Glacial catastrophe of 20 September 2002 in North Osetia

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Received 25 February 2006; revised 18 August 2006; accepted 2 September 2006; published 28 November 2006.

[1] The aim of this study was to reconstruct the main parameters of the catastrophe, using the data obtained as a result of instrumental measurements. The parameters of the catastrophe were estimated, and the volumes of the collapsed firn massif and body of the Kolka Glacier were calculated. Also reported in this paper are the results of the topographic monitoring of the glacier barrier in the Karmadon Basin. Using the seismic records available, the speed of the glacier demolition down the Genaldon Ravine was calculated. It is assumed that the main cause that had initiated the beginning of the catastrophic process was the seismic effect resulting in the origin of fumarolic emanations under the firn field in July 2002 (two months before the catastrophe) and its gradual destruction in the course of termocarst development. *INDEX TERMS:* 0720 Cryosphere: Glaciers; 1620 Global Change: Climate dynamics; 1621 Global Change: Cryospheric change; *KEYWORDS:* mountain glaciers, firn massifs, avalanches, landslides, earthquakes.

Citation: Drobyshev, V. N. (2006), Glacial catastrophe of 20 September 2002 in North Osetia, *Russ. J. Earth. Sci., 8,* ES4004, doi:10.2205/2006ES000207.

Introduction

[2] The year of 2002 happened to be a disastrous year for North Osetia. In 21 June a catastrophic shower broke down. Thousands of large, huge, and small mud flows produced devastating destructions of the roads, high-voltage electric energy transmission lines, bridges, living houses, and industrial buildings in mountainous regions. The northern part of the Gornaya Osetia territory was paralized for a long period of time. Three months later the echo of the new tragedy in the Genaldon Ravine flied around the world.

[3] The dismal reputation of the small Kolka Glacier residing at the northern slope of the Bokovoi Range in the Central Caucasus, not far from the Kazbek Mountain, was attested by its new catastrophic demolition of 20 September 2002 (see Figure 1).

[4] This catastrophe took place during deep twilight and was highly impetuous. As reported by eyewitnesses, the glacier avalanche moved down the Genaldon Ravine at the rate of 200–300 km hour^{-1}. It travelled a way of 19 km for the time slightly more than 6 min and left a gigantic trail more than 500 m wide (Figure 2). The splashes of the leading wave over the sides of the ravine rose as high as 200–250 m. The natural obstruction for the further motion of the gigantic avalanche was the escarpment of the Skalistyi Range, after the crossing of which the Genaldon Ravine lost its classic valley shape and was transformed to a deep and narrow canyon. Nevertheless, this canyon did not serve as an obstacle for a mud and ice wave traveling in front of the avalanche. The mudflow swell, as high as 30–40 m, travelled over 5.5 km of the canyon, 30–80 m wide, at a rate of more than 100 km hour^{-1}. It was only after it left the zone of the Skalistyi Range, where the canyon grows wider again, the wave began to slow down, still travelling over a distance of almost 12 km. Only 2 km remained to reach the Gizel large flat-land settlement. To sum up, the total size of the zone affected by the catastrophic processes amounted to 37 km, covering an area of 15.7 km^2 (Figure 3).

[5] The not numerous eyewitnesses of the avalanche movement, namely, the natives of the Karmadon basin region, guessed immediately that the Kolka Glacier was falling (Figure 4). The old Osetian villages are located in this ravine high above the river, and could not be reached by the avalanche. Since old times the high-landers knew about the periodical landslides of this glacier. The scarce data about the 1835 catastrophic landslide are followed by the much more detailed description of the catastrophe of 3 July, 1902, reported by R. R. Leitsinger, including the death of 32 human beings and 1700 of cattle. On the third day after the catastrophe, one more avalanche rashed along the ravine, which killed four men who were looking for the lost people. At that time the ice and rock mass stopped at a distance of 6 km from the Skalistyi Range escarpment. During the motion which began in the autumn of 1969 the Kolka

ISSN: 1681–1208 (online)

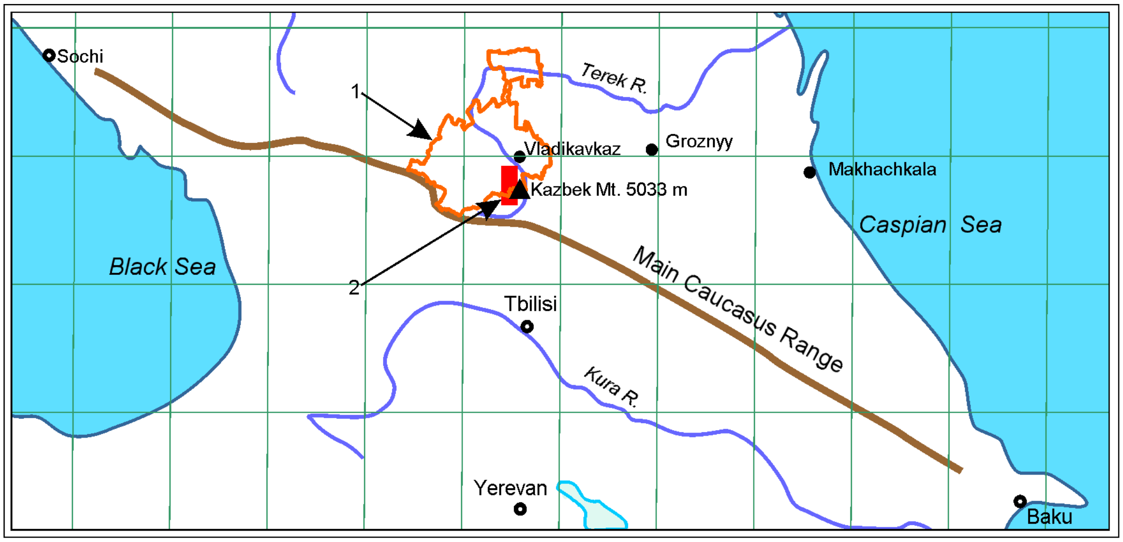

Figure 1. Geographic explication for the area of the glacial catastrophe of 20 September 2002, in the Genaldon Canyon, North Osetia (North Osetia-Alaniya Republic). 1 – Boundary of the North Osetia-Alaniya Republic; 2 – Area of glacial catastrophe.

Glacier manifested itself as an obvious pulsating glacier. Its surface was highly fractured, and its ice tongue moved at a variable speed down the valley during five months, covering a distance 4.6 km long. At that time the glacier did not leave its bed. No people were killed (Figure 5). Note that all of the above mentioned catastrophes took place with a time interval of 67 years between them.

[6] A new catastrophe turned out to be an absolutely unexpected event. The historically formed view of the periodicity of the Genaldon catastrophes suggested the hope of some 30 quiet years, yet, the nature of the glacier turned out to be much more complicated. The expected "time table" was violated.

[7] As follows from the official data, discovered by 10 November, 2002, were the remains of 18 dead people, 108 people were not found. The dangerous zone included a 24-kilometer segment of the local road. A small relatively new settlement, built at the bank of the Genaldon River in the Karmadon Basin, was obliterated. Two tourist centers, located at the outlet from the canyon, were wiped off by a mud flow. More distant buildings were damaged significantly. It should be noted that during the first weeks after the catastrophe the damaged area grew in size at the expense of the filling of the dammed lake produced by the right tributary of the Genaldon River, which was dammed by ice avalanche.

[8] The Kolka Glacier has been of great interest as an unstable natural formation constituting a threat as a potential hazard. The inspection of the catastrophe zone immediately after the event allowed the estimation of its hazard and the first suggestions concerning the mechanism that had caused it and its potential consequences.

The Source of the Catastrophe

[9] The upper reaches of the Genaldon Ravine close up in the south by a chain of three majestic peaks, namely, Kazbek (5033 m high), Maili-Khokh (4598 m), and Dzhimarai-Hoh (4780 m), all being the constituents of the Bokovoi (Lateral) Range of the Central Caucasus. The northern Dzhimarai-Hoh spur, including the also significant Shau-Khokh Peak (4636 m) shuts off the gorge from the west and northwest, forming a basin which is occupied by the Kolka small glacier, 3.1 km long. The system of these peaks is combined, conventionally, into an individual high-mountain massif, known as the Kazbek-Dzhimarai Massif. Restricted to this massif is a glaciation center, measuring 13 km^2 in area. Its largest glacier is the Maili Glacier covering an area of 7 km^2. Its feeding zone embraces the northwestern slopes of the Kazbek Range and the northern slopes of the Maili-Khokh Volcano. It drains to the Genaldon Ravine in the form of a huge ice fall. This glacier tongue descends to the elevation of 2300 m (Figure 6).

[10] In contrast to the Maili classical valley glacier, the Kolka Glacier is classified as a glacier of a cirque-valley avalanch feeding. The feeding zone of this glacier consists of the firn fields of the northeastern Dzhimarai-Hoh slopes having no contacts with the glacier itself. Their thicknesses vary from 40 m to 70 m. Their firn masses flow to the glacier tongue in an avalanche manner over a distance of about one kilometer along a steep (about 40°) slope, involving a significant volume of a lithogenous material. This factor controls the formation of a dense mantle of the surface moraine cov-

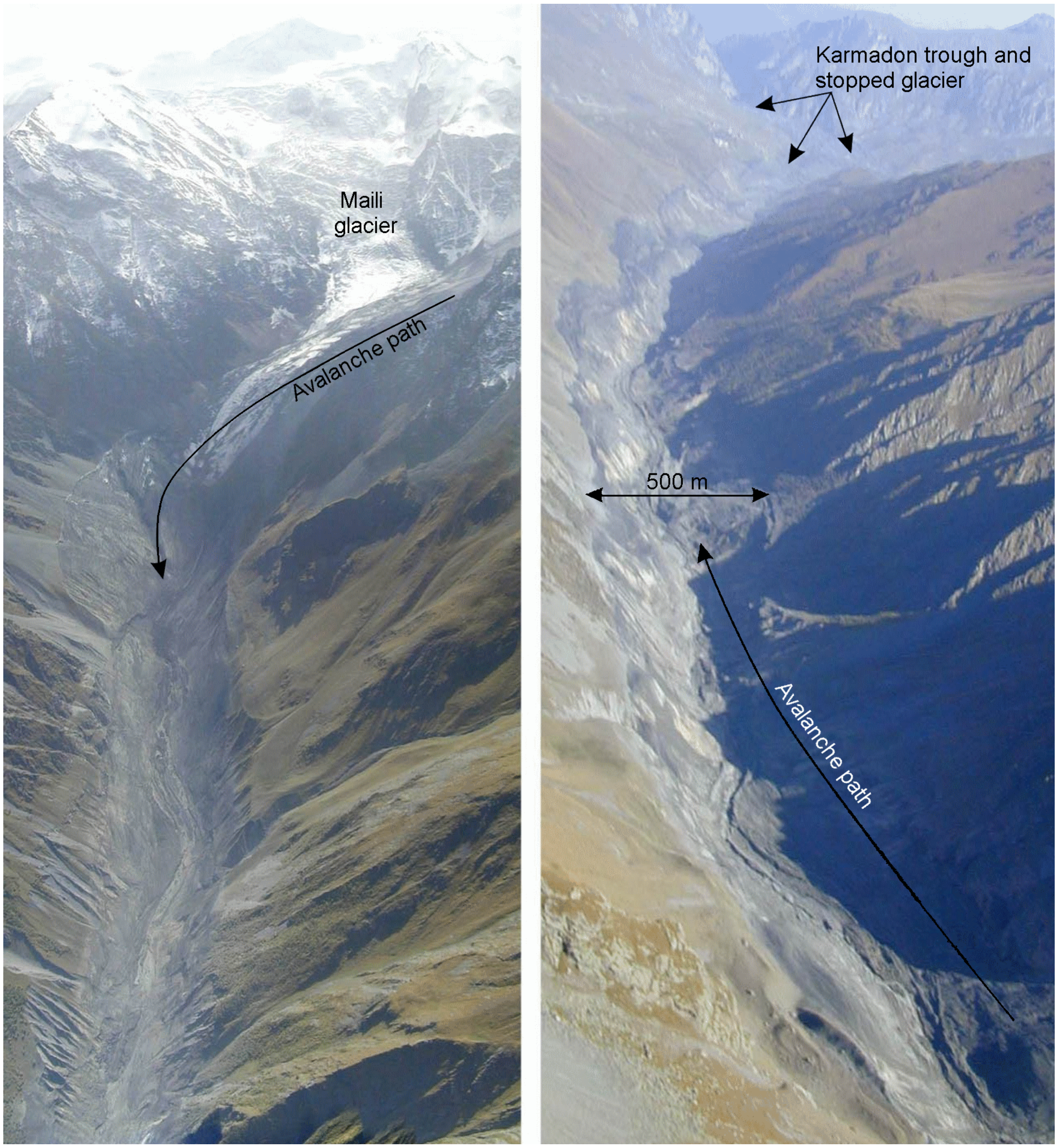

Figure 2. Genaldon Ravine. The trace left by the glacier avalanche of 22 September 2002.

ering almost the whole of the glacier. The thickness of the moraine cover grows closer to the frontal part of the tongue (absolute elevation of 2960 m) and amounts to 80 cm. The glacier bed is inclined slightly (6–7°) in the east-west direction, this resulting in the relatively low dynamics of the plastic deformation of its body. Single fissures were observed only in its rear (Figure 7).

