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Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002

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ABSTRACT

In September 2002, a catastrophic geomorphic event occurred in the Caucasus Mountains, southern Russia, in which almost the entire mass of Kolka Glacier detached from its bed, accelerated to a very high velocity (max. 65–80 m/s), and traveled a total distance of 19 km downstream as a glacier-debris flow. Based on the interpretation of satellite imagery obtained only 8.5 h before the event occurred, the analysis of seismograms from nearby seismic stations, and subsequent detailed field observations and measurements, we suggest that this remarkable event was not a response to impulse loading from a rock avalanche in the mountainside above the glacier, or to glacier surging, but due entirely to the static and delayed catastrophic response of the Kolka glacier to ice and debris loading over a period of months prior to the September 20 detachment. We reconstruct the glacier-debris flow using field observations in conjunction with the interpretation of seismographs from nearby seismic stations and successfully simulate the behaviour (runout, velocity, and deposition) of the post-detachment glacier-debris flow using a three-dimensional analytical model. Our demonstration of a standing-start hypothesis in the 2002 Kolka Glacier detachment has substantial implications for glacier hazard assessment and risk management strategies in valleys downstream from unstable debris-covered glaciers in the mountain regions of the world.

1. Introduction

Hazardous, glacier-related processes have caused significant disasters in the glacierised mountains of the world in the last 100 years (Evans and Clague, 1994; Petrakov et al., 2008). They include outbursts from moraine and glacier-dammed lakes, glacier avalanches, and landslides/debris flows in the glacier environment. These events have taken place in the context of dramatic retreat of glaciers in response to climate change (e.g., Duyurgerov and Meier, 2000).

Shortly after 20:00 h in the evening of 20 September 2002, a complex catastrophic mass movement occurred in the Genaldon Valley, Caucasus Mountains, Republic of North Ossetia, Russian Federation (Fig. 1). It involved the almost complete mobilization of the ice mass of the Kolka Glacier and its extremely rapid transport to the Karmadon Depression, 19 km downstream from the highest point of the glacier detachment (Fig. 2). The event has previously been documented and described (Kotlyakov et al., 2002; Popovnin et al., 2003; Kotlyakov et al., 2004; Haeberli et al., 2004; Huggel et al., 2005; Lindsey et al., 2005; Drobyshev, 2006), but its mechanism is only understood in broad outline and important questions remain.

Two major conflicting hypotheses have emerged to explain this exceptional event in which a 2.7-km-long glacier mass detached from its bed (Fig. 3), accelerated to 65 m/s in under 6 km, and then traveled a further 13 km downstream as an extremely rapid glacier-debris flow. The first hypothesis requires a massive rock slope failure to occur on the slope above the glacier surface and impact on the glacier thus giving the ice mass a kick-start in its catastrophic movement (the impact hypothesis) (Haeberli et al., 2004; Huggel et al., 2005). The second hypothesis, in contrast, suggests that the catastrophic movement of the Kolka Glacier was due to a sudden conventional glacier surge initiated by high water pressures within and beneath the Kolka Glacier (the surge hypothesis) (Kotlyakov et al., 2002, 2004).

In this paper we present a third hypothesis which suggests that the Kolka Glacier detached from its bed due to a catastrophic loss in effective stress due to excess water pressures developed within the ice mass and/ or in the glacier bed without the kick-start of the impact of a rock avalanche from the adjacent mountain wall. As we note below the event was not witnessed neither were detailed glaciological observations

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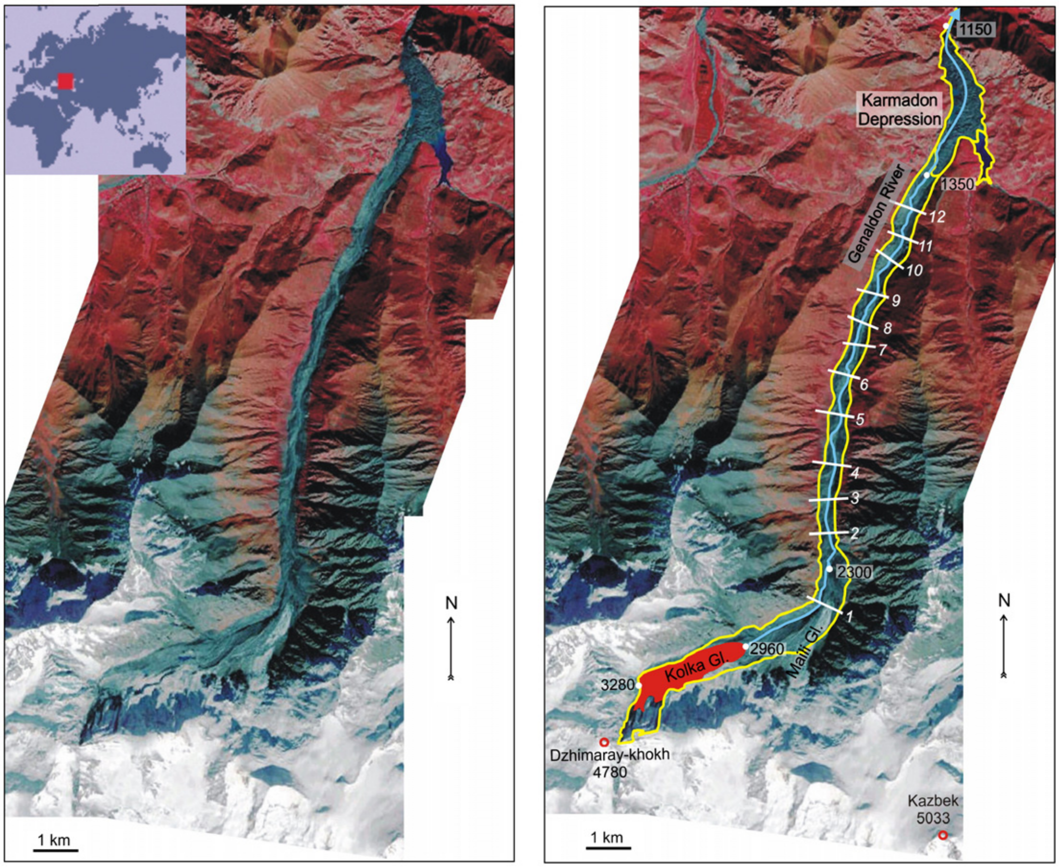

