwaters from flowing north through narrow canyons of the West Sayan mountains, so we ran the simulation from the Darkhadyn Khotgor down to the Kyzyl Basin, and further west where it reaches the mouth of the gorge through the West Sayan mountains. We discuss below three sections of the upper Yenisei River, where insights on flood behavior are drawn from the simulation.

6.2. Breakout point

The total-instantaneous-failure scenario yields the maximum discharge rate possible from the 1710-m level lake. It is plausible that the failure was not as catastrophic as this scenario: instead, smaller outburst from lifted ice dams may have been much more common. In addition, subglacial water streams may have caused runaway outbursts by carving larger tunnels by frictional heating (Konrad, 1998). The geological observations of the breakout point do not give much information as to which processes operated. It is also not clear whether the outwash sediments downstream of the ice dams were obstacles to the floods. The calculated hydrograph from our simulation is shown in Fig. 23. Shortly after the breakout, the model discharge increases to approximately $3.5 \times 10^6$ m$^3$ s$^{-1}$, before dropping steeply to less than $1 \times 10^6$ m$^3$ s$^{-1}$, and then declines gradually after about 3 h. Physically, the flood appears to be stacked in the narrow gorges of the Shishkhid Gol, Kyzyl Khem and Kaa Khem rivers. The estimated peak discharge rate is approximately one-fifth of the value found for the Channeled Scabland flooding (peak discharge rate estimated at $17 \times 10^6$ m$^3$ s$^{-1}$; O’Conner and Baker, 1992) or for the Altai superfloods (peak discharge rate estimated at $18 \times 10^6$ m$^3$ s$^{-1}$; Baker et al., 1993), or about one-third of the peak discharge rate obtained by Herget (2005) for the Altai flood ($10 \times 10^6$ m$^3$ s$^{-1}$). It is also an order of magnitude greater than the estimate of Grosswald (1987, 1999). We caution that the our discharge-rate estimation method assessing hydraulic routing differs from the ones used by the above authors who derived the discharge rates by the HEC-2 program on flows in restricted reaches, and this difference make an accurate comparison of floods difficult. Nonetheless, our estimation again testifies to the cataclysmic nature of the flood along the Yenisei River.

6.3. The Shishkhid Gol, Kyzyl Khem, Kaa Khem rivers

A number of sections of the upper Yenisei River (the Shishkhid Gol, Kyzyl Khem, Kaa Khem rivers) are characterized by relatively narrow gorges a few kilometers in width. In order to understand how floodwater flows down such gorges, we plot water depth/coverage diagrams (Fig. 24). Water depths in these gorges remain fairly large (50–100 m) long after the initial flood head passes. Canyon walls and floors, and the basalt flood sequence (Fig. 10) that once filled the gorges could have been eroded by undercutting, and plucking of large blocks of basalt rocks. The deep erosion would have removed the toes of alluvial fans deposited from side valleys, as observed. A notable exception is the low-gradient, wide Busiin-Gol structural basin, which may have experienced inundation by floodwater, probably resulting in deposition of flood transported sediments there (Fig. 24). The simulated floodwater was especially deep downstream of the Busiin-Gol basin (Fig. 24). This is probably due to hydraulic ponding of water in the narrow section of the Kyzyl Khem.

6.4. Kyzyl Basin

It is of great interest to study the behavior of the floodwater from the Darkhadyn Khotgor in the areas of the gravel dunes in the Kyzyl Basin. Due to the uncertainty in correlating coordinates of the DEM and gravel dunes and also the low DEM resolution, obtaining a hydrograph at a precise location was difficult. A point (A) was chosen south of a gravel dune field (#4 in Fig. 3b) where the floodwater was probably one of the deepest in the area (Fig. 25a), and a second point (B) was selected in a position likely representing the top of the gravel dune field (Fig. 25a). Floodwater arrives in this area about 40 h after breaching of the ice dam at the Tengis Gol (Fig. 25b–c), with flow depth peaking 20–30 h after the first arrival of the flood, and after the peak discharge probably due to the hydraulic damming effect of the narrow Kyzyl Basin outlet. Peak water depth at point A was nearly 55 m with a flow velocity of approximately 4–4.5 m s$^{-1}$ (Fig. 25b–c). At point B, maximum water depth was c. 20 m, with a water velocity of $>2$ m s$^{-1}$ (Fig. 25b–c). The simulation result illustrates how a cataclysmic flood from the Darkhadyn Khotgor behaves in the Kyzyl Basin, and it is consistent with the presence of the gravel dunes.