The Geologic Structure of the Catastrophe Area

[11] The upper reaches of the Genaldon Ravine have a complex geologic structure. The close vicinity of the Kazbek Volcano caused the presence of effusive rocks, in-

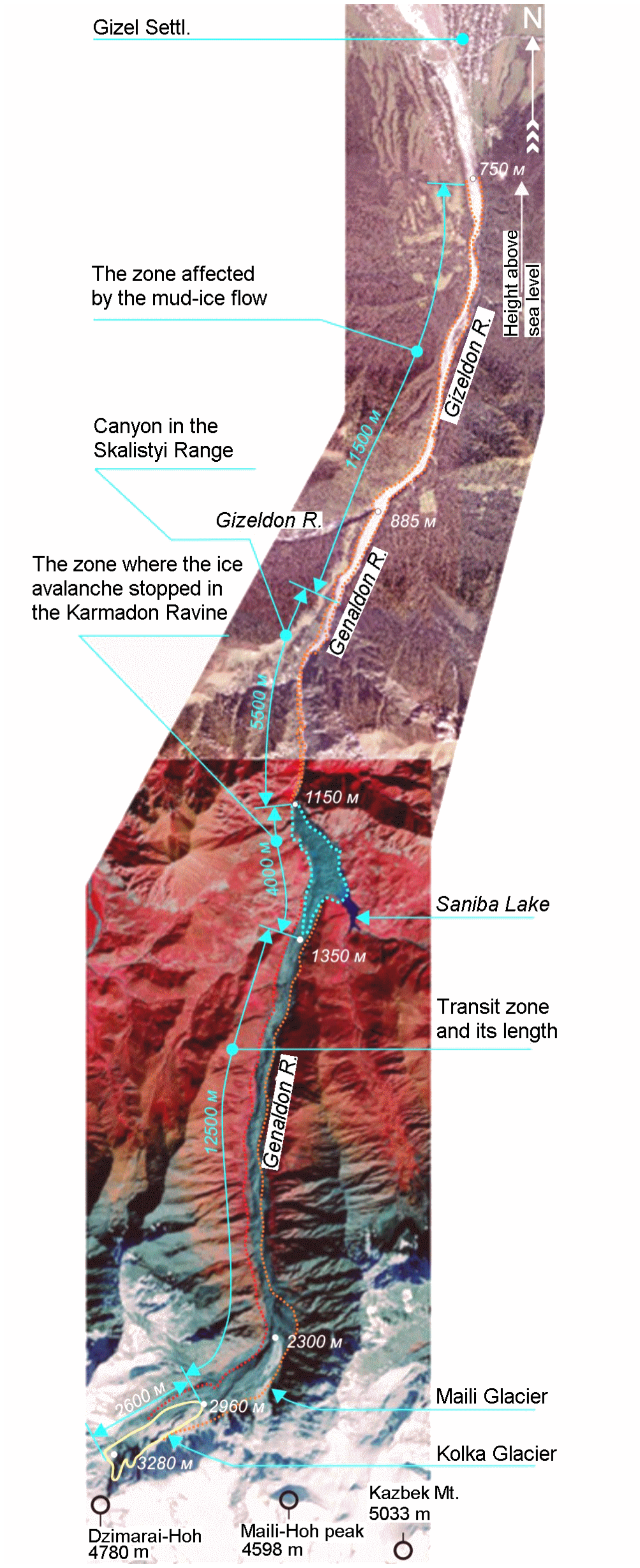

Figure 3. Space photograph of the area damaged by the catastrophic avalanche of the Kolka Glacier on 20 September 2002. ASTER-type photograph compose of two photos: spectrozonal photo of 6 October 2002, and common photo of 25 September 2002. Scale 1:200000.

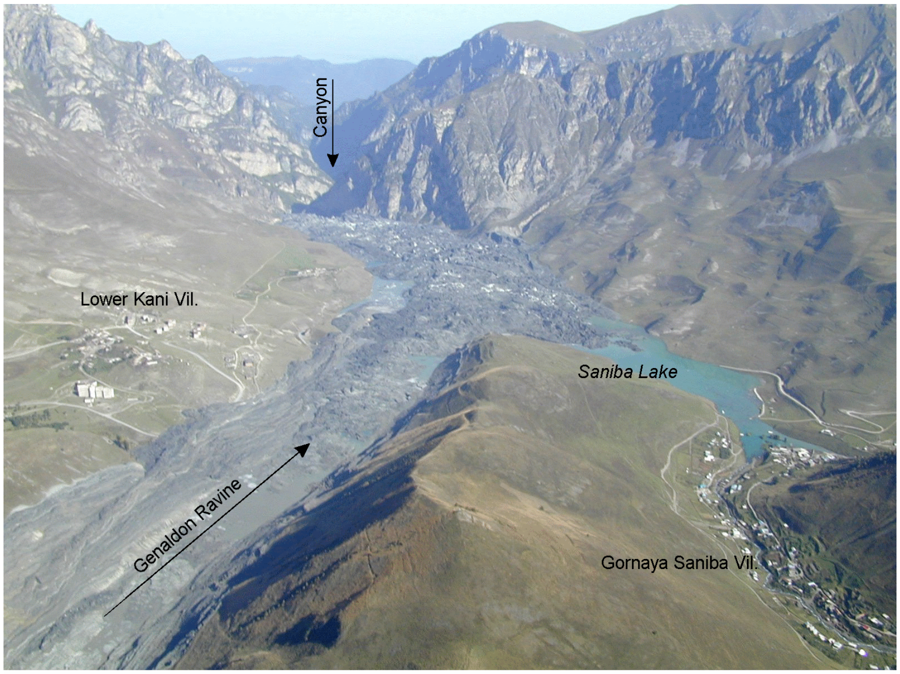

Figure 4. Karmadon Trough. Glacier avalanche stop in the Skalistyy Range escarpment.

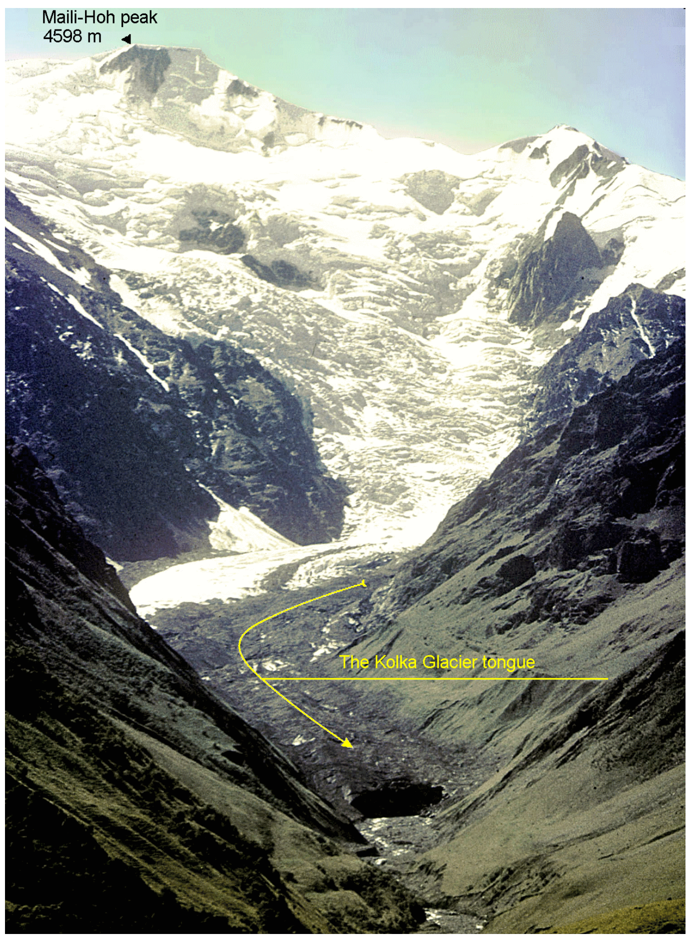

Figure 5. The Kolka Glacier tongue after the 1970 pulsation.

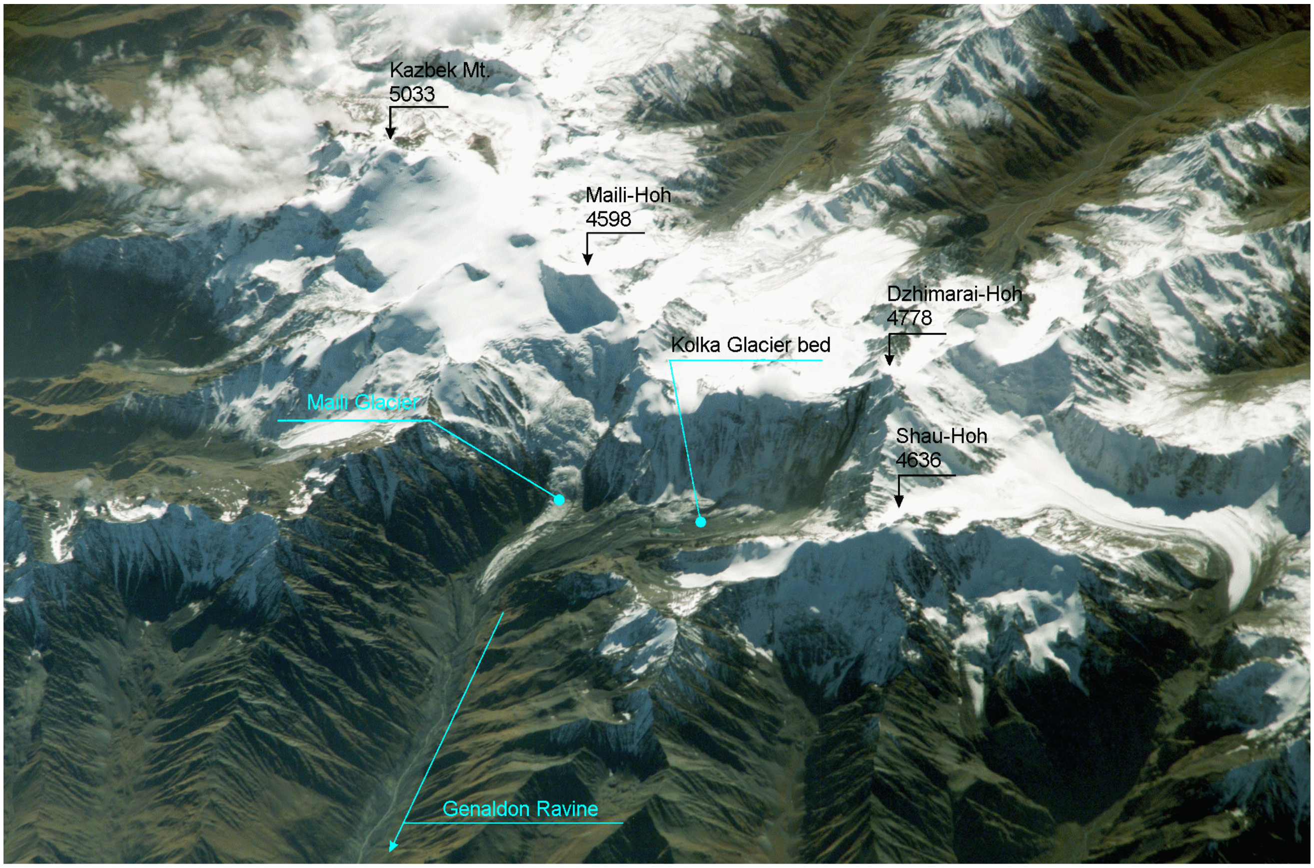

Figure 6. The area of the glacial catastrophe source.

cluded stratigraphically into the Tsiklaur Formation (J_{1-2}) represented by siltstones and silty sandstones. The members of sedimentary and volcanic rocks compose the southwestern slope of the Shaukhokh anticline with a diorite body exposed in its core. In the area of the Kolka Glacier, diorite is exposed in the lower part of the left side of the Maili ice fall and in the lower part of the eastern Dzhimarai-Hoh wall, exposed by the glacier descent.