Fig. 1. A post-event Terra ASTER satellite image of the Genaldon valley obtained 6 October 2002. Annotated version is on right. Yellow line outlines the path of the 20 September glacier-debris flow. It also shows the boundaries of the ice-debris dam formed in Karmadon Depression and of a large temporary lake SE of the dam. Kolka Glacier (in red) lies at the base of the northern slopes of Mt Dzhimaray-khokh. Mount Kazbek is a dormant Quaternary volcano. Light-blue line along the Genaldon River is the approximate centerline of the glacier debris flow. Numbers of cross sections correspond to those in Fig. 5. Some elevations are shown along the path. Inset map shows location of study area.

carried out immediately before the catastrophe. Thus our hypothesis is constructed exclusively from the interpretation of indirect evidence.

We note that Kolka Glacier has been comparatively well studied since at least 1969 (Rototayev et al., 1983) and its behaviour has been generally known since the beginning of the twentieth century (Stoeber, 1903; Pervago, 1904; Poggenpohl, 1905). It is known to be an unstable glacier, and conventional surges, during which the glacier ice mass was not dislocated, occurred in the autumn/winter of 1834/1835 (Pastukhov, 1889–91) and 1969/1970 (Rototayev et al., 1983). Similar catastrophic, glacier-related events involving Devdorak Glacier have occurred in the same region during the last 120 years (Statkowsky, 1879).

2. Pre-event conditions at Kolka Glacier

Early in the summer months of 2002, mountaineers noticed many rockfalls and ice falls originating in the steep northern slope of Mt Dzhimarai-khokh (4780 m) and the deposition of this debris on the surface of the Kolka Glacier between el 3100 and 3300 masl (Fig. 3). Our analysis of satellite imagery shows that this supply of debris continued in July and August through to 20 September 2002 in sporadic but large rock slope failures and glacier avalanches. Examination of a Landsat 7 ETM+ image taken at 11:31 local time on 20 September shows the immediate pre-detachment conditions which existed on the surface of Kolka Glacier and the northern slopes of Dzhimarai-khokh (Fig. 4A). Comparison of this image with a post-event QuickBird image (Huggel et al., 2005) taken on 25 September shows no significant difference in the rockslope geomorphology immediately prior to the event that was initiated shortly after 20:00 h on 20 September (Fig. 4B).

We therefore conclude that no massive catastrophic rock slope failure occurred immediately prior to the event sufficiently large to produce the triggering impact. However, the images of 20 September

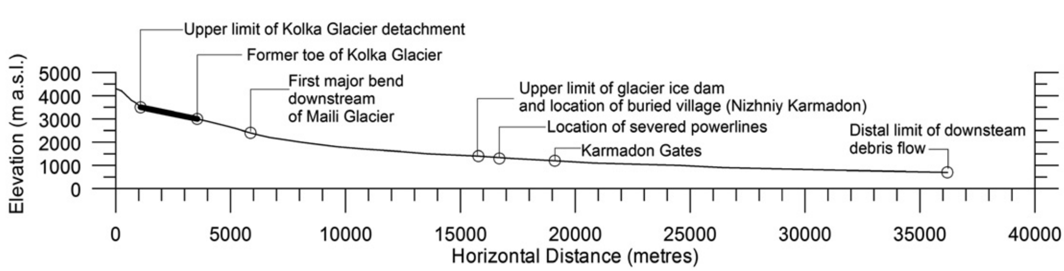

Fig. 2. Profile of 2002 Kolka Glacier detachment and subsequent catastrophic glacier-debris flow. Localities are referred to in text. Kolka Glacier debris was retained by Karmadon Gates. Distal debris flow continued downstream from this point to a total of 36 km from the source of the event.