7. Discussion

In this section we explore the cause–consequence relationships between the sources, landforms and deposits we presented above. The flood history of the upper Yenisei River is complex, mainly because the region has a number of basins and drainage systems. Each basin and drainage appears to have its own unique evolution in the fluctuating Quaternary climate. The study of flood landforms and deposits is at its early stage and we still lack detailed investigation of their magnitude and age determination. Therefore there remain many uncertainties about the relationships between the cause and the consequence of cataclysmic flooding, and the uncertainties include temporal association.
Great floods may be caused by mechanisms such as heavy precipitation and failure of lakes formed by ice-jamming. In particular, ice-jamming can produce a condition that leads to damming and ponding of river water, and it possibly leads to rapid failure of the river lake. It is a process operating even under the modern climate for many major high-latitude river systems. However, some features including

Fig. 18. Reconstructed paleolakes in the western Todza Basin during the middle–late Pleistocene (a) and late Pleistocene–Holocene (b).

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Fig. 19. The area of damming of the Todza paleolakes. 1 – dashed line showing the location of the tectonic scarp possibly responsible for the late Pleistocene–Holocene damming; 2 – dashed line contouring; a – the debris flow; b – the landslide block, possibly responsible for the middle–late Pleistocene damming; 3 – arrows showing a complex of terraces along the Ospyur River valley, suggestive of tectonic activity along the Taskyl Ridge; 4 – arrows showing the debris flow direction. ASTER image 2004974011.

The gravel dunes require an explanation by floods much greater than those produced by ice-jamming under the modern conditions. Floods of cataclysmic scales could have been originated from the catastrophic failures of large paleolakes. Cataclysmic floods from the Darkhadyn Khotgor were likely responsible for the formation of a number of landforms and deposits along the Little Yenisei River drainage (the Shishkhod Gol, Kyzyl Khem and Ka Khem rivers). These include deep gorges, possible deposition of sediments in the Busuin-Gol basin, and gravel dunes in the Kyzyl Basin. This view is consistent with our computer simulation indicating the passage of a very large flood, likely resulting from rapid drainage of a deep lake following catastrophic failures of its impoundment. The formation of some gravel dunes in the Kyzyl Basin prior to or during the extremely cold period of Sartan age may find correlations with large paleolakes in the Darkhadyn Khotgor (OIS 2 or OIS 3) or even earlier ones. The flooding may have occurred more than once from the paleolakes in the Darkhadyn Khotgor in the late Quaternary, but the mode of dam failure was probably diverse depending on the type of the dam (e.g., ice dam or sedimentary dam). The linear sandy deposits that are widely distributed in the Kyzyl Basin and features downstream of the Ulug Khem (e.g., purported flood sediments in the West Sayan mountains and paleochannels in the Minusa Basin) may also be linked with such floods from the Darkhadyn Khotgor. However, other potential flood sources complicate the interpretation of these links.

The Todza paleolakes that formed during the middle–late Pleistocene and late Pleistocene–Holocene times may have been sources of flooding through the Bii Khem. We note, however, that we as yet have identified clear cataclysmic flood indicators, such as gravel dunes, along the Bii Khem. This makes the hypothesis of cataclysmic flooding from the Todza Basin somewhat speculative.