[12] The subvolcanic rocks are represented by the numerous diabase dikes feathering the Kazbek volcanic channel, known as the Kazbek Diabase Belt.

[13] Kazbek is not ranked as an extinct volcano. In the recent time the peak of its igneous activity is dated 280–180 thousand years ago. The next peak was recorded 50 thousand years ago. Its latest activity was dated 10,000 and 6000 years ago [*Rogozhin et al.,* 2001].

[14] The neotectonic activity of the region at the present time is ranked as a fairly substantial one. The vertical crustal movements (VCM) attain the values of 0.7–0.9 mm year^{-1}, which are the maximum values for the Caucasus region. These values were obtained by A. S. Teplyakova in terms of her dissertation work aimed to study the vertical crustal movements in the Gornaya Osetia region [*Teplyakova,* 1984]. It should be noted that the values of the vertical crustal movements decline abruptly in the northern direction from the Kazbek-Dzhimarai Massif. At the distance of 2–4 km this value declines to 0.4 mm year^{-1}. It is possible that this significant change of the vertical crustal movements in the meridional direction controls the highly active collapsibility down the slopes of the Dzhimarai Massif, which is the main glacial area of the Kolka Glacier (Figure 8).

[15] The tectonic structure of the region proves the active geodynamic environment in the crustal block discussed. Numerous faults of different ranks cross the territory discussed, both in the least-west and north-south directions, causing upthrust and overthrust deformations.

Climatic Conditions

[16] The total glacial zone of the Kolka Glacier resides in the nival zone. The average annual air temperatures are positive up to the elevations of 2000–2300 m, become negative at higher levels, and amount to $-10°C$ at the height

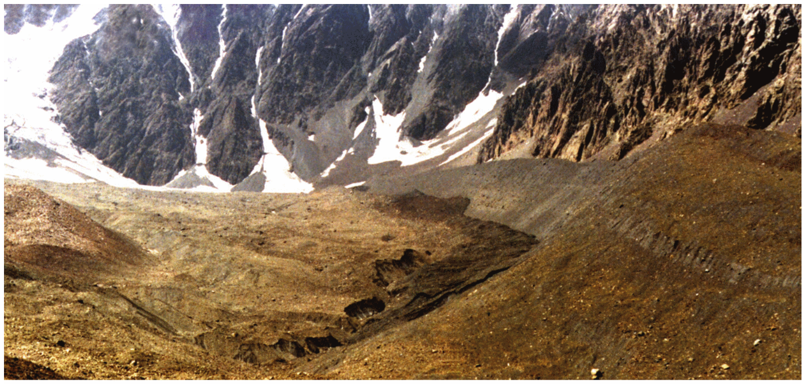

Figure 7. Kolka Glacier in 2000.

of 4000 m. Precipitation is highly irregular for the basin territory, both in time and space. According to the data reported by K. P. Rototaev, very characteristic is a summer maximum, associated with the reactivation of the cold fronts of the Atlantic cyclones [*Rototaev,* 1974]. During the anticyclone conditions the bulk of the summer precipitation is provided by the local vertical convection. Most of the days with solid precipitation fall to January. The precipitation amounts are distributed by the seasons in the following way: 500 mm and more in summer, 199–150 mm in autumn, 150–200 mm in winter, and 200 mm and more in spring.

Reconstruction of the Catastrophe Preparation Process

[17] Information of the anomalous reactivation of the Dzhimarai firn-field avalanches began to be reported at the end of July, 2002. Occasional tourists visiting this remote mountainous region photographed the disintegrating firn fields, the avalanches, and the alluvial fan of the collapsed material at the surface of the Kolka Glacier (Figure 9). These areas are known for their frequent and impressive avalanches, taking place at any time of the year. Accordingly, nobody could foresee any tragic end of these processes. It should be noted that the belt of the catastrophic shower, mentioned above, passed 2–3 km north and did not affect the glacial area of the Kolka Glacier. In order to answer the question: what might cause this menacing natural phenomenon, special-purpose work was carried out to reconstruct the factor of seismic effect in the area of Mountainous Osetia, using an analytical (calculation) method. As a result of this work, maps were plotted for each month of the 2002 year, showing the mark of the maximum seismic effect, which enabled the estimation of the factor discussed at any, even not easily accessible site.

[18] This work revealed that on 14 July, 2002, the rock mass of the Dzhimarai-Hoh peak had experienced shaking of intencity 5.2 on the MSK-64 scale. The epicenter of this earthquake was located 8 km west of the Dzhimarai-Hoh peak. In the initial KMV-2002 data sample this earthquake has a number of 244. Its main parameters are: No. 244 (Md = 3.88; K = 9.8; depth = 5.4 km). The same day witnessed two earthquakes more: No. 245 (Md = 3.11, K = 8.3) and No. 246 (Md = 3.20, K = 8.4).

[19] The earthquake No. 246 was recorded at a distance of 10 km northwest of the Dzimarai-Khokh peak. Chronologically associated with these earthquakes was the onset of landslide activity in the local area of the North shale depression which borders the Skalistyi Ridge in the south and is distinguished by a great number of landslide deformations because of plated shaly texture of the rocks. The width of this zone varies from 5 km to 7 km (Figures 10 and 11). As the additional information specifying the intensity of the seismic effect on the region of the glaciologic catastrophe source, it should be mentioned that:

[20] (1) The shaking corresponding to magnitude 5, communicated to the Dzhimarai-Hoh pyramid from the earthquake no. 244, had the following parameters: the acceleration (a) of $\sim$0.28 m sec^{-2}, the displacement rate (v) of $\sim$0.056 m sec^{-1}, the absolute displacement (L) of $\sim$0.04 m.

[21] (2) The effect of this intensity on the hanging firn fields of the "Kolka" glacial rock complex (the thickest and steeply dipping in the mountainous area discussed) can increase the momental value of their sliding down force almost by 9%, which will decrease their stability by the same value. Essentially, this effect can cause significant mechanical damages in the ice-firn massif and, eventually, its complete disintegration.

[22] Did the Dzhimarai-Hoh Massif experience any more powerful seismic effects during the previous 10–15 years? As follows from the data reported by *Savich et al.* [1996], the calculated shaking of the Dzhimarai-Hoh Massif from the Racha earthquake (MPSP = 6.6; 29.04.91) and from the Borisakh earthquake (MPSP = 6.6; 23.10.93) was as high as 5.6. No stronger seismic effects were recorded.

Reconstruction of the Main Parameters of the Catastrophic Collapse of the Kolka Glacier

[23] The procedure of reconstructing the depolished objects, namely of the glacier and the firn field included the tacheometric survey of the glacial region of the Kolka

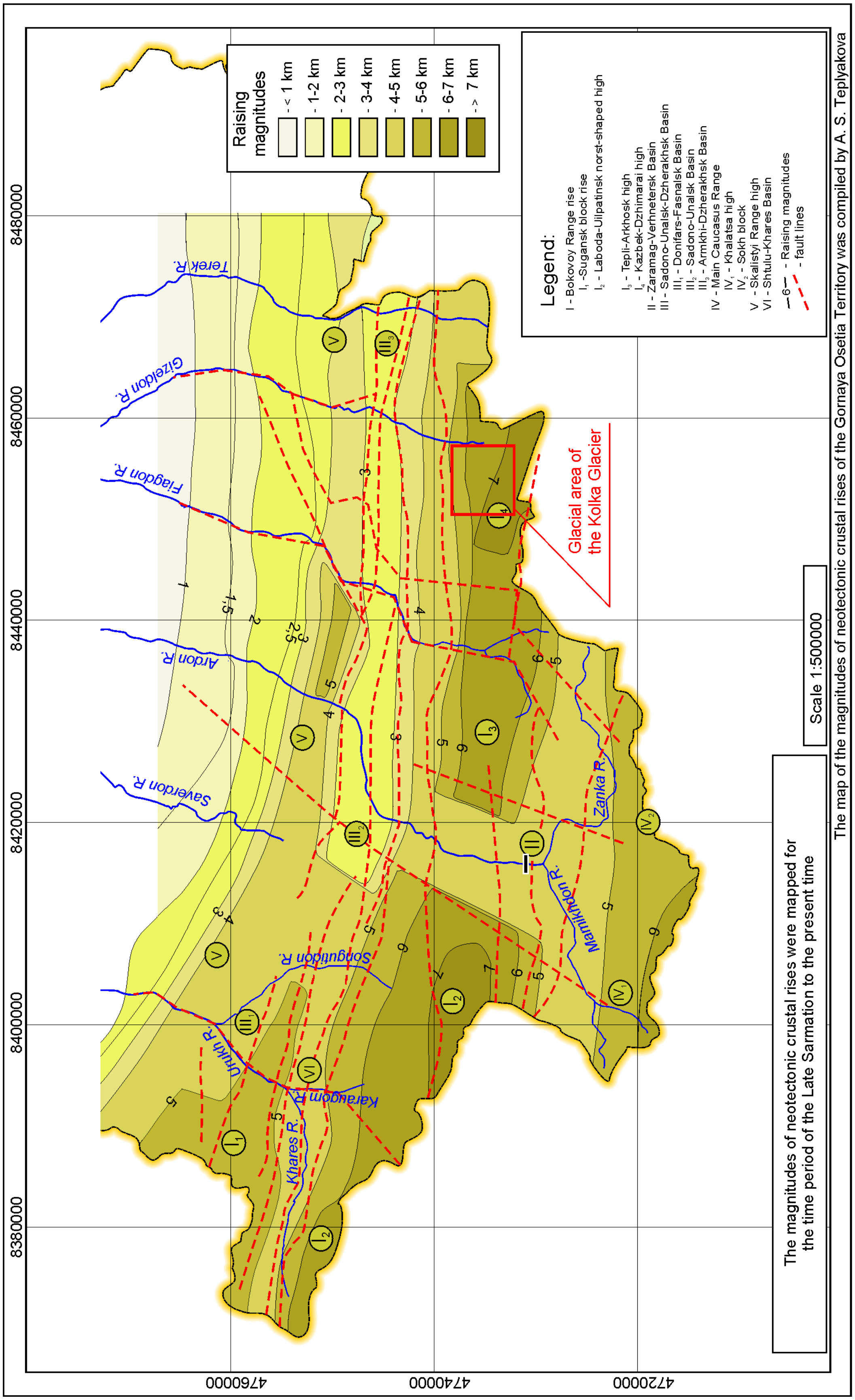

Figure 8. The neotectonic conditions in the vicinity of the glacial catastrophe.

Figure 9. Cover of a landslide material on the Kolka glacier at the end of August, 2002.

