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Glacier and debris flow disasters around Mt. Kazbek, Russia/Georgia

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ABSTRACT: We present a study of glacier and debris flow disasters in the Mt. Kazbek region (central Caucasus). Glacier disasters were registered here in 18th -21st century (Devdorak, Abano and Kolka glaciers) and catastrophic debris flows occurred also in 1953 and 1967. We argue that glacier disasters on different sides of and nearby the Kazbek volcano should be considered as phenomena potentially of the same origin. For the next 30 years the region is likely to experience frequent rain-induced debris flows and less frequent glacial debris flows, which will be most active in the Genaldon River valley due to abundant material deposited by the 2002 glacier disaster. The naming of the multi-stage catastrophic events like the Kolka glacier disaster in 2002 and the determination of the exact role of debris flows in such events require further work.

1 INTRODUCTION

Debris flows are widespread in periglacial areas of the Central Caucasus. They are triggered by thermal erosion and thermokarst processes in the stagnant ice, by glacial lake outburst floods (GLOFs), by extreme rains, and by regional glacier recession. Sometimes they reach the scale of debris flow disasters, leading to large changes in valley floors, significant damage to infrastructure and casualties. There is also a phenomena of glacier disasters, which we define as events which involve detachment of large glacier masses (several million m^3) and their very rapid movement down valleys, with speeds of tens of metres per second for distances up to tens of kilometres (Chernomorets 2005b).

These phenomena are typical for the region of the dormant Kazbek volcano (Fig. 1), which is noted for the highest concentration of glacier and debris flow disasters in the Caucasus. In 2002 a series of large rockfalls from the slopes of Mt. Dzhimaray-khokh (adjoining Mt. Kazbek) contributed to destabilising Kolka glacier. The resulting ice-debris flow travelled 19 km at an extremely high speed, covered Nizhniy Karmadon settlement by a thick layer of ice and initiated debris flows, killing 125 people. Although a lot of factual data are available, the origin of this disaster is still unclear. However, glacier disasters occurred at Kolka glacier and two other Kazbek glaciers, Devdorak and Abano, in the past. These events provide historical perspective.

Historically research of glacier and debris flow disasters in this region considered isolated events. For example, 19th century studies of Devdorak glacier do not mention Kolka events. The majority of

Figure 1. Mt. Kazbek (right). View from the south. Aerial image by S.S. Chernomorets, July 9, 2006.

20th century studies of Kolka glacier disasters (e.g. Stoeber 1903; Poggenpohl 1903, 1905; Pervago 1904; Rototaev et al. 1983) as well as early 21st century studies (Kotlyakov et al. 2004; Huggel et al. 2005; Haeberli et al. 2004) mention that Devdorak glacier is nearby, but only Kolka events are analysed. Similarly events at Abano glacier in 1909 and 1910 have not been considered in a regional context, possibly distorting the broader picture. We note success of region-wide hazard assessments, e.g. for the glaciated Iliamna volcano, Alaska, where potential hazards are associated with volcanic activity (Waythomas & Miller 1999).

The goal of our study is, therefore, to review the glacier and debris flow disasters in the entire Mt. Kazbek region to facilitate regional hazard assessment and risk management, as well as general understanding of such hazards.

2 STUDY AREA

Mt. Kazbek (5033 m a.s.l.) is the sixth highest summit in the Caucasus. It belongs to the Main Caucasus Range. To the west of Kazbek are Mt. Maili-khokh (4598 m), and Mt. Dzhimaray-khokh (4780 m). Together they form the so-called Kazbek-Dzhimaray mountain massif (Fig. 2).