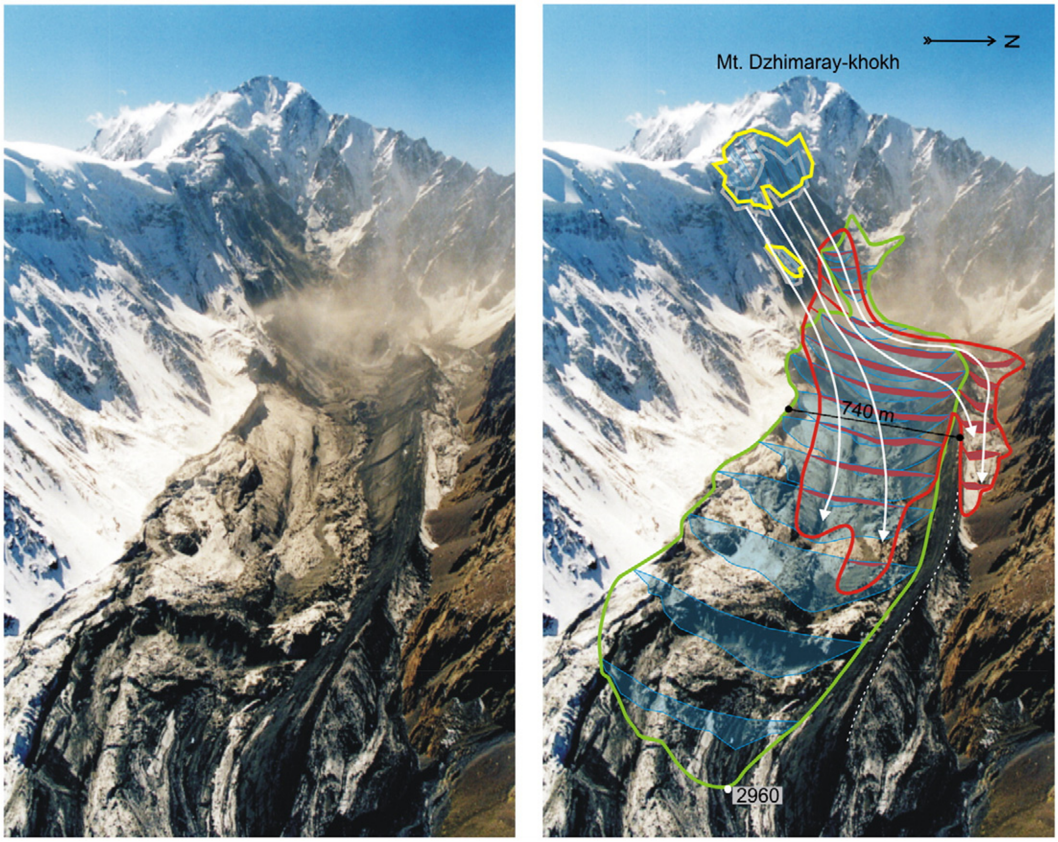

Fig. 3. Reconstruction of the predetachment volume of Kolka Glacier and of hanging glaciers that collapsed onto the Kolka Glacier in the period July–September 2002 (modified after Drobyshev, 2006). Background photograph is a post-event image by G.A. Dolgov, looking from the NE, taken on 22 September 2002. Annotated version is on right. Cross sections showing removed glacier ice (blue) and debris cover (orange) were reconstructed by comparison with four oriented and scaled ground photos taken in the period 2000–2002. In 2004, the cross sections were validated geodetically in the field. According to our reconstruction, the total volume of the ice and debris removed from the Kolka Glacier cirque on 20 September 2002 exceeds 130 M m^3. Yellow outlines show the reconstructed top surface of collapsed hanging glaciers (grey: bottom surface); blue outlines show the boundary of Kolka Glacier in August 2002; red outlines show boundary of the main ice and debris trail accumulated in July–September 2002; white arrows show the primary directions of ice and debris failures in July–September 2002; white dotted line shows left lateral moraine of Kolka Glacier.

do show a differential vertical displacement and partial dislocation of the Kolka Glacier ice mass indicating its response to ice and rock debris loading. A similar response to ice and debris loading has been noted in studies of other unstable glaciers elsewhere in the world (Post, 1967; Reid, 1969; Gardner and Hewitt, 1990; Hewitt, 1998; Milana, 2004, 2007). We note that these are not surge-type movements in the conventional sense.

The newly dislocated and elevated area of Kolka Glacier was displaced across the left lateral moraine to form a positive relief feature. From the shadow geometry (Fig. 4A) we estimate its height to have been about 50 m above the lateral moraine of the glacier. We estimate the volume of the supraglacial ice and debris to be in the order of 15 M m^3, and note that it is asymmetrically piled with greatest thickness near the base of the slope of Mt Dzhimaray-khokh, i.e., the southern margin of Kolka Glacier. We suggest that the surface rise northward was due to glacial ice deformation resulting from glacier sliding under the debris load, involving the development of a depression in the glacier surface along its southern margin. Strongly suggestive of this is the presence of a fresh ice cliff on the south side of the Kolka Glacier (4 in Fig. 4A), which runs parallel to the northern boundary of the new surface rise. Satellite imagery shows that the cliff appeared shortly before the 20 September event and formed part of the main trace of the Kolka Glacier detachment 8.5 h later (Fig. 4B).

We thus propose a third hypothesis (the standing-start hypothesis) which requires the debris-covered glacier to catastrophically detach from its bed, independent of a surging movement and without the kick-start of a massive ice-rock avalanche impact on its surface.