We also envisage a possible complication from volcanism. Lava erupted from volcanic centers along the upper Yenisei River flowed upstream and downstream, in some cases for more than 100 km. The lava flows there are appropriately called “lava rivers” by local geologists. One of the eruptive centers was along the Terektig River, a tributary of the Kyzyl Khem, and lava flowed down along the Kyzyl Khem and Ka Khem rivers filling both the main river valley and its tributaries (Fig. 10). The lava sequences in the Kaa Khem are dated to be 340–200 ka (Sugorakova et al., 2001), possibly coinciding with the Samarovo Glaciation (270–230 ka, OIS 8). The flow sequences are locally a few hundred meters thick, and therefore they could have blocked river streams in the upper Yenisei River valleys and impounded deep lakes upstream, particularly in the Busuin-Gol basin, although they are deeply incised by the modern Yenisei River. These lakes could serve as sources for cataclysmic floods if the lava dams were breached rapidly.

The Yenisei flood story is remarkable in the sense that there seems to have been a wide range of lake-damming and flood-release mechanisms. The dams could have formed by ice, sediments, tectonic
scars, and even lava flows. Each dam type can fail differently (from catastrophically to gradually). Flooding from the paleolake could be generated by lake water overtopping the dam, or by waves resulting from landslides into the lake overtopping the dam, leading to its total and catastrophic failure in some cases. Earthquakes could change the dam level instantaneously, allowing rapid release of the lake water. In the case of ice dam, hydraulic lifting of the dam is also possible. Furthermore, subglacial water streams may have a capacity to cause runaway outbursts by carving larger tunnels by frictional heating. The wide range of possible flood-release mechanisms, combined with the amount of stored water and geometry of the valleys through which the flood moved, could cause the resulting hydrograph to be extremely variable.

8. Conclusions

A wide range of geomorphological and sedimentological features along the upper Yenisei River in the Sayan mountains of southern Siberia strongly implies multiple cataclysmic floods down the river. Gravel dunes in the Kyzyl Basin probably provide the best evidence of these floods with estimated peak flood stream power values based on dune geometry being comparable to those estimated for the
Channeled Scabland floods in eastern Washington State, U.S.A. Other landforms including hanging valleys and paleochannels have been noted, and sediments that were likely deposited by movement and stagnation of high-energy floodwater in a tributary valley also exist.

Potential sources of floodwater in the form of paleolakes, primarily middle–late Pleistocene to Holocene in age, existed in the upper Yenisei River catchment along the Little Yenisei River and the Big Yenisei River. The lakes (the largest ones in the basins of Darkhadyn Khotgor and Todza) were likely impounded by a variety of dams including ice, sediments, tectonic scarps, and lava flows.

The Darkhadyn Khotgor hosted large paleolakes (up to at least 373 km$^2$, about one sixth of the size of Lake Missoula in the northwestern USA). Flooding from the lakes appears to explain many of the inferred flood features, although contributions by flooding from other paleolake basins cannot be ruled out. The estimated peak discharge rate of a great flood from the Darkhadyn Khotgor based on our computer simulation of an ice-dam failure scenario is approximately $3.5 \times 10^6$ m$^3$ s$^{-1}$, less than that of the Channeled Scabland floods but still catastrophic. Based on the paleolake data, and the pristine appearance of the flood-related features, we conclude that many of the cataclysmic floods occurred in the late Quaternary, but this does not exclude earlier floods.

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![Fig. 22. Section of the 4–6-m terrace in the area of the Siberiachka River mouth.](image)

![Fig. 23. Simulated hydrograph at the breakout point derived from a cataclysmic flood originating from the Darkhadyn Khotgor paleolake at 1710-m level. Two plots (a, b) with different time scales are shown.](image)

![Fig. 24. Inundation map showing a flood flow originating from the Darkhadyn Khotgor paleolake at 1710-m level.](image)

<table>
<thead>
<tr>
<th>Lake level (m)</th>
<th>Lake depth relative to modern lake level, 1538 m (m)</th>
<th>Average depth (m)</th>
<th>Area of the lake (km$^2$)</th>
<th>Volume of the lake (km$^3$)</th>
<th>Manning coefficient – M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1710</td>
<td>172</td>
<td>114</td>
<td>3272</td>
<td>373</td>
<td>0.07</td>
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</tbody>
</table>

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References