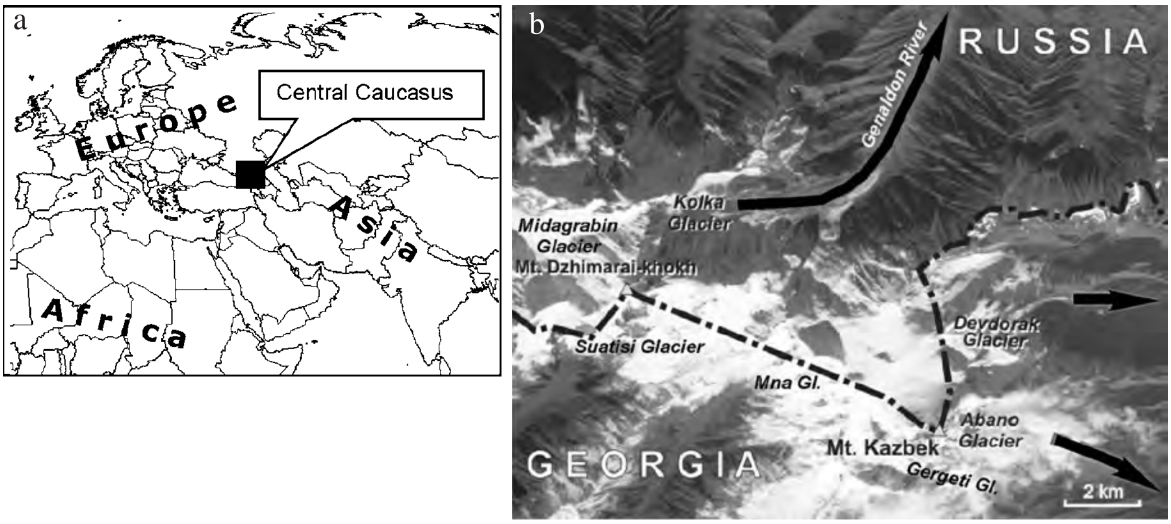

Figure 2. a) Location of the study area; b) Kazbek-Dzhimaray massif and origination sites of glacier disasters at Kolka (1902, 2002), Devdorak (1776, 1778, 1785, 1808, 1817, 1832) and Abano (1909, 1910). Image taken by V. G. Korzun from the International Space Station on October 19, 2002, within the *Uragan* monitoring programme.

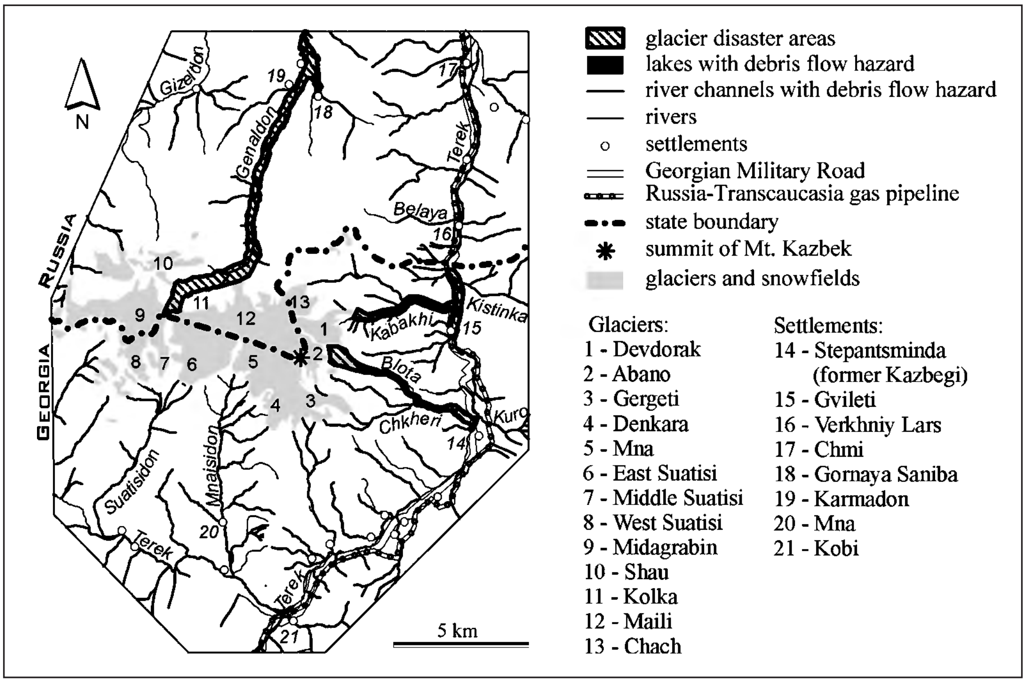

Figure 3. Glacial disasters and debris flows in Kazbek region.

This massif is a large center of contemporary glaciation covering about 13 km^2 (Katalog 1977). Since mid-19th century the glaciers here are receding. However, several are surging or advancing from time to time.