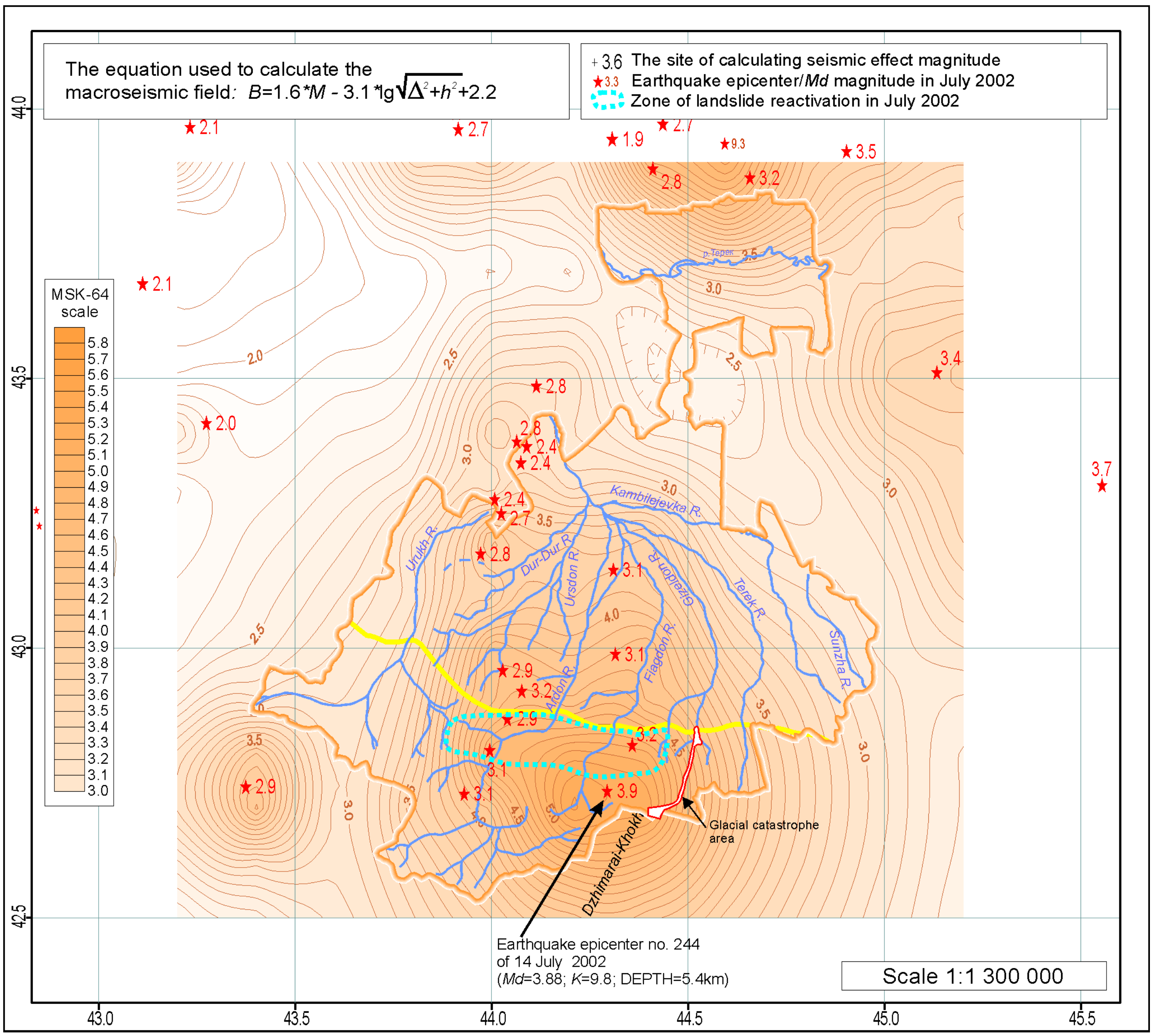

Figure 10. Calculated macroseismic field of July 2002 for Alaniya territory. Initial Catalog: KMV-2002.

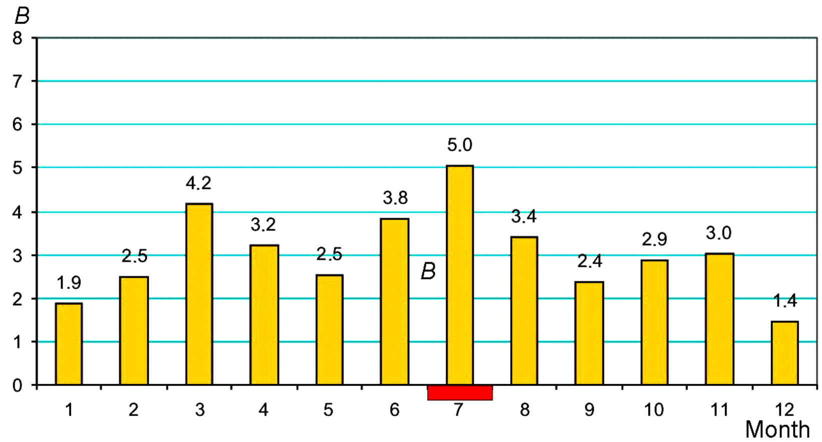

Figure 11. Monthly distribution of the maximum seismic effect on the Dzhimarai-Hoh Massif in 2002 (42.72°N; 44.46°E). Data sample: 41°–45°N, 42°–46°E, KMV-2002, N=275.

Glacier on the scale of 1:5000 (see the deminished version in Figure 12). Then, after the drawing of a topographic plan, 12 transverse profiles were plotted, parallel to one another, with a distance of 250 m between them, and one longitudinal profile was plotted along the valley thalweg. The profile of the glacier surface was reconstructed for the time before the onset of the glacier movent in each site, using the method of trace propagation: the fairly distinct trace on the internal slope of the left shore moraine, reflecting the glacier surface level, was conjugated with the break-off edge, extending along the whole of the glacier right shore. The search for the most probable form of the desired line along the cross-sections was accompanied by the plotting of a latitudinal profile which provided some corrections in the course of more detailed work. At the same level, the profiles were updated in order to obtain the maximum similarity between the form of the reconstructed surface and the morphology of the glacier surface shown in photograph A (Figure 9).

[24] Similar work was done for the zone of firn field destruction. The architecture of these constructions is demonstrated in Figure 13. The results of the automatic calculations (Figure 14) are as follows:

[25] (1) the volume of the firn material that collapsed onto the glacier: $V_{\rm firn} = 22$ million m^3;

[26] (2) the volume of the ice, involved into the catastrophic motion of 20 September 2002 (including the avalanche material): $V_{\rm ice}1 = 137$ million m^3;

[27] (3) the volume of the ice which stopped in the Karmadon Trough (Figure 15) on 28 September 2002: $V_{\rm ice}2 = 115$ million m^3;

[28] (4) the volume of the mud flow traveling along the Genaldon Canyon (Figure 16) was estimated to be $V_{\rm mud} =$ 3–5 million m^3;

[29] (5) the volume of the ice left along the transit path as selvage and blocks lagging behind: $V_{\rm ice}3 = 22$ million m^3.

[30] The huge avalanche of the Kolka Glacier was recorded by many seismic stations of the Caucasus area. The most complete record (lasting about 16 min) was obtained by the Tsei seismic recording unit, located 44 km west of the catastrophe site. The detailed description of the seismic records, with the beginning and end of each seismograph operation, is provided in the paper of (A. A. Godzikovskaya, in press, 2004). The main result of this study was the discovery of the high variation of all record characteristics in time:

[31] 1. 1605:13.0 recording onset (Greenwich time: hour-min-sec).

[32] 2. 1605:13.0 – 1609:05.0 noise at the level of the seismograph sensitivity.

[33] 3. 1609:05.0 – 1610:21.0 interval of notable amplitude growth.

[34] 4. 1610:21.0 – 1615:30.0 interval of substantial amplitude growth.

[35] 5. 1615:30.0 – 1621:10.0 interval of notable amplitude reduction.

[36] 6. 1621:10.0 end of record.

[37] Shown in Figure 17 are only intervals 3 and 4, for which V. B. Zaalishvili and K. S. Kharebov calculated the seismic energy produced by a moving glacier, using the seismogram recorded by the "FIG" seismic station of the local "Alpha-Geon" network.

[38] This level of the seismic data processing allowed the interpretation of the avalanche movement using the topographic map of scale 1:10,000 (the area of the Genaldon Ravine from the Dzhimarai-Hoh Peak to the Karmadon Gate) (Figure 18).

[39] Taking into account the fact that the description of the process is based on the circumstantial facts, it should be treated as a hypothesis.

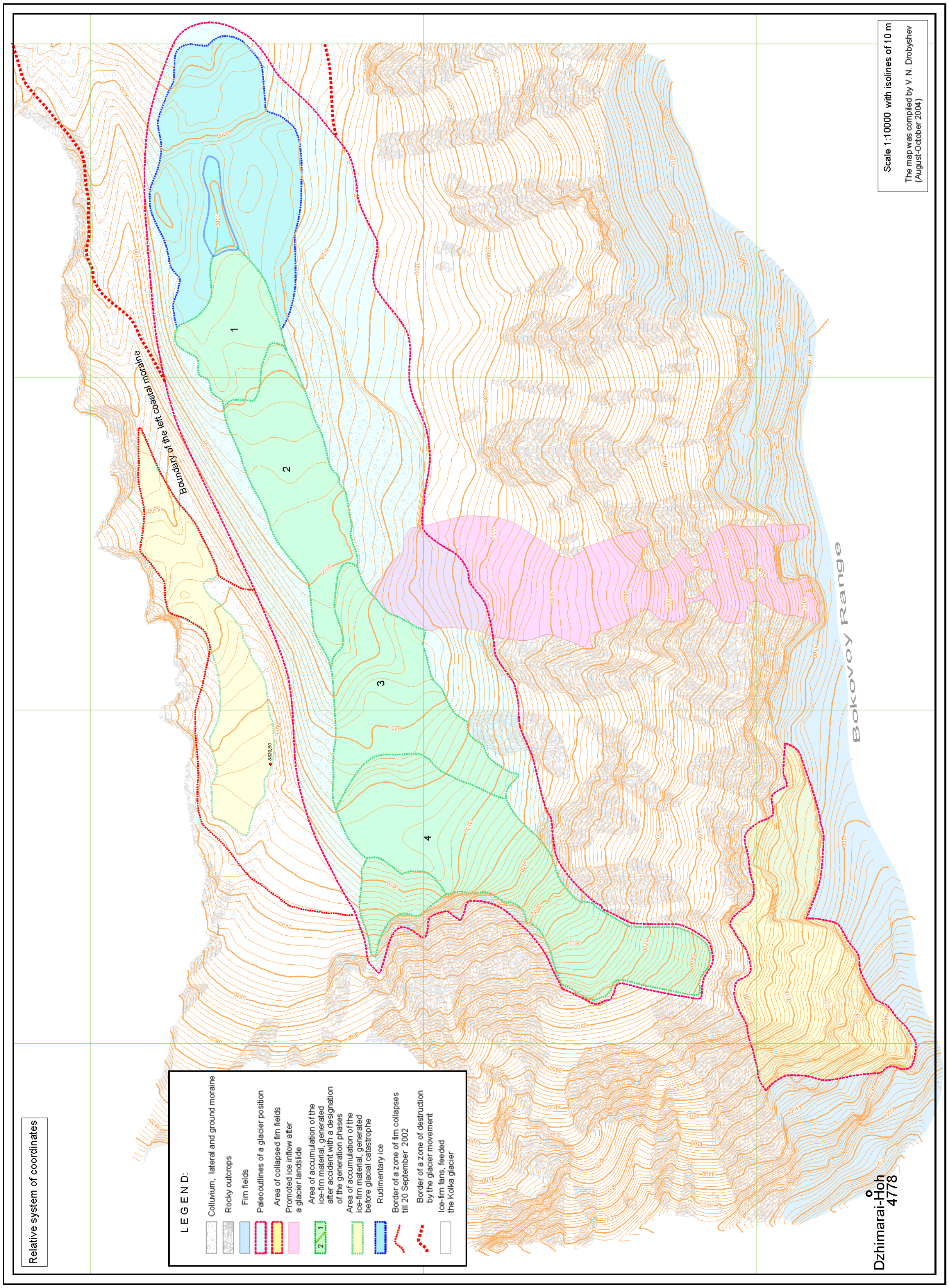

Figure 12. The Kolka glacier area.