We hypothesise that the dislocation of the Kolka Glacier in response to ice-debris loading disrupted the internal drainage of the glacier (e.g., Fountain et al., 2005) and led to the development of excess water pressures at its base. This in turn led to a catastrophic decrease in effective stress and an almost complete loss of frictional resistance at the base of the glacier, which subsequently led to the detachment from its bed that has an average slope of only 9°. The thickness of the detached ice mass varied from about 85 m near the glacier toe to a maximum of about 175 m. Examination of post-event satellite imagery (Fig. 4B) suggests that the downstream detachment was initiated by the upper part of the glacier sliding over the toe region below el 3150 masl. (where it spilled over the left lateral moraine) incorporating it into the movement. In order to detach on such a low angle surface, this mechanism requires the development of extremely high water pressures, resulting in catastrophic basal instability.

The summer of 2002 had not been particularly warm but June–September precipitation was approximately 40% higher than average. We should also note the presence of geothermal springs in the vicinity of Kolka Glacier, with the hottest springs (up to 58 °C) in the upper part of the Genaldon Valley, only 3.5 km from the Kolka Glacier terminus. This is linked to the activity of the Mt. Kazbek volcanic centre, and it is possible that similar geothermal activity takes place under the bed of Kolka Glacier and contributes to its instability.

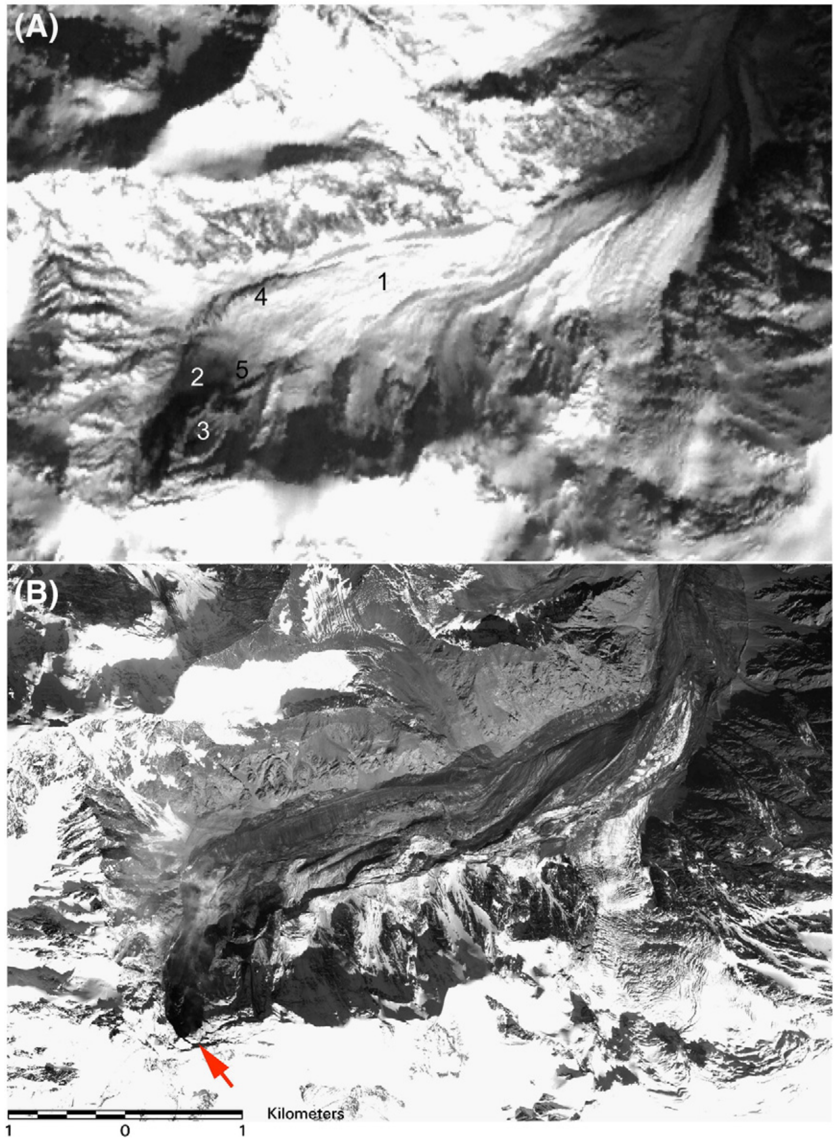

Fig. 4. (A). Landsat ETM+ satellite image obtained 20 September 2002, 11:31 am (local time); Kolka Glacier (1) is covered by new snow, with a very fresh and large (0.17 km^2) debris trail (2). Also note exposed bed (3) of the former hanging glacier that entirely collapsed between 19 August and 20 September 2002, a pronounced shadow (4) indicating a 50-m-high margin of a northward glacier surface rise, and another shadow (5) of a high ice cliff where Kolka Glacier has already started to deform 8.5 h before the catastrophic detachment at about 20:05 h local time. (B) QuickBird image taken on 25 September 2002 (©2007 Google™, 2008 DigitalGlobe). Note that there is very little difference in morphology of the mountain slope above the Kolka glacier (arrow), compared to the image of 20 September 2002 in (A).

Prior to 20 September 2002, the Kolka Glacier was broadly 3.1 km long, 450 to 800 m wide (average width 700 m), and extended from 4300 to 2960 masl (Fig. 2).