In the south and east the Terek River flows around Mt. Kazbek (Fig. 3), and then crosses the Main Caucasus Range through the Daryal gorge and flows into the Caspian Sea. All rivers originating at Mt. Kazbek are in the Terek River basin. The most significant rivers are Genaldon, Chach (Amalidon), Amilishka, Kabakhi, Blota, Chkheri, Mnaicidon, Suatisidon, and Midagrabindon. The Terek River also has several tributaries in this area, which originate outside Mt. Kazbek but are important sources of debris flows. These are Saudon, Belaya, Tagaurka, Kistinka, Kuro and some others. Debris flow deposits from these rivers and from the periglacial valleys of Mt. Kazbek form a united impact area in the Terek River valley.

Kazbek is a dormant volcano which has a principle two-headed cone and several side cones. The main cone erupted about 185,000 $\pm$ 30,000 years ago, while the side cone of New Tkarsheti erupted about 6 thousand years ago (Chernyshev et al. 2002).

3 OUR PREVIOUS STUDIES

Prior to this study we have analysed details of the 2002 disaster at Kolka glacier (Popovnin et al. 2003; Lindsey et al. 2005; Tutubalina et al. 2005) and disasters at Devdorak glacier in 18th-19th centuries (Zaporozhchenko & Chernomorets 2004), examined modern natural hazards in the area (Petrakov et al. 2004) and potential damage they can bring (Chernomorets 2005a, b), and carried out field investigations of the 2002 Kolka disaster area. We have also studied Devdorak and Abano glaciers and made field observations at Midagrabin glacier, in headwaters of Gizeldon and Tsatadon rivers, as well as in the Terek River valley. We have conducted a bathymetric survey of post-disaster temporally dammed Lake Saniba and compiled thematic maps of the Kolka glacier disaster area and its origination zone. Our group monitors glacier and debris flow hazards in the Kazbek region using satellite imagery, field research and surveying. A geographic information system of Mt. Kazbek region has been created. Results of our 12 field trips to the area and of satellite/aerial image interpretation laid the foundation for prediction of glacier/debris flow hazard development in the region until 2025 (Chernomorets et al. 2006).

4 KAZBEK BLOCKAGES: DISASTERS PRODUCED BY DEVDORAK GLACIER

4.1 *The Georgian Military Road and Kazbek blockages*

Devdorak glacier on the east slope of Mt. Kazbek has produced repeated glacier disasters in 18th-19th century, known as “Kazbek blockages”. These were dislocations of a part of the glacier snout, followed by a rapid transport of ice masses mixed with water and debris down Amilishka and Kabakhi River valleys, resulting in blockages of the Terek River valley and a major road.

This path crossing the Caucasian mountains through the valleys of Aragvi and Terek Rivers has been known for several millennia. In 1st century BC the Roman geographer Strabo wrote: “From the Nomades on the north there is a difficult ascent for three days, and then a narrow road by the side of the river Aragus, a journey of four days, which road admits only one person to pass at a time” (Hamilton & Falconer 1903, p. 231).

In early 19th century the South-Caucasian lands were added to the Russian Empire. The only way through the Caucasus range was the ancient road through Aragvi and Terek. As the traffic grew, the road was improved, fortified and named the Georgian Military Road. And then the Russian military and civil authorities faced the “Kazbek blockages”. These events forced travellers and road workers to walk on ice across the Terek River above a fearful precipice. There were casualties. Each blockage (registered in 1776, 1778, 1785, 1808, 1817 and 1832) interrupted traffic along the Georgian Military Road for long periods of time. A detailed analysis of these events is published in (Zaporozhchenko & Chernomorets 2004).

The 1776 blockage was the largest. As reported by J. Reineggs, on June 19 a thunderstorm occurred after a period of hot weather, and during the storm a gigantic ice-debris flow came from Mt. Kazbek, blocking the Terek River for three days (Statkowsky 1877). A temporary lake formed, flooding several villages. Many villagers, their cattle and possessions were drowned. Then the Terek River broke the ice dam and flooded the valley downstream, destroying bridges, dwellings and crops (Statkowsky 1877). Another event in October 1817 blocked the Terek River for one day. The resulting ice dam was about 3 km long and over 100 m high. In 1818 movement along the road was still hampered. Remains of the ice masses were still found *in situ* three years later. The blockage of 13 August 1832 is the most studied event. The ice dam in the Daryal gorge was about 100 m high and spread to the full width of the gorge (Khatisyan 1889). The dam was 2166 m long and it reached the mouth of the Kistinka River (Fig. 3). The Terek River was stopped for eight hours. Fifteen million m^3 of debris was deposited in the Terek River valley. The total deposited volume, including that in the Kabakhi River valley amounted to 22 million m^3 (Statkowsky 1877). Ice blocked the Terek River valley for two years, while the river flowed under the ice.