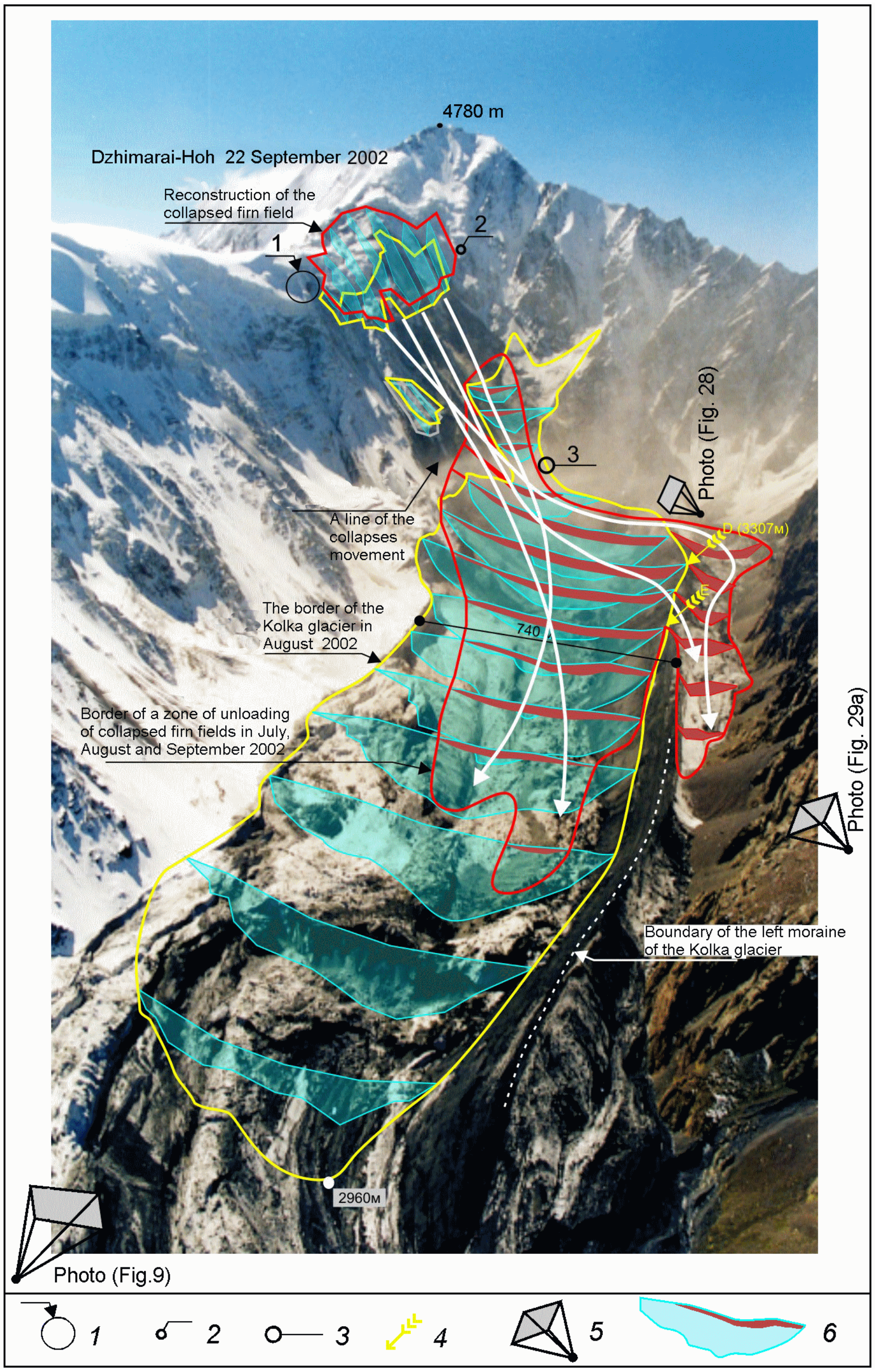

Figure 13. Focus area of glacial catastrophe. 1–3 – identification areas and points; 4 – a line of the collapses movement; 5 – points of shooting for the photos; 6 – reconstructed sections of the Kolka glacier body with a designation of thickness of the collapse-rocky material.

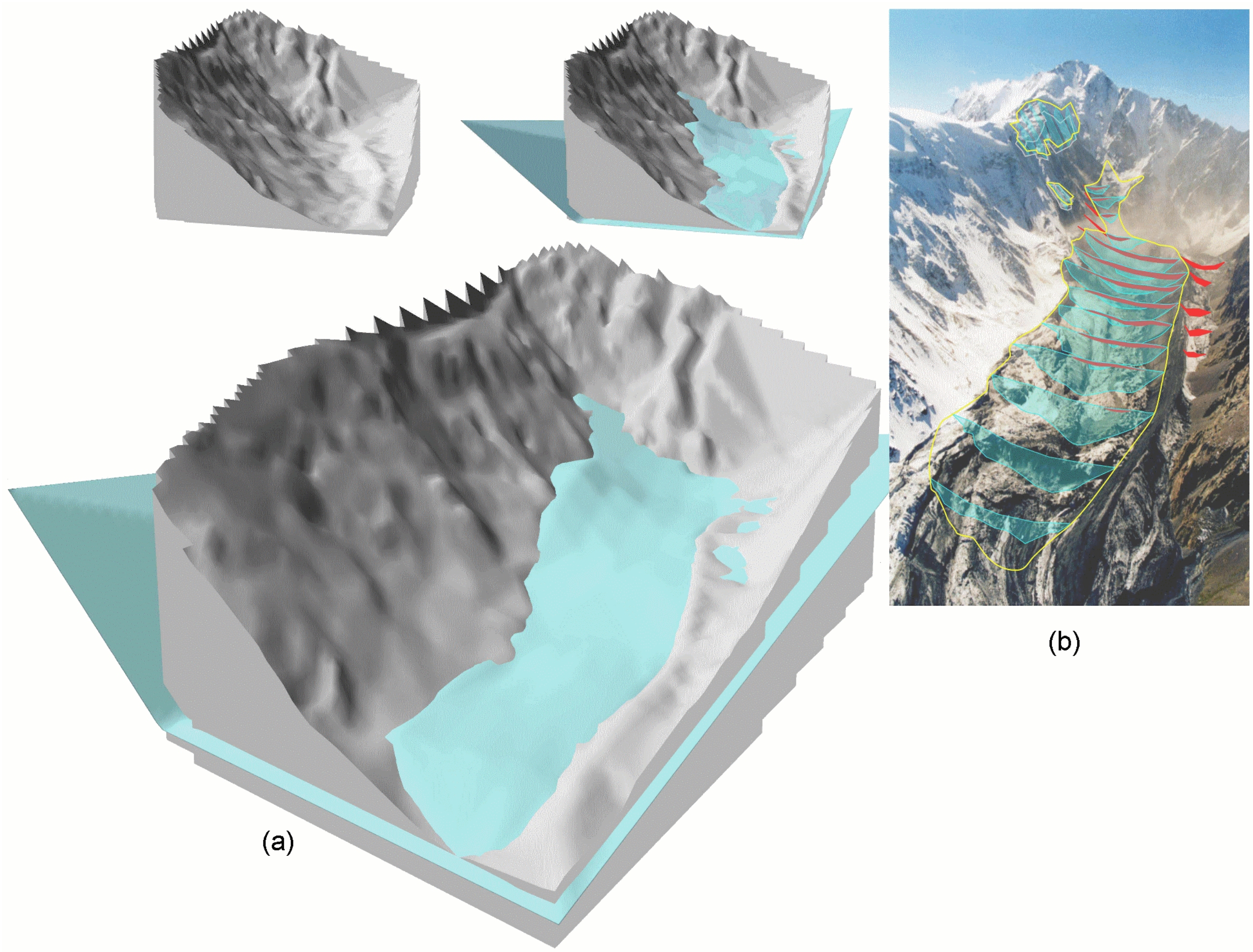

Figure 14. Reconstruction of the surface of the collapsed Kolka glacier. Model of a physical surface (a) and paleosurface of an abandoned glacier (b) (see explanation in text).

[40] Proceeding from the data available, it can be noted that:

[41] (1) the initial velocity of the active body was equal to zero;

[42] (2) no large shock, capable of communicating any significant (additional) acceleration to the glacier body of 137,000,000 tons was recorded by the seismographs;

[43] (3) the process of adding new rock material to the glacier rear because of avalanches continued more than two months. The photographs A and B in Figure 9 suggest that the avalanches from the firn fields produced a large and sufficiently thick alluvial fan on the surface of the Kolka Glacier as early as the end of August, 2002. Shear stresses in the glacier body continued to grow until reaching the critical values. The interval No. 2 in the seismic record obtained by the Tsei seismic recording unit (1605:13.0–1609:05.0) can be interpreted as the rapid development of faults in the active glacier body, which produced a large cleavage in the layer of the bottom ice (Figure 13) and, hence, the loss of stability. The amplitudes of seismic waves in this time interval are 10–40 times lower than in the interval No. 3.

[44] (4) The value of the seismic effect which stabilized after the date of 1609:05 was high enough to be recorded by the seismographs of the "Alpha-Geon" local network, including the "FIG" seismic station. This fact can be treated as the beginning of the gravitational active glacier body movement.

[45] The glacier body lost its stability and began to move along the ice gully at an angle of 6–7° with the acceleration of about 1 m sec^{-2} (Figure 19). With this acceleration the speed of 220 km hour^{-1} can be achived after 60 sec with the racing length of 1800 m. The approximate length of the mass center acceleration path for the back half of the glacier is about 2000 m. In its own path, the motion of the ice mass can be treated, with a certain degree of certainty, as a progressive one. The formation of a shear fracture measuring about 2 km^2 overcame the cohesive strength of 7–8 t m^{-2}. The coefficient of the ice-ice friction was very low. In the case of semiquantitative calculations its variations can be neglected. This radically simplified calculation allows one to treat the evidence of the extremely high rate of the catastrophic avalanche as not contradicting the laws of a physical body motion under such conditions. Figure 20 shows the re-

Figure 15. Karmadon hollow. The ice avalanche has stopped here.

construction of the longitudinal vertical section of the Kolka Glacier, performed in August-Early September 2002, using a topographic map of M1:10000 and the photographs made after its catastrophic collapse. The resulting cross-section suggested the inclination angle of the thalweg bed to be 6° and the roll-down force T to be 13,600,000 tons. It also allowed the schematic interpretation of the avalanche material on the surface of the glacier (for its state at the end of August 2002) and of the position of the ice-rock breccia which acted as a retardation dam.

[46] The acceleration of the active body motion was recorded by the seismographs during the time of 1 min 16 sec (see interval No. 3 in the seismic record obtained by the Tsei seismic station). This time interval is sufficient for an active body to attain a velocity of 220–240 km hour^{-1} over a distance of about 2 km. At the time interval of 80–90 sec the avalanche front reached the Maili moraine and, having rebounded from it, began its gentle turn to the left at a fairly large angle (up to 50°). In this turn the avalanche flow over the right side rose to a height of 250 m above the thalweg (in the cross-section). The left flank of the avalanche, moving along the thalweg of the Kolka-Don River, left its trace along the left side of the canyon at the height of 30–40 m. This height difference, with same width of its trace (∼700 m), can be explained by a significant centrifugal force produced by the high-velocity turn. The sesmographs recorded the first high interaction. This site is marked as point 1 in the topographic map. Shown in the frame of this drawing are several inserts which help to percieve and interpret this information. In the inserted diagram "The time distribution of the total energy vector", the point no. 1 is shown though not in the figure plan, but in the time scale. The arrival time of the "FIG" seismic signal is tied to the time scale of the "Tsei" seismic station and is marked as 1609:05 (Greenwich time). The numbers of the observation sites, shown in the topographic map, and those shown in the diagram correspond to one another. Farther on, the avalanche followed a relatively rectilinear trough with the width varying from 100 m to 150 m, the slopes consisting of loose deposits, varying in steepness from 30° to 40°. The bedrock outcrops have an "island" character and are located mainly at the right side of the valley. The area discussed has a length of 9.5 km, where the avalanche trace resembles the trace of a slalomist. The maximum height of these traces is 180 m, the minimal height being 10–20 m, with the arc length of each turn measuring not less than 1000 m. Of particular interest is Site no. 9 which corresponds to the absolute maximum of seismic energy produced by the moving glacier. Here the avalanche overflow was as high as 248 m.

Figure 16. A segment of the Genaldon Canyon after the sell flow.

[47] Table 1 shows the results of the computations used to plot the curve of the glacier avalanche speed along the Genaldon Canyon (Figure 19: B-2). The headings of the columns of the calculation table:

[48] 1. The name of the object or the number of the trajectory point

[49] 2. The distance between the neighbouring sites

[50] 3. The distance from Dzhimarai-Hoh Wall

[51] 4. Acceleration of an active body at the beginning of its motion

[52] 5. The time needed to cover the distance from the previous site

[53] 6. Time from the motion onset

[54] 7. Time from the seismogram

[55] 8. Calculted speed (m sec^{-1})

[56] 9. Calculated speed (km hour^{-1})

[57] The aim of the calculation was to plot the curve of velocity distribution for the movement of the glacier avalanche from the Dzhimarai-Hoh wall to the Skalistyi Rocky Ridge escarpment.