3. Reconstruction of the 20 September event

The event was not witnessed and the sequence of events can only be reconstructed from indirect evidence, which in our case consists of seismograms from nearby seismic stations (Godzikovskaya et al., 2004; Zaalishvili et al., 2004), pre- and post-event satellite imagery, and post-event field observations and measurements obtained in eleven field expeditions to the Kolka Glacier in the period 2002–2008. The seismic stations used were Tsey (regional state station, 45 km west of Genaldon valley — continuous analog recording), ATsRSS-11 Zaramag (temporary station, 38 km west — trigger-based digital recording), and a North-Ossetian network of five Alpha-Geon trigger-based digital stations located in Vladikavkaz, Ardon, Fiagdon, Chikola and Zamankul.

The local time for the seismic records of the Kolka glacier disaster was calculated as Greenwich Mean Time recorded at Station Tsey + 4 h minus 30 s (an offset to account for signal delay over 45 km distance from Genaldon valley to Tsey). We interpreted the seismic data following Zaalishvili et al. (2004) in which they defined "arbitrary energy units" which are simply a velocity of displacement of the seismic sensor V, raised to the power of two. The velocities were taken from velocigrams recorded at the seismic stations noted above. They assumed that V^2 is proportional to the energy produced by the catastrophic mass movement, as recorded by the seismic station.

Based on our interpretation of seismograms recorded at the seven seismic stations in the Caucasus region, we reconstruct the event as follows. According to the Tsey Station record, the detachment was initiated at 20:04:43 h local summer time on September 20, 2002. Initial deformations and loss of glacier stability are indicated by weak signals (Fig. 5A). We note that the seismograms do not show any evidence of an impact that may have been associated with a large slope failure from Mt. Dzhimaray-khokh as is required with the impact hypothesis. At about 20:08:35, seismic signals start to increase (Fig. 5A) as ~130 M m^3 of glacier ice (including about three-quarters of the entire mass of the Kolka Glacier together with all of the recently