Since 1832 new blockages were forecasted from time to time, but either the ice-debris masses did not reach the Terek River or the forecasts failed altogether. In 1843 and 1855 Devdorak glacier advanced, raising alarm and forcing researchers to monitor its position. But the advances were slow and the Terek River valley was not blocked (Statkowsky 1877).

4.2 *Kazbek blockages as an impetus for debris flow research in the Russian Empire*

Academician German Abich attracted attention to the blockage hazard in 1861. Since 1862 special commissions studied the origin of these glacier disasters. One of these commissions was led by Boleslav Statkowsky, a pioneer of debris flow research in the Russian Empire. He introduced the Russian term *sel’* (debris flow) (Statkowsky 1859). In a later paper he wrote: “Let me describe one astonishing phenomena which is not rare in the mountains, the phenomena which no protective structures can withstand, and which is commonly named discharge or *sel’* in the Caucasus, while in the Alps it is called *Nante, Nante sauvage* and *cône de déjèction*. Usually these follow a thunderstorm in the mountains, when certain gullies, which have favourable location, eject great masses of rocks, stones, and mud.

These entrain everything on their way, and stop the transportation on the roads, sometimes for a long period of time" (Statkowsky 1877). The current meaning of the term *sel'* in Russia includes both debris flows and mudflows.

4.3 *Expectations of a new disaster*

Glacier hazards were discussed repeatedly when the glacier was active, e.g. when it advanced or seemed to start advancing in 1876 (Abich 1877; Khatisyan 1889), and 1894 (South Jersey Republican, 1 December 1894). In 20th century the glacier was subject to field research. This is the fastest moving Caucasian glacier, according to measurements of summer 1974 (Tsomaia & Aliev 1989). While most Caucasian glaciers are retreating, the Devdorak glacier snout was stationary between 1912 and 1960s and even advanced in 1969-1979. The area of the glacier was estimated at about 7 km^2 and its ice volume at about 0.5 km^3 (Panov 1993). Average thickness of the glacier snout is estimated as 70 m (Nikitin et al. 2005).

Having analysed 19th century data, we have undertaken our own field expedition in 2005 (Chernomorets et al. 2006). The Devdorak glacier terminus is currently at 2250 m (August 2005, GPS measurements on the WGS84 ellipsoid). We have georeferenced a topographic map of 1876 (Statkowsky 1877) during the fieldwork and found that the glacier terminus has retreated by about 400 m to the west from its 1876 position. It is also about 550 m west of the narrow gorge in the valley, where initial (triggering) ice blockages occurred during the disasters. The overall retreat is confirmed by comparison of multitemporal photos (Fig. 4). The initiation zone of the catastrophic ice-debris flows in 18th-19th century is located at 2050-2200 m a.s.l.

Initially Devdorak ice and entrained debris moved along the Amilishka River valley. One can still see clearly the glacier striations on the rocks exposed in the right valley wall. Below the confluence of the Amilishka River and the Chach River the mass moved along the Kabakhi River valley. Where the Kabakhi River flowed into the Terek River (1345 m a.s.l.) the flows hit the right side of the Terek River valley, turned north and then followed the Daryal gorge. Here blockages formed due to deceleration and change to low gradients.

4.4 *Discussions of the origin of Kazbek blockages*

Statkowsky (1879) explained the blockage trigger mechanism as follows: the glacier terminus jams into a narrow gorge, ice accumulates there, and lakes form behind this temporary ice dam.

When a critical mass of water and ice accumulates, it collapses down the valley. Below the narrow gorge the resulting ice-debris flow accelerated along the steep valley bed. Khatisyan (1889) criticised this description and suggested that new blockages would be possible only when the glaciers begin a new

Figure 4. Devdorak glacier terminus. Origination area of the "Kazbek blockages" of 18th-19th centuries. Left: in 1899 (Mushketov 1905); right: in 2005 (photo by O.V. Tutubalina).

period of advance. Abich (1877) considered the increase of rock failures onto the glacier as the main reason for the glacier disasters. Viskovatov (1864) mentioned that local people knew the precursors of Devdorak glacier disasters: crackling sounds at the glacier, and intermittent flow and turbid waters of the Kabakhi River, which carried chunks of ice and snow. Dukhovskoy (1916) hypothesized that the disasters stopped when the narrow gorge downstream of the glacier had widened. Vardaniants (1932) discussed possible influence of earthquakes. In our view, there is one more possible reason of the glacier activation: occasional warming of the glacier bed due to underground volcanic activity of Mt. Kazbek. This could explain exceptionally high movement velocities of Devdorak glacier.