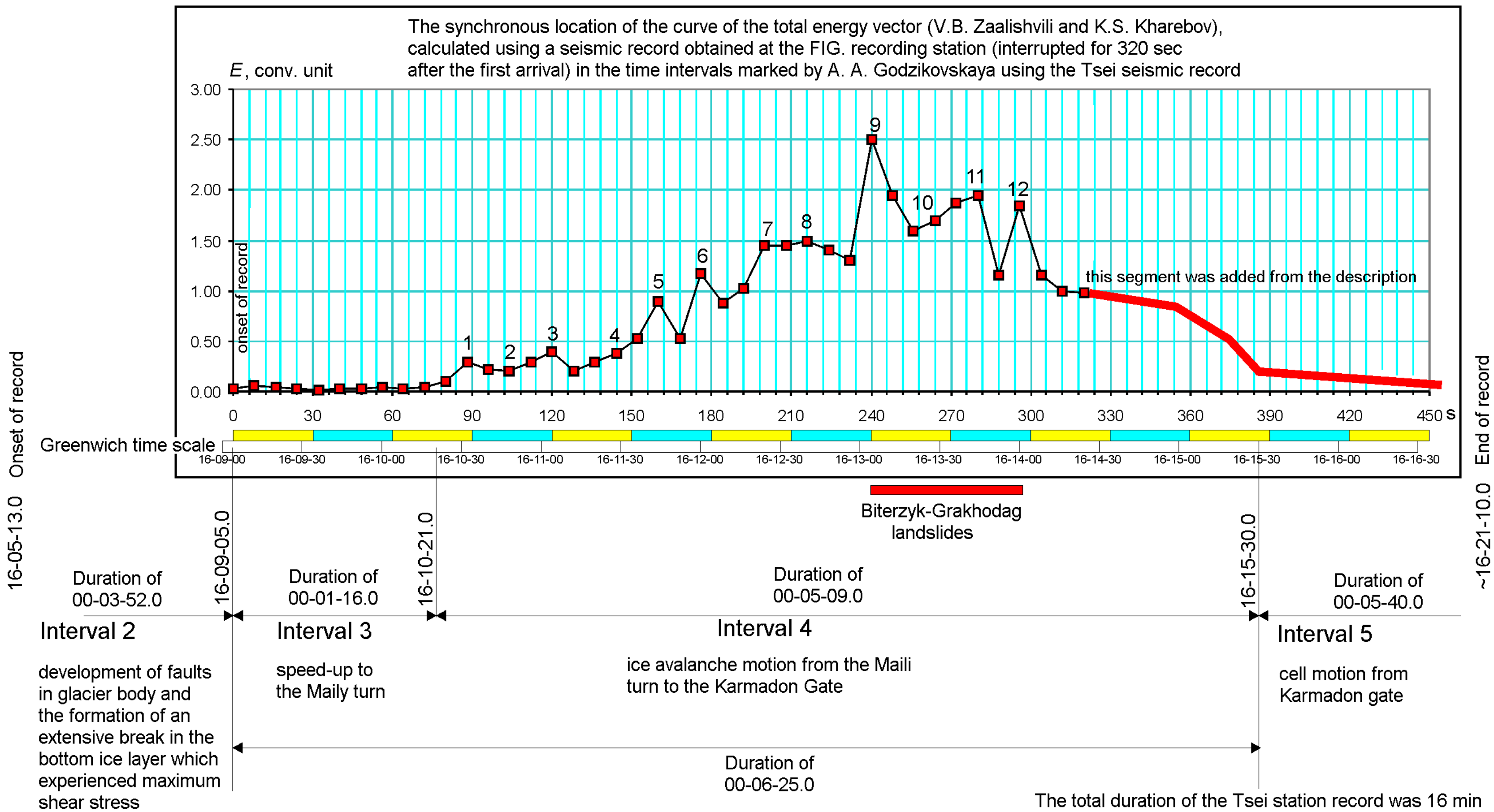

Figure 17. The phases of the glacier fall development in the Genaldon Canyon of North Osetia on September 20, 2002, reconstructed after the joint analysis of the seismic data, the morphometry of the transit path, and the specific kinematics of ice mass motion.

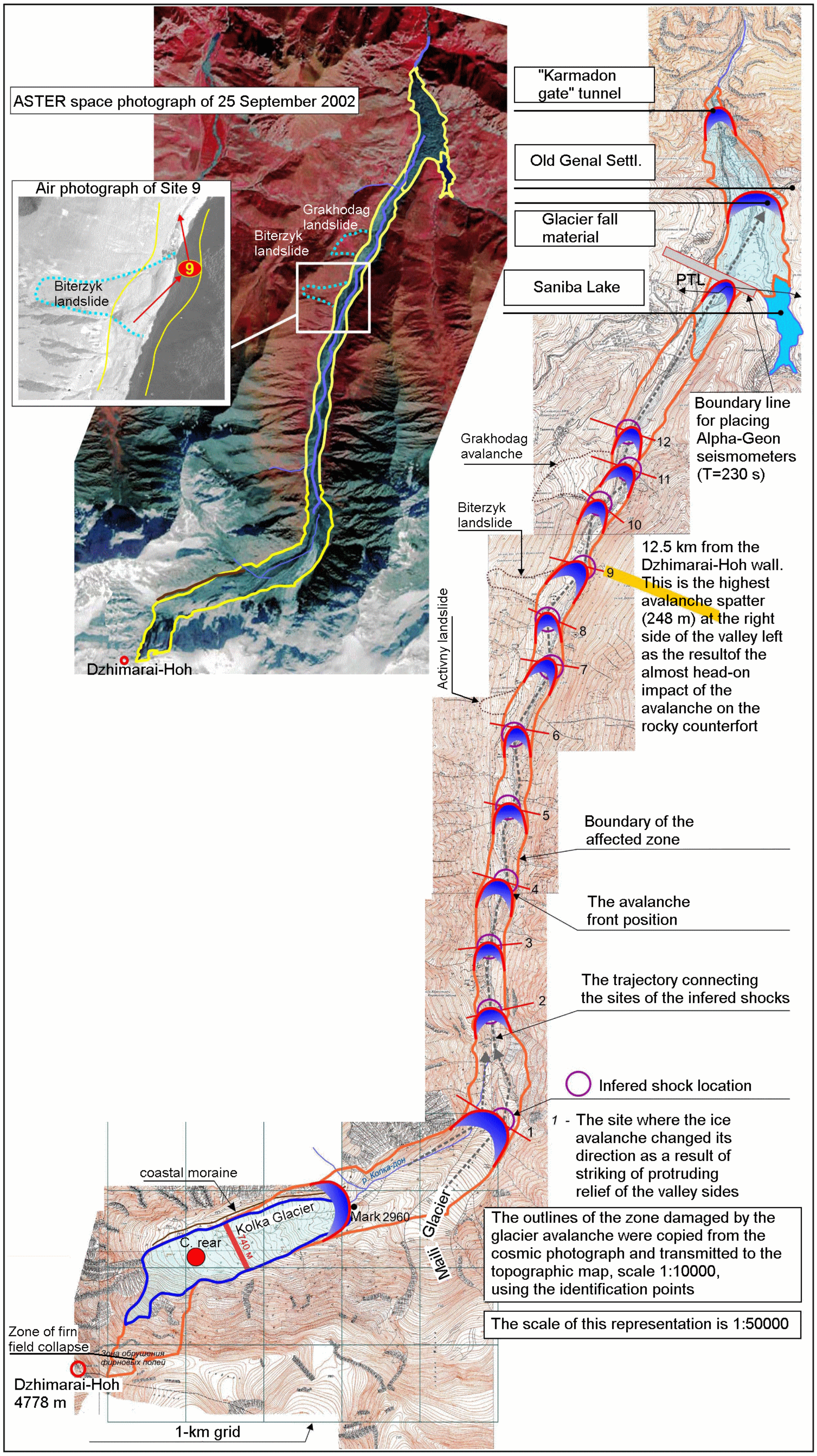

Figure 18. Analysis of the Kolka Glacier specific motion trajectory down the Genaldon Ravine.

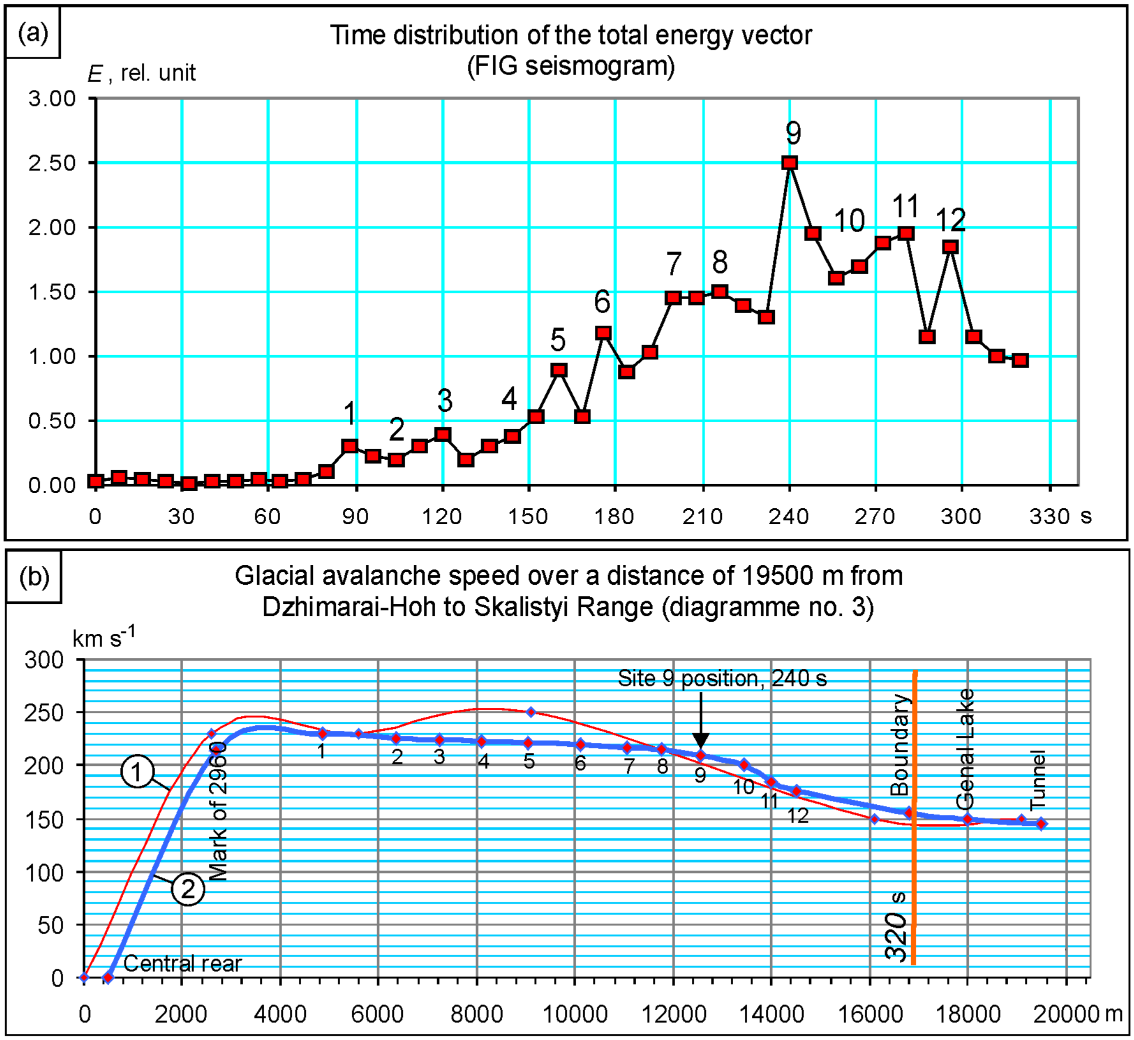

Figure 19. The diagrams illustrating some of the parameters of the Kolka Glacier caving. Shown in Diagram B are (1) the curve of the avalanche velocities, calculated from the geometry of the trace left by the avalanche and (2) the curve of velocity distribution, satisfying the seismic records.