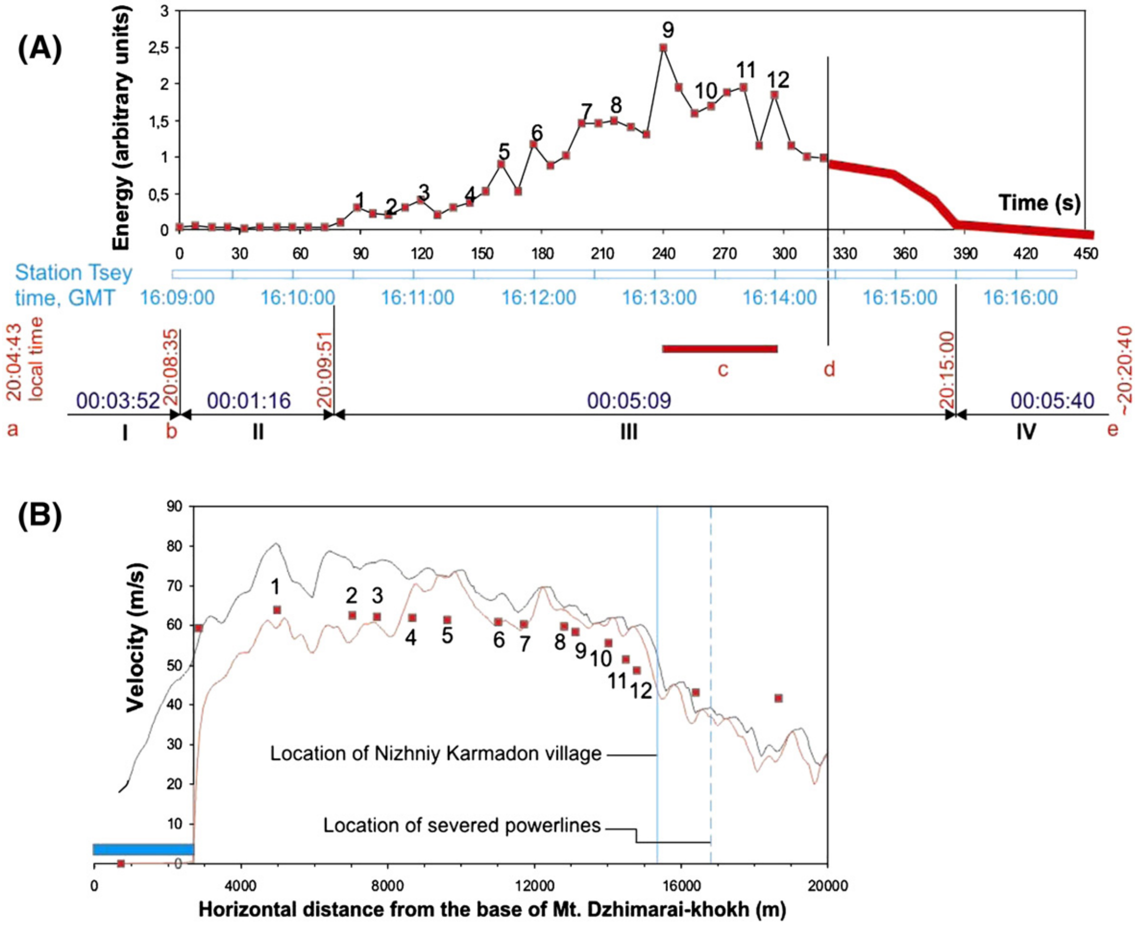

Fig. 5. Reconstruction and modeling of the 20 September 2002 Kolka Glacier detachment and subsequent catastrophic glacier-debris flow. (A) Summary energy vector graph from the 320-s-long digital seismic record of the trigger-based Fiagdon Station, matched to the timescale of the 960-s-long analog record of the continuously recording Tsey Station. Numbers correspond to numbered cross sections of Genaldon Valley in Fig. 1. Key to time marks: a — an arbitrary start of the Tsey Station record; b — start of the triggered Fiagdon Station record; c — period of maximum summary energy vectors corresponding to the deflection from the lobes of two landslides present in the valley-side slopes of the Genaldon Valley; e — end of the Fiagdon Station record. The remaining part of the energy vector graph (thick red line) is reconstructed using the Tsey Station record: e — end of the Tsey Station record. Key to time intervals: I — development of fractures in Kolka Glacier and its loss of stability; II — acceleration of the glacier-debris flow toward the turn downstream of the Maili Glacier; III — movement of the glacier-debris flow from the Maili Glacier turn to the Karmadon Depression and impact with the Skalistyi Range; IV — distal debris flow downstream of the Skalistyi range. Blue numbers show duration of the intervals (hh:mm:ss). Seismic and velocity data derived from primary seismological interpretations (Drobyshev, 2006). Numbers refer to cross sections in Fig. 1 (modified after Drobyshev, 2006). (B) Comparison of velocities estimated from superelevation geometry (calculated from Chow, 1957) and seismic data (red squares) with those modeled by DAN-3D (red and black continuous lines). The simulated velocity from DAN-3D is that of the front of the glacier-debris flow (red line) and the maximum velocity (black line) along its path. Predetachment extent of Kolka Glacier is shown by blue rectangle. For the velocity estimates, the starting point of the movement is taken to be 500 m downstream from the foot of Mt. Dzhimarai-khokh. Numbers refer to cross sections in Fig. 1.

accumulated ice and debris on the glacier surface) detached from its bed and rapidly accelerated in its travel down the Genaldon valley. The mass literally flew over the distal part of the Maili Glacier and made a 50° turn to the north, over 4.8 km from its starting point.

At this bend (located on Fig. 2), the surface of the debris was dramatically superelevated as it deflected off the east valley wall and was diverted downstream (Fig. 1). The Fiagdon Station seismogram records the impact of the mass against the valley side after this turn, and it is timed in the interval of 76 to 90 s (ending at cross section 1 in Fig. 5A), indicating a velocity of about 65 m/s, equivalent to an acceleration of 0.8 m/s^2 for the initial part of its travel. The mass of glacial ice and debris continued downstream following the bends in the Genaldon valley. The collision of the debris with the valley wall in these bends is recorded in the seismograms recorded at the Tsey and Fiagdon Stations. From these records, we are able to construct a detailed energy profile of the glacier-debris flow (Fig. 5A) from which we derived velocity estimates. We matched these velocities with those calculated from the superelevations of the debris surface measured in the bends in the valley path and obtained a good correspondence (Drobyshev, 2006). In Fig. 5B, the derived estimates of velocity along the path are shown.

At a path distance of 15.5 km (and 5.5 min after the initiation of the event) the village of Nizhniy Karmadon was overwhelmed in the valley bottom of the Genaldon River. Several dozen people were killed, including the famous Russian actor Sergey Bodrov who was filming in the valley that day. Power cables crossing the Genaldon valley at a path distance of 16.5 km (located in Fig. 2) were snapped by the debris at 20:14:30 h, and the glacier mass came to a halt as it slammed into the Skalistyi mountain range at 20:15:00 h local time (Fig. 5A and B).

All these data indicate an event duration of about 390 s over a travel distance of 19.2 km from the toe of Mt. Dzhimarai-khokh (or 19.5 km from the upper boundary of pre-disaster Kolka Glacier) and a remarkable average velocity of about 50 m/s over an average valley gradient from the rear part of the glacier of only 6°. We note that this slope angle is coincident with estimates of the coefficient of kinetic friction of rock debris sliding on ice (McSaveney, 1978, 2002). Some saturated debris moved through the Karmadon Gates and traveled farther down the Genaldon valley as a rapidly moving debris flow resulting in further casualties, bringing the total number of fatalities to 125. At the end of the movement, we estimate that 110 M m^3 of glacier ice was deposited in the Karmadon Depression between 1350 and

1150 masl (Figs. 2 and 6). Approximately 3–5 M m^3 of glacial ice and debris constituted the downstream debris flow (Fig. 2).

Similar events to that of September 2002 involving the Kolka Glacier have previously occurred in the Genaldon River valley, suggesting that the Kolka glacier is especially prone to catastrophic detachment. In 1902, Kolka Glacier experienced a two-stage detachment on 3–6 July (Stoeber, 1903; Poggenpohl, 1905). The glacier mass traveled a shorter distance than in 2002, stopping 6 km upstream of the Skalistyi range, for a total travel distance of about 11 km. In 1902, there were 36 fatalities.