In any case, up to the present (2006) there are no suitable conditions for a new glacier disaster at Devdorak. However, debris flows originate periodically from the glacier terminus and ice-cored moraines and reach the Terek River.

5 KOLKA GLACIER AND CATASTROPHIC FLOWS IN THE GENALDON RIVER VALLEY

The first well-documented disaster at Kolka glacier happened in 1902. On July 3 and 6, 1902, the glacier collapsed down the Genaldon River valley, and destroyed a popular hot-spring resort. Thirty-six people were killed. According to a survey 1.5 months after the disaster, the volume of ice brought to the valley amounted to 57 million m^3 (Popov 1902), and was probably closer to 70 million m^3 initially.

The Kolka glacier disaster on September 20, 2002, is the largest recorded disaster in the world involving a mountain glacier (volume of the transported material about 140 million m^3). The exceptional volume, extreme velocities and numerous casualties in the Genaldon River valley (125 people) single out this event. Origins of this disaster are the subject of ongoing discussions. The main hypotheses are: slope instability above the glacier due to small earthquakes in 2002 near the disaster origin site; warming of the glacier bed by a heat flux from the Kazbek volcano and a possible gas-dynamic explosion under the glacier; an unusually snowy winter in 2001-2002, leading to excess snow accumulation in the snowfields above the glacier; overloading of the glacier by slope failure material; and a combination of several of these factors.

The disaster was triggered by a series of unusually intensive rock and ice falls from the slopes of Mt. Dzhimaray-khokh onto the rear part of Kolka glacier. These falls started about two months before the disaster, as recorded in satellite images and mountaineers' photographs. A Landsat ETM+ image of 20 September 2002 (recorded 8.5 hours before the disaster) shows signs of activation in the rear part of the glacier. The rock and ice falls hit the south-west corner of the glacier like a billiard-cue striking a ball, and the weight of fallen rock and ice was probably pressing the glacier out to the north. A discharge of ice from the rear part of the glacier have destabilised the glacier snout. As a result, most of the glacier vacated its bed and collapsed down the valley, transforming into ice-water-debris flow on the way (Tutubalina et al. 2005).

We discriminate four subsequent stages of the disaster: i) a series of ice-debris falls from the slopes of Mt. Dzhimaray-khokh onto the rear part of Kolka glacier; ii) initial movement of the destabilised part of the glacier; iii) ice-water-debris flow across Maili glacier snout along the Genaldon River valley to the Karmadon Gates (a narrow gorge of the Skalistyy Range north of Kolka); iv) a 'conventional' glacial debris flow downstream of Karmadon Gates.

The ice-water-debris flow moved along the Genaldon River valley, running up the slopes within a belt up to 500 m wide, with velocities up to 250 km/h. Superelevations (run-ups of the flow on the slope) reached 200 m. The flow left chunks of ice pressed into channels and ravines on the slopes. The moving mass, mainly composed of Kolka glacier ice, travelled 19 km until it stopped in the narrow gorge of the Skalistyy Range. About seventy people were killed. Three to five million m^3 of material travelled further downstream as a debris flow. Waves of the flow reached 50 m in the gorge, while further down where the valley widened the waves were 1.5-2 m high. The flow contained many ice floes. It destroyed recreation centres and killed dozens of people. The impact area of the disaster was 12.7 km^2, including the initial rockfall area, zone of the initial movement, the transit path, the accumulation area in the populated Karmadon depression (Fig. 5) and the zone of the glacial debris flow further downstream.

Figure 5. Ice-debris deposits of the 2002 disaster in the Karmadon depression. 1 – Nizhnee Kani settlement not damaged by the disaster; 2 – cliffs of the Karmadon Gates. Photo by S.S. Chernomorets, August 9, 2004.

The area of the ice dam in the Karmadon depression immediately after the disaster totalled 2.1 km^2, its length 3.6 km and the volume was 115 ± 10 million m^3.