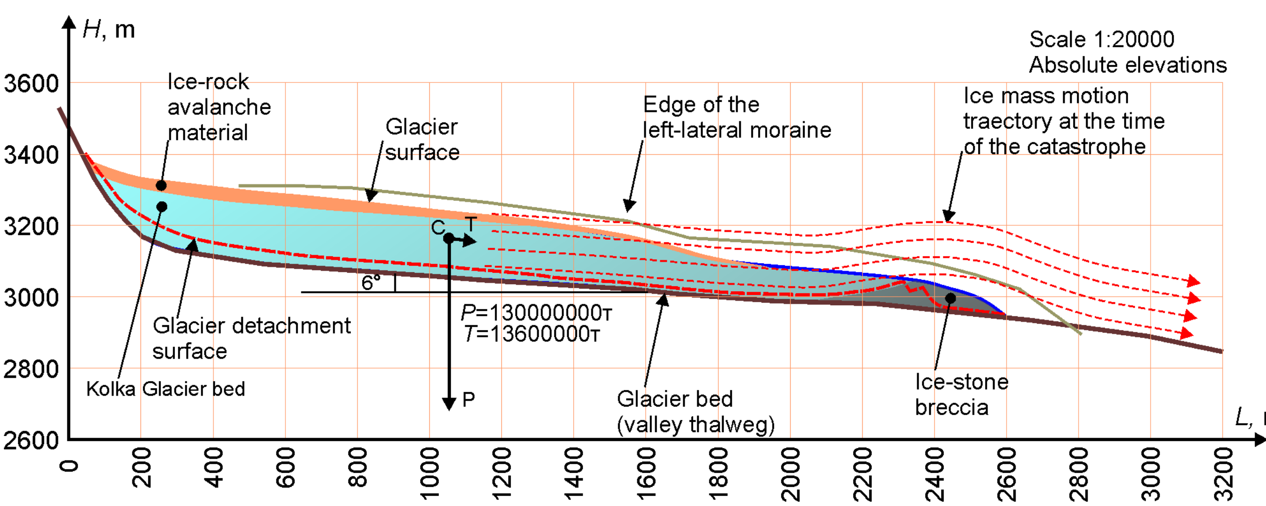

Figure 20. The reconstruction of the longitudinal vertical section of the Kolka Glacier.

Table 1. Table of calculating the time during which the ice avalanche travelled along the Genaldon Canyon

Sites	DL (m)	Total L(m)	Accel. (m sec^{-2})	T(sec)	total T(sec)	T(sec)	av. V (m sec^{-1})	V (km hr^{-1})
DJ wall								
	500							
Centr. Rear		500		0	0	0	0	0
	2200		0.8					
2960 border		2700		74.16	74.16		59.33	213.59
	2150							
1		4850		34.90	109.06	87.00	63.89	230.00
	1500							
2		6350		23.74	132.80	103.00	62.50	225.00
	900							
3		7250		14.43	147.23	120.00	62.22	224.00
	850							
4		8100		13.69	160.92	142.00	61.94	223.00
	950							
5		9050		15.41	178.32	160.00	61.39	221.00
	1050							
6		10100		17.18	193.51	176.00	60.83	219.00
	950							
7		11050		15.69	209.19	200.00	60.28	217.00
	700							
8		11750		11.67	220.86	217.00	59.72	215.00
	800							
9		12550		13.55	234.41	240.00	58.33	210.00
	900							
10		13450		15.80	250.22	257.00	55.56	200.00
	500							
11		14000		10.29	260.50	280.00	51.39	185.00
	500							
12		14500		10.00	270.50	297.00	48.61	175.00
	2300							
Boundary		16800		50.18	320.69	320.00	43.06	155.00
	1200							
Genal		18000		28.33	349.01		41.67	150.00
	1500							
Tunnel		19500		36.61	385.62		40.28	145.00
Total	19500			385.62				

[58] The Greenwich time of 16-15-30 which terminated the time interval no. 4 in the seismic record obtained by the Tsei seismic recording unit did not show any amplitude peak. This proves that there was no significant shock of the glacier on the Karmadon Gate. This was indirectly proved by the morphology of the day surface of the newly formed avalanche: no counter slope was formed (Figure 15). Although the retardation of the avalanche was fairly high over the distance from the Genal settlement to the Karmadon Gate tunnel, yet, there was no shock.

The Glacier Body in the Karmadon Basin

[59] The ice that filled this basin changed substationally its appearance. The absolutely lifeless territory looked as the piling up of large dirty ice blocks covered by ash-color fine ice crumb. It was notably colder in the basin. During the first two months the ice grew more compact with its individual blocks being frozen together. The ground surface became notably lower, levelled and passable. The surface moraine began to form.

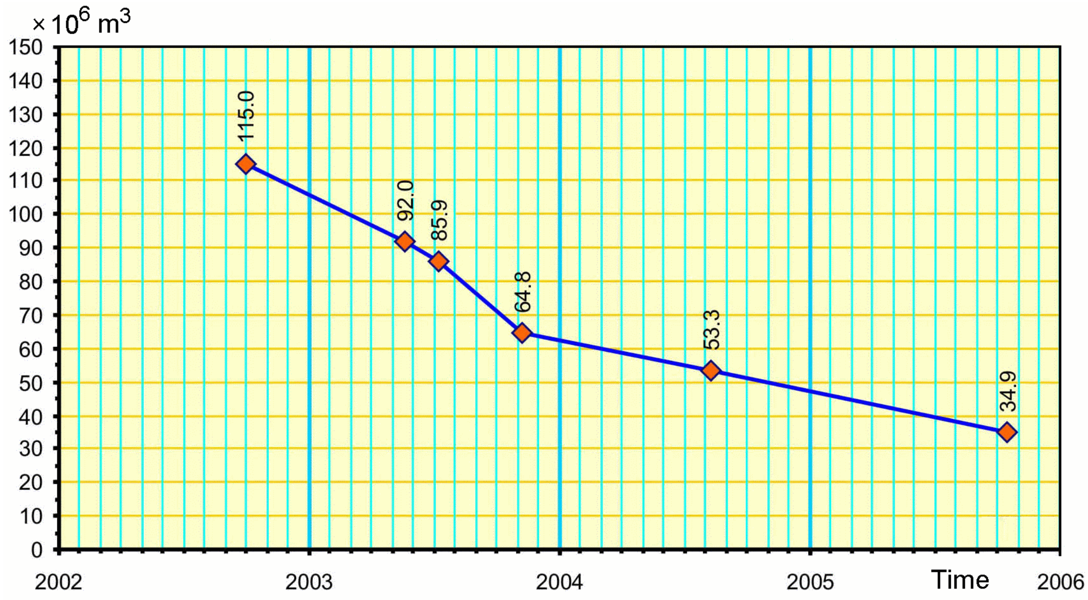

Figure 21. The curve showing the degradation of the ice avalanche in the Karmadon Basin, plotted using the results of topographic monitoring.

[60] The results of the topographic survey of the glacier avalanche (September 2002) were used to calculate its volume (115 million m^3) and area (2.1 km^2). Because of its forced stopping the avalanche acquired the form of a lying wedge about 3.8 km long with the maximum thickness of about 160 m in the frontal part of the avalanche, and the width varying from 600 m to 900 m. During its retardation, the block material of the avalanche produced a significant promontary which filled the mouth of the right-side ravine damming the Kauridon small river. As to the Genaldon River, which lost its channel in the avalanche area, one week was enough for it to form a channel on the ice surface along the left side of the valley. In the lower part of the avalanche, the water flowed to its internal hollows and was thrown out into the canyon. All of the back-water pools that formed along the Genaldon River were of the flow-through type and disappeared very rapidly.

[61] The results of the topographic monitoring of the avalanche surface suggest the duration of the process of the avalanche disappearance. During the time period from the catastrophe which took place on 20 September 2002, to May 2003, the ice body lost 21% of its initial volume. During the time of 5.5 months (May–October) the ice lost another 18% of its initial volume, mainly as a result of its surface melting and the actively developing bottom thermal erosion restricted to the Genaldon and Kauridon river flows. As a result of these processes the area of the ice avalanche surface diminished by 0.4 km^2 and measured 1.7 km^2 now. The further changes in the ice volume are illustrated in Figure 21. Proceeding from the fact that the active melting phase in the region discussed lasts merely 4–5 months of a year, the complete degradation of the glacier body can be expected after a time interval of 5–6 years. In some areas the dead ice buried under the thick moraine cover may remain for a long time. The photograph presented in Figure 22 shows the ice avalanche barrier which existed in August 2005.

Figure 22. The Carmadon Basin. The view of the ice avalanche in August 2005.

The Dammed Saniba Lake

[62] This lake began to form after the formation of an ice avalanche (Figure 4) in the Karmadon Trough on 20 September 2002. The ice mass blocked the exit from the right lateral canyon damming the channels of two small rivers: the Kauridon R. with the flow rate of 1.2 m^3 sec^{-1} and the Fardon R. with the flow of 0.8 m^3 sec^{-1}. This produced a basin of a future lake, which began to be filled with water. The total debit of these two rivers was about 2.0 m^3 sec^{-1}, capable of the water accumulation of 170,000 m^3 day^{-1}.

[63] However, the situation developed much more rapidly.

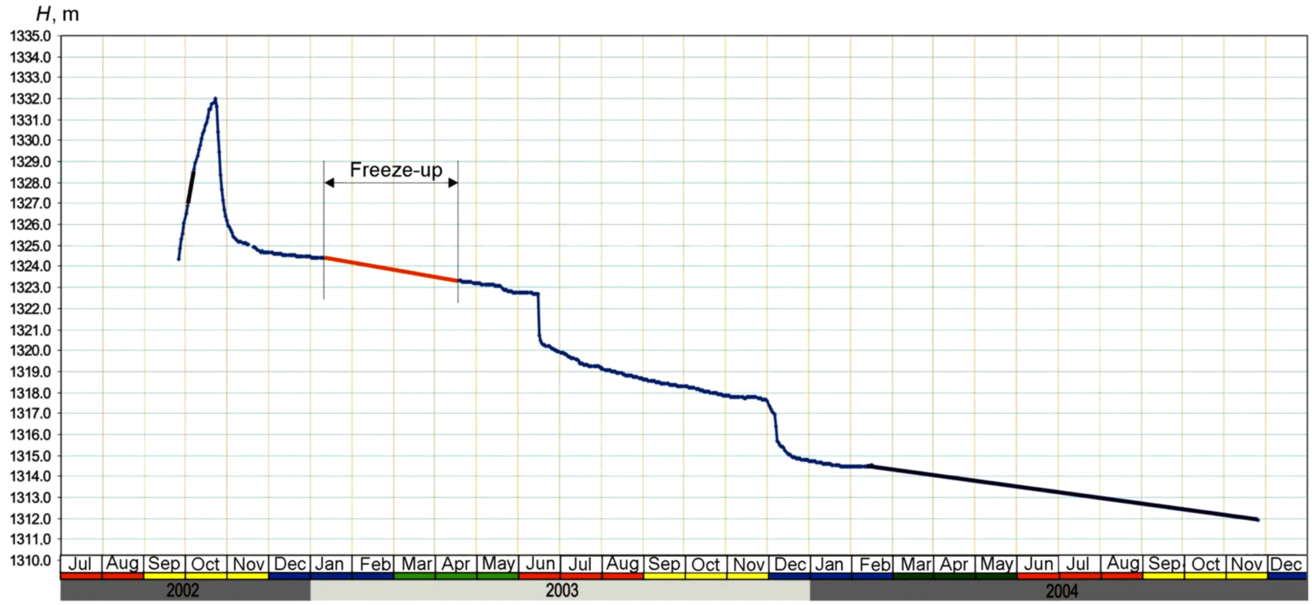

Figure 23. Dynamics of the Saniba Lake from 28.09.2002 to 25.11.2004.

On 24 September 2002, trying to find an exit, the water of the Genaldon R. broke through the right side and flowed to the lake during four days. By the beginning of this break, the lake contained about 0.6 million m^3 of water. On 28 September this break through terminated, yet, the water of the lake rose to the height of 20 m more, its volume being 2.5 million m^3. Two small streets were flooded in the Gornaya Saniba Village. On 18 October, 2002, the lake water level ceased to grow, but on October 22 a water channel was formed at the surface of the ice along the right side of the valley. By that time the area of the lake was 260,000 m^2, and its volume was 3.5 million m^3. No one knew how all of this will end.