In the winter of 1969–1970 Kolka Glacier experienced a conventional surge, advancing for 4 km over a period of more than 100 days (Rototayev et al., 1983).

4. Dynamic analysis using DAN-3D

A digital-terrain model (DTM) at a resolution of 50 m was developed from existing detailed topographic maps and used as a topographic base to model the 2002 Kolka event with a numerical dynamic model DAN-3D (McDougall and Hungr, 2004; Hungr and McDougall, 2008). The model was developed expressly for simulation of motion of extremely rapid landslides. Input consists of a DTM of the rupture surface of the landslide and the pre-slide path downslope from the source and a thickness file mapping the distribution of material within the source. The model assumes that the source volume instantly changes into a fluid with specific, non-Newtonian properties and flows over the irregular surface describing the pre-slide topography. Rheology of the flowing material can be represented by several alternative relationships (Hungr, 1995; McDougall and Hungr, 2004; Hungr and McDougall, 2008). The numerical algorithm is based on a Lagrangian solution of the equations of momentum and mass conservation, implemented in the framework of smoothed-particle hydrodynamics (McDougall and Hungr, 2004). The model has been extensively tested and applied to a variety of mobile landslide types and is described in detail by Hungr and McDougall (2008).

The rheological relationship selected for the present analysis was the Voellmy resistance model (Voellmy, 1955), which has previously showed good results in a number of analyses of rock avalanches, some involving glacial ice (Hungr and Evans, 1996). The model combines frictional and turbulent behaviour, so that the resisting stress at the base of a flow equals:

$$\tau_{zx} = -\left(\sigma_z f + \frac{\rho g v_x^2}{\xi} \right) \qquad (1)$$

where σ_z is the total normal stress at the base, f is the friction coefficient, ρ is density of the material, v_x the mean flow velocity, and ξ is the so-called turbulence parameter (equal to the square of the Chézy coefficient). The first term on the right side accounts for the frictional component of resistance (moderated by water-pressure effects). The second term is similar to the Chézy equation for turbulent flow and covers all possible sources of velocity-dependent resistance. Following the "Equivalent Fluid" approach (Hungr, 1995), these parameters must be determined in a back-analysis by trial and error, so as to optimally match velocity, depth and travel distance of the flow. In this case, the best match was obtained with an $f=0.05$ and $\xi=1000$ m/s^2, parameters that are close to those used in several other analyses of large landslides involving substantial percentage of glacial ice, in the flowing mass, or in the substrate (Hungr and Evans, 1996). No rheology changes were implemented along the path, as there was no evidence of a significant change in the behaviour of the actual event upstream of the Karmadon Gates. The density of the moving mass was taken as 1000 kg/m^3, assuming that most of the mass was glacier ice, contaminated with englacial rock debris.

After careful consideration of the evidence interpreted from satellite images (see Fig. 4) the glacier-debris flow was simulated from a standing start (initial velocity=0). The model successfully simulated the velocity profile along the path, event duration, the sinuous motion of the flow, the depositional pattern along its path (including the main deposit in the Karmadon Depression), and the run-out distance (Figs. 5B and 7). We note in Fig. 5B that the correspondence to the derived velocity estimates is good for the modeled front velocities but slightly below the results for maximum velocity of the flow.

The friction coefficient, defined by Voellmy as the ratio of total bed-normal stress to basal shear stress, represents the threshold slope

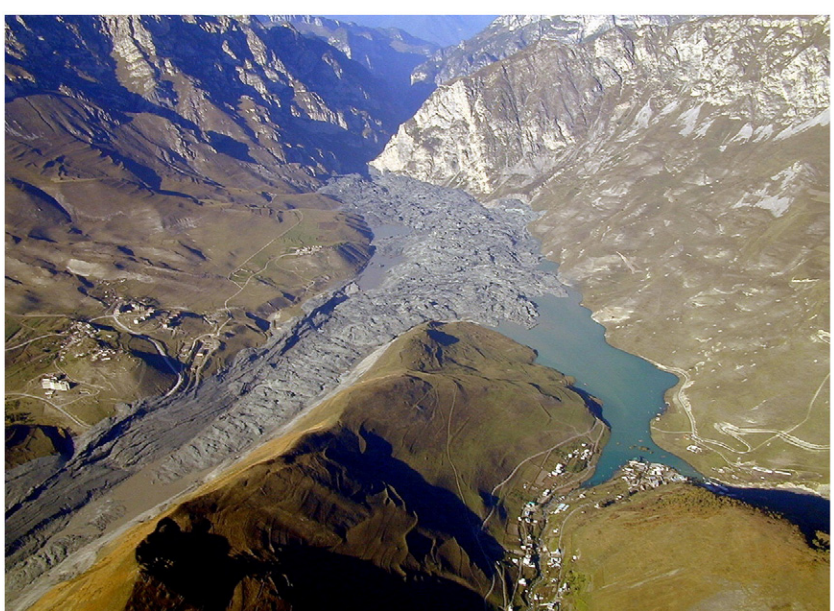

Fig. 6. Glacier ice mass deposit in Karmadon Depression, looking from the south toward the Skalistyi Range. Left foreground: roads towards the buried village of Nizhniy Karmadon disappear under the ice and debris mass. Large temporary dammed lake formed in the village of Gornaya Saniba is visible to the right of centre, and the narrow gorge in the Skalistyi Range (the Karmadon Gates) is visible just above the left of centre (helicopter photo by Igor Galushkin, 6 October 2002).