After the 2002 disaster the dominant processes in the upper Genaldon river valley were rock falls, ice accumulation and regeneration of Kolka glacier. Debris flows and hyperconcentrated flows of average magnitude occurred from time to time (e.g. we observed one on August 12 2004). In the Karmadon depression the Genaldon River channel is now open, having eroded through the ice dam. Near the Karmadon Gates the river is flowing through the former road tunnel, while the original river channel is still blocked by a huge ice plug (as of spring 2007).

After the disaster there were 13 temporally dammed lakes in the valley. Their number later reduced to 4, and the area of the surviving lakes diminished. The largest Lake Saniba decreased in volume from 4.9 million m^3 in October 2002 to 0.25 million m^3 in autumn 2005. The level of this lake dropped 19 m in the same period. A catastrophic outburst of this lake could bring extensive geomorphic changes, e.g. such as documented in Nepal (Cenderelli & Wohl 2003) but fortunately it has not happened, the surface drainage started and the lake is steadily reducing.

6 ABANO GLACIER DISASTERS: DEBRIS FLOWS IN BLOTA AND CHKHERI RIVER VALLEYS

Abano glacier is situated on the south-east slopes of Mt. Kazbek in Georgia. In early July 1909 there was a large rockfall from Mt. Bagni onto the glacier. Subsequent overloading led to fast movement of the glacier and to blockage of englacial channels. Accumulated ice, water and debris produced a series of gigantic debris flows on July 6, 1909, and again on June 14, 27 and 29, and July 3, 1910 (Dukhovskoy 1917). They went along the Blota and Chkheri rivers, destroyed the Chkheri bridge, temporarily dammed the Terek River, damaged crops and killed cattle near the Georgian Military Road. The total volume of transported material is not known (likely several million m^3). The travel path of the debris flows was 7.7 km. In 2006 Abano glacier terminus was at 2915 m. There were traces of average debris flows (tens to hundreds m^3) at its margin. These flows follow the Blota River valley and then discharge into the Chkheri River towards Terek. Average-size debris flows also arrive to the Chkheri River from moraines of Gergeti glacier.

7 RAIN-INDUCED AND GLACIAL/RAIN-INDUCED DEBRIS FLOWS IN THE KAZBEK REGION

Rain-induced and glacial/rain-induced debris flows occur nearly everywhere in the study region. Our map (Fig. 3) shows river channels which pose such hazard. Below we summarise larger debris flow events, noting that only some of them are being registered, namely those in the populated area along the Georgian Military Road.

Debris flows on the Kuro River were described as early as 19^{th} century. The river then had a Russian name of Beshenaya Balka, meaning Furious Gully. Russian poet Alexander Pushkin who crossed this river in 1829 before and after a debris flow was stunned by changes in the river channel: the gully stream, having been filled by rain waters, became mightier than the very Terek River, which also roared nearby. The river banks were torn to pieces; great boulders moved and blocked the flow (Pushkin 1974). Debris flows along the Kuro River happen 1-2 times a year. The river is now crossed by two interstate gas pipelines from Russia to Transcaucasia. Debris flow-like floods on the Genaldon River are first referenced in the archive documents in 1889. In 1885 and 1889 bridges and roads were destroyed, and field crops were damaged. Rain-induced debris flows on the Chkheri were registered on August 8 and 22, 1937 (Yermakov and Ioganson 1957).

Rare extremely strong rains induce debris flows in nearly all basins in the region. This happened in 1953 and 1967. On August 17, 1953, an extreme shower brought 127 mm of precipitation. The Terek River discharge reached 450 m^3/s (which exceeded the average flow by several times). The Chkheri River carried over 0.5 million m^3 of deposits into the main valley. A temporary lake formed where the Terek River was blocked by fans of the Ckheri and the Kuro Rivers. A subsequent outburst debris flow destroyed road and bridges for 10 km downstream. The Kabakhi River experienced a debris flood. Another debris flood along the Kistinka River brought boulders to the site of Kistinka hydropower station (Yermakov and Ioganson 1957). On August 18, 1953, a lake outburst at the edge of Mna Glacier and a flow wave 4-5 m high and 80-100 m wide went through the Mna village (Grigolia & Tsomaia 2000).

On August 5-6, 1967, debris flows occurred in most high-mountainous debris flow basins of the Central Caucasus. This was preceded by abundant rains for over a month, including a shower on August 5, 1967, which brought more than a monthly amount of water. The most catastrophic debris flow occurred in the Genaldon River valley where it transported 1.9 million m^3 of solid material (Rototaev et al. 1983). Buildings, bridges and a motor road were destroyed. Debris flows on the Terek River tributaries had volumes of 60,000 to 120,000 m^3. The Georgian Military Road was destroyed for dozens of kilometres. The Terek River discharge reached a new record of 500 m^3/s (Agibalova 1983). A gas pipeline was torn apart and the Daryal gorge was filled with flames (Grigolia & Tsomaia 2000).

On June 21-22, 2002, following prolonged extreme rains, there was a mass occurrence of small debris flows and flash floods in low to medium-height mountains of the Northern Caucasus. A flash flood on the Terek River led to closure of frontier control posts for several days. There was also damage in the Gornaya Saniba village north of Mt. Kazbek.

8 FUTURE SCENARIOS AND HAZARD ASSESSMENT

To assess future glacier disaster/debris flow hazard for the next 20 to 30 years, we should consider several scenarios. They could be subdivided into endogenically-induced scenarios and these without critical endogenous events. The first group includes eruptions, geothermal heating of glacier beds and seismic events.

Eruption of Mt. Kazbek in the next few decades is highly unlikely. However, in case lava does erupt on the plateau above Maili glacier or near Kolka glacier, the melting ice would supply the liquid component to lahars. This would have a catastrophic influence on the terrain and population along the whole Genaldon river valley. The runout distance of lahars will depend on the magnitude of the eruption. A more likely phenomenon is geothermal heating of glacier beds due to the proximity to the Kazbek volcanic centre. This can lead to glacier activation and serve as a precursor of new glacier disasters.

Earthquakes measuring over M7 on the Richter scale occurred in the Kazbek region in 1915 and 1946 (Agibalova 1983). The Racha earthquake on April 29, 1991, in a neighbouring region (80 km south-west of Kazbek) led to formation of several dozen seismogenic lakes. The two largest lakes had the total volume over 66 million m^3 and later outburst (Grigolia & Tsomaia 2000). Such events cannot be ruled out in the Kazbek region. Overall, the probability of endogenically-induced scenarios is low. More likely is the ‘usual’ scenario, involving frequent rain-induced debris flow and less frequent glacial debris flows.

Variations of debris flow activity within the region can be better explained using our concept of the cycle of catastrophic debris flow formation. The cycle includes four stages: pre-disaster preparation, the disaster, post-disaster adaptation and inter-disaster evolution (Chernomorets 2005a). Most of the Kazbek region basins are at the stage of inter-disaster evolution; however one of them, the Kolka-Genaldon basin, is at the stage of post-disaster adaptation. Therefore the Genaldon River valley is the most dynamic and presents the greatest hazard. The most likely scenario here includes events such as blockage of intraglacial drainage channels in the ice dam in the Karmadon depression, accelerated regeneration of Kolka glacier, and extreme meteorological events. However, the current debris flow potential of the Genaldon River valley is much higher than before the 2002 disaster, because the amount of ice-containing loose material is extraordinary. The greatest debris flows in the next 20-30 years are likely to be triggered by extreme rains. 80-100 mm of liquid precipitation (rains of 1-2% probability) can result in a 4 million m^3 debris flow. Such a flow can travel for 10-20 km and destroy bridges and buildings in populated areas downstream.

Currently the Devdorak glacier snout in the Kabakhi River valley has receded greatly upstream. Although no disasters happened here since 1832, they may repeat in the future if the glacier advances again due to climatic factors or geothermal heating. There is also a current hazard of glacial and rain-induced debris flows down the valley, with volumes up to 1-2 million m^3. Like the Genaldon valley, such flows are most likely in case of 60-100 mm rains over debris flow origination sites. Catastrophic flows from Devdorak glacier in Georgia potentially threaten Russian territory and interstate objects, including gas pipelines from Russia to Georgia and Armenia, and the Georgian Military Road. In case of the most extreme events bridges over the Terek River, a dam of the hydroelectric power station, frontier posts and customs terminals will come under threat. The ultimate object in danger downstream is Vladikavkaz, the capital city of the Republic of North-Ossetia-Alania in Russia. Abano, Suatisi and Mna glacier valleys will produce average debris flows, both glacial and rain-induced. At Suatisi a new glacial lake (about 300 m in diameter) may outburst, threatening a Georgian frontier guards station. Midagrabin and Chach glaciers are likely to induce small and average debris flows.