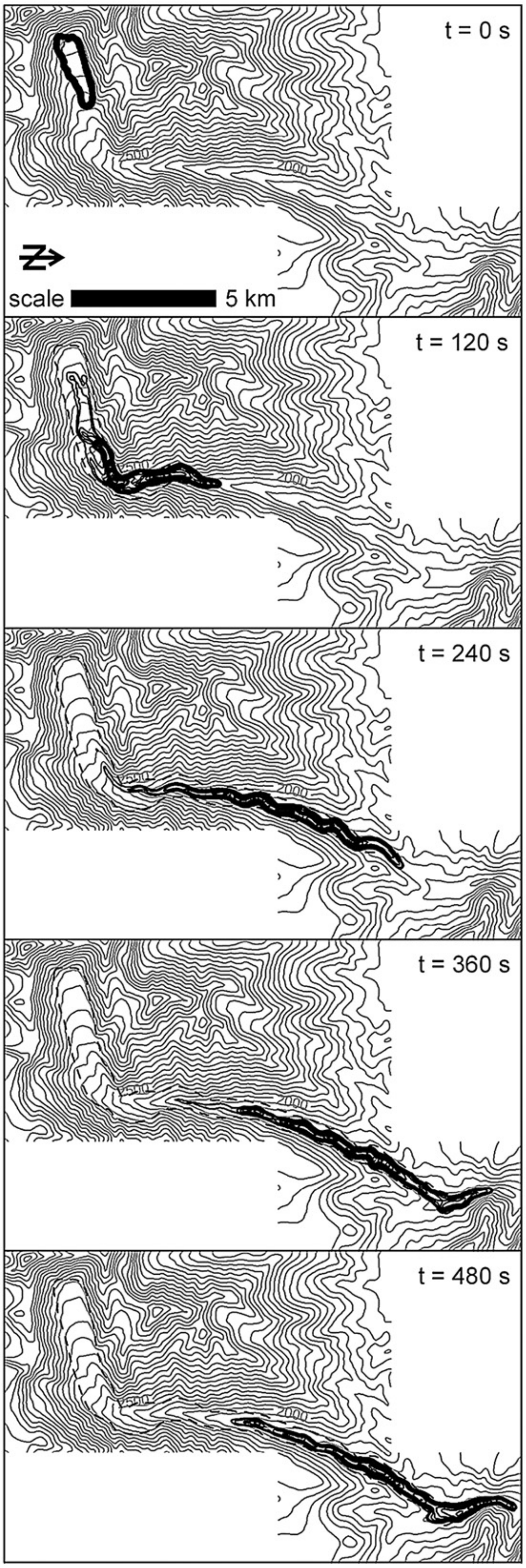

Fig. 7. Results of DAN-3D simulation of the post-detachment glacier-debris flow showing progression of movement in four 120-s time intervals. The dashed line represents the simulated flow trimline, and the solid lines represent the simulated flow/deposit depths at 10-m intervals. The surface elevation contours are at 100-m intervals.

gradient above which the slide mass will move. In this case it was tightly constrained by the limiting equilibrium conditions at both startup and finish of the glacier-debris movement; the value we used was slightly lower than the average slope gradient in the initiation zone, to reflect water pressure effects in reducing frictional resistance in initial detachment, but slightly higher than the average slope gradient in the Karmadon Depression, which allowed the bulk of the mass to deposit there. The turbulence parameter was tightly constrained by the requirement to match the independent velocity and duration estimates.

Although our approach is empirical, physical justification for use of the Voellmy model may have been provided by the results of Bagnold (1954), who showed that both the effective normal stress and the shear stress in a dense dispersion of grains in a fluid, rapidly sheared at constant volume, are proportional to the square of the shear strain rate. While this is still frictional behaviour, Voellmy's frictional term, defined only in terms of total stress, is unable to account for it. In effect, the turbulence-style term provides a correction that mimics the influence of velocity-dependent effective stress changes.

5. Conclusions

The catastrophic detachment of a glacier from its bed, which we term “Kolka-type behaviour,” may be viewed as the ultimate expression of glacier instability. The resultant phenomenon can be termed a glacier-debris flow and has important differences from a conventional glacier surge. The extreme velocities (>10 m/s) documented in the Kolka case compare to velocities measured in surging glaciers (>10 m/d) and the velocities of “normal” glacier advance (>10 m/year). This spectrum of velocities suggests a new typology of glacier movement.

Glacier instability involving Kolka-type behaviour involves a complete catastrophic detachment of the glacier mass from its bed, extreme velocities, and large superelevations of the traveling glacier-debris flow along its long runout path. Such characteristics make the Kolka events of 2002 and 1902 a distinctive type of glacier hazard that requires a distinctive mitigation approach. Our demonstration of the standing-start hypothesis in the 2002 Kolka case has substantial implications for glacier hazard assessment and risk management strategies in valleys downstream from unstable, debris-covered glaciers in the mountain regions of the world.

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