The Kuro River will continue to experience yearly debris flows. The gas pipeline crossing here requires frequent maintenance and is a site of a potential disaster as both pipelines can be damaged. Dangerous situations will also occur in the case of the debris flow fans of Kuro and Chkheri meet and produce a joint flow down the Terek River. Debris flows along the Kistinka River will threaten the Georgian Military Road, frontier posts and customs terminals.

9 DISCUSSION

We would like to stress the potential role of the Mt. Kazbek’s volcanic centre as a possible trigger of glacier disasters. Volcanic factors in the preparation of glacier disasters at Devdorak and Abano have not been discussed previously in the scientific literature, although these glaciers have unusually high velocities for the Caucasus (Tsomaia & Aliev 1989). In the case of Kolka glacier disasters researchers did consider the possibility of volcanic influence as early as 19^{th} century. Archives (Central State Archives 1889) mention that G.S. Khatisyan hypothesised a volcanogenic disaster in 1881. There are two pieces of indirect but strong evidence of volcanic factors in the Kolka glacier disaster of September 20, 2002. Firstly, a crew from the Russian Ministry of Emergencies landed on helicopter at the disaster origination site on September 24, 2002. They experienced a strong sulphuric gas smell (supposedly CO_2 with H_2S) and had to evacuate very quickly. Secondly, the Genaldon River valley has several springs with hot mineral water, whose temperature rises markedly upstream, towards the Kazbek volcanic centre. A hypothesis of explosion-like expansion of volcanic gases within the Kolka glacier has been put forward to explain the 2002 disaster (Muravyev 2004). We strongly believe that Kazbek glacier disasters on different sides of and nearby the volcano should be considered as phenomena potentially of the same origin. There is no other locality in the Caucasus with repeated glacier disasters. Since the

Kazbek volcanic chamber is still heated (Muravyev 2004), the resulting geothermal flux could be one of the keys to unusual behaviour of Kazbek glaciers.

Why were disasters noted on only three of over a dozen of glaciers in the Kazbek locality? This could be because of local conditions (such as seismotectonics, geothermal flux values, orographic features, etc.) or perhaps because disasters on other glaciers were simply not registered.

We would also like to note some acute terminology problems. The 19th century term ‘blockage’, applied to both the process of Devdorak glacier disasters, and the ice dams in the Terek River valley created by these disasters, is no longer in use. The more contemporary terms also do not describe the glacier disaster phenomena adequately. For example, Statkowsky (1877) considered Kazbek blockages as debris flows. However, in modern terms, glacier disasters differ from conventional debris flows by very high velocities and also by mechanism of movement. Analysis of the Kolka glacier disaster in 2002 indicates that such gravitational mass movements have properties of several processes at once. Various sources termed this disaster as glacier collapse, catastrophic glacial surge, glacier-slip which triggered floods, ice-rock avalanche/debris flow, mudslide, glacier disaster, ice avalanche, rock-ice slide etc. (Chernomorets 2005a). We can say that this is a special case of a multi-stage catastrophic event which includes rockfall-, avalanche-, landslide- and debris-flow-type movement, but does not belong entirely to any single type.

A more general question arises: where is the boundary between glacier and debris flow disasters? It is clear that catastrophic flows such as Kolka are not conventional debris flows, but they do have a debris flow component. Glacier disasters are also precursors to catastrophic debris flows because glacier flows leave a lot of solid material and decaying ice masses. Slope processes become more active and for several years after a glacier disaster debris flows occur in the impacted valley with much increased frequency. Small debris flows occur nearly daily in summer in many slope channels until the ice remnants melt away. Average and large debris flows also occur, and their origin sites are located in new places compared to the period before the glacier disaster.

10 CONCLUSION

The current period of climate change increases geological hazards in periglacial areas. Glacier degradation frees large volumes of water. Water accumulates in glaciers during the ablation period, in glacial lakes and when the stagnant ice melts. In summer this water abruptly increases river discharge and slope instability. Often this leads to catastrophic flows, sometimes also influenced by geothermal heating. Depending on the presence of a dam and on the ratio between the debris, water and ice available, debris flows, ice-debris flows, ice avalanches, debris floods, hyperconcentrated flows and glacial lake outburst floods can form. These processes may be likened to ‘arrows’ from the periglacial areas, which hit downstream areas. The ‘flight’ of such an ‘arrow’ can be for dozens of kilometres. Detailed studies of glacier and debris flow disasters in the Mt. Kazbek region can help hazard assessment in other glaciated regions of the world.

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