[64] The inhabitants of the flat land settlements, located along the banks of the Gizeldon R., (the Genaldon R. being its right tributary, see Figure 3), felt a great danger and were ready to abandon their houses in the case of the lake breaking through. Observations of the lake state were carried out during the days and nights. The channel in the ice surface grew notably deeper. The water level in the lake began to decline very rapidly and became 7 m lower during 15 days. The second break of water took place in mid-July 2003, when the water level became 2.5 m lower during 2 days.

[65] On 10 and 11 July the lake was inspected by the experts of the Moscow University, and the first topographic survey was carried out. In 10 July, 2003, the lake contained 1.32 million m^3 of water. The lake water table was at the level of 1319.63 m.

[66] The third break-through occurred at the beginning of December. During ten days the level of the lake water descended by 2.8 m. By 1 January, 2003, its water level was 1314.45 m. In 2004 the water level of the lake continued to decline at a rate of 1 cm a day. In 25 August its level was 1312.77 m, and in 25 November, 1311.9 m. About 0.5 million m^3 of water remained in the lake (Figure 23). In August 2005 the lake looked fairly stable (Figure 24).

Mud Flow

[67] As has been noted above, after the termination of the ice avalanche in the Skalistyi Range escarpment, the catastrophic process continued in the form of an ice-rock mud flow, 30–40 m high. Moving at a speed of more than 100 km/hour, this deadly hurricane crossed the distance of 5.5 km in the Genaldon Canyon (Figure 16). Most of the victims were restricted to this band ranging from 30 m to 80 m in width. The mud flow material covered an area of 3 km^2. Its thickness declined in the direction away from the ice barrier, where it is as high as 11 m, to 4 m at the exit from the canyon, and to 2 m at the junction of the Genaldon and Gizeldon rivers (Figure 25). The volume of the mud flow material has been estimated as 3–5 million m^3.

[68] By the present time, at the lower stages of the mud flow, the Gizeldon R. flow returns to the initial basis of the bottom erosion with the formation of terraces, the vegetation winning back its lost territories. New roads and bridges are being built in the segments of the demolished roads. No road is planned to be built along the canyon.

Figure 24. Saniba Lake in August 2005. View from the ice dam. The nearest buildings were flooded totally.

Figure 25. The avalanche material after flowing from the canyon.

Transit Zone

[69] The demolition of the Kolka Glacier in the Genaldon Ravine is ranked as an event of planetory significance. The extremely rapid transportation of a huge rock mass over the distance of several tens of kilometers was accompanied by a huge energy liberation, part of this energy being propagated as the seismic disturbances of the rock material, part of this energy was spent for the exaration of the sides and bottom of the valley, and part was spent on the overcoming of the internal friction. The energy of the mechanical effect of the ice avalanche on the sides of the valley was sufficient to violate the stable state of three landslide slopes. The landslide process involved about 30 million m^3 of the earth material (Figure 26). The hardly estimated volume of the loose material accumulated in the flood plain of the valley. The threat of a catastrophic mud flow remains to be a real event. The huge masses of loose material at the floor of the valley are certainly involved into the processes of the valley floor evolution, this material moving down under calm conditions. It appears that the mud flow danger consists of the inverse dependence upon these conditions.

Discussion of Results

1. The Break Up of the Firn Fields

[70] The photographs of the source area, obtained from the helicopter on 22 September 2002, clearly showed two fumaroles on the northeastern Dzhimarai-Hoh slope (Figure 27).

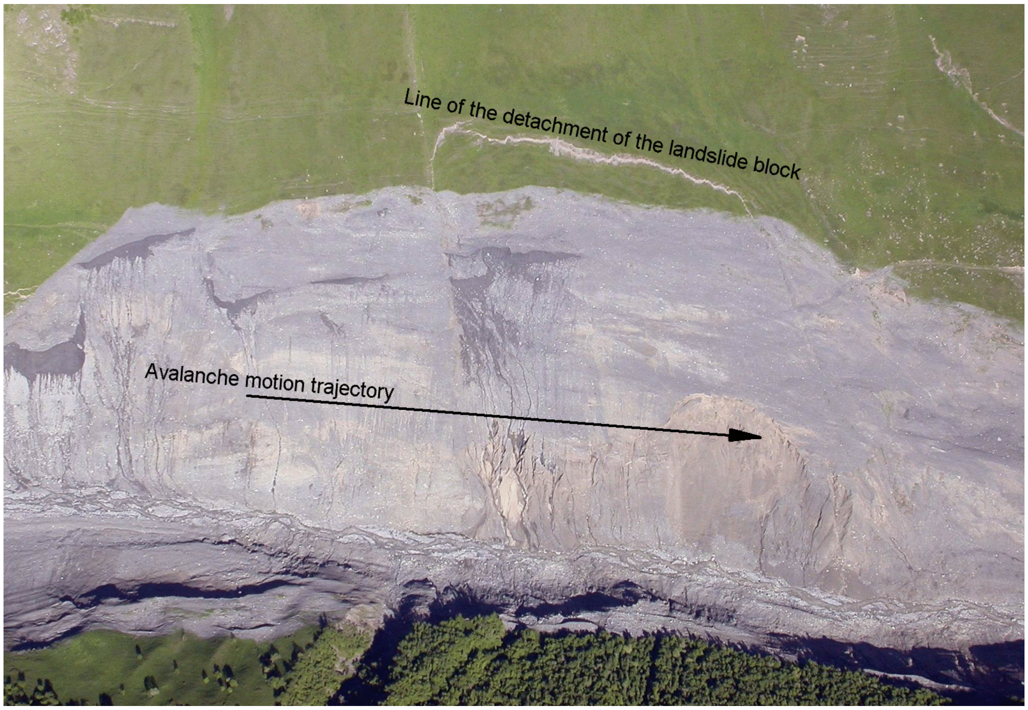

Figure 26. Genaldon Ravine. Landslide acivity after the ice avalanche.

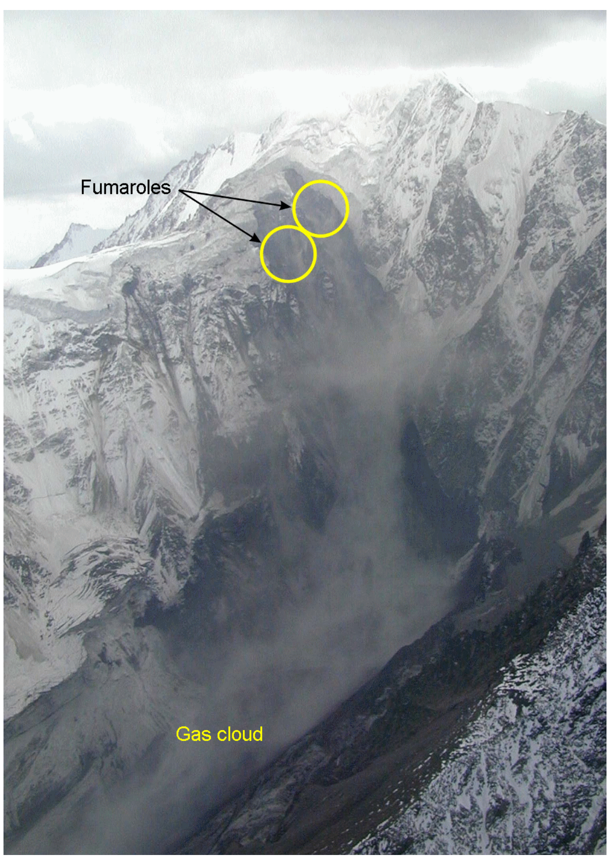

Figure 27. Source area during the first hours after the catastrophe.

Both of them emitted light-color opaque gas which slided slowly downward as a long cloud. The attempt of landing a group of researchers in the vicinity of the glacier was cancelled because of the strong hydrogen sulfide odor. The landing was cancelled.

[71] It cannot be excluded that the reactivation of the fumarole emanations was caused by seismic dislocations during the earthquake no. 244 (KMV-2002 data sample). The vicinity of the Kazbek Volcano explains this phenomenon. The upper reaches of the Genaldon Ravine include a great number of flowing thermal highly mineralized water springs, this being indicative of deep heat vicinity.

[72] This scenario agrees with the potential slow decay of the firn fields in some local area. The endogenic gas flows at the bottom of the firn field were accompanied by thermocarst development. During the further development of this destructive process, the ice-firn massif lost its integrity and, hence, its strength. The firn field, loosened by the thermocarst, began to crumble and collapse (Figure 28). This photograph was made simultaneously with the photograph A (see Figure 9) by the tourists who visited this area at the end of August 2002. These photographs were included into the field of Figure 13, where the review photograph (13-1) shows all of the sites of this survey. Comparing Figure 28 and Figure 9A, one can see that the degradation of the firn fields proceeded in accordance with the fumarole positions.

[73] Of particular interest is the fact of the rapid cessation of the fumarolic emanations after the catastrophe. It is most likely that another reconstruction of the stress field took place as a huge rock mass vanished from the ground surface. After about a week, no evidence of gas emanation was recorded.

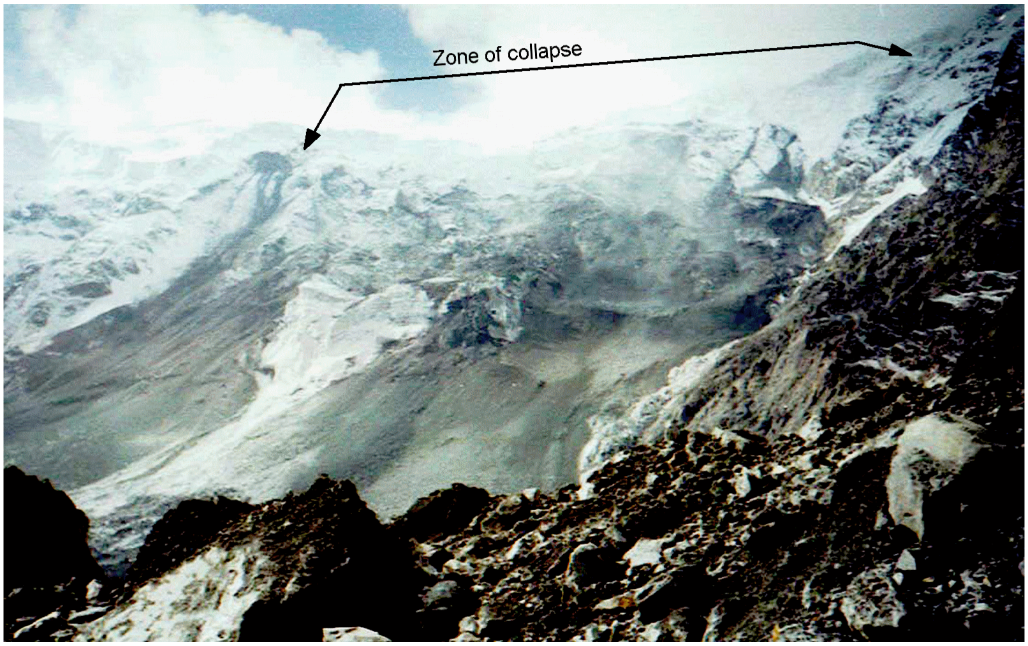

Figure 28. Zone of collapse of breaking up firn fields. The picture was made on 28 August, 2002.

2. The Ice-Rock Body in the Lower Part of the Kolka Glacier Basement, Known as "Rigel"

[74] Examining photograph 1 in Figure 13, one can see a transverse ledge in the lower part of the glacier bed. This body, consisting of ice with the high content of a lithogenic material, is geographically inside the paleoboundary of the gone glacier. Its morphology does not agree with the appearance of the post-catastrophe formation. Apparently, this is the terminal part of the glacier, which played the role of a dam which prevented the Kolka Glacier to act as a valley glacier.

[75] It was mentioned earlier that a large amount of lithogenic material had been transported to the Kolka Glacier by the firn avalanches. As the ice masses were transported plastically from the rear area to the tongue, the content of lithogenic material increased because of the surface, in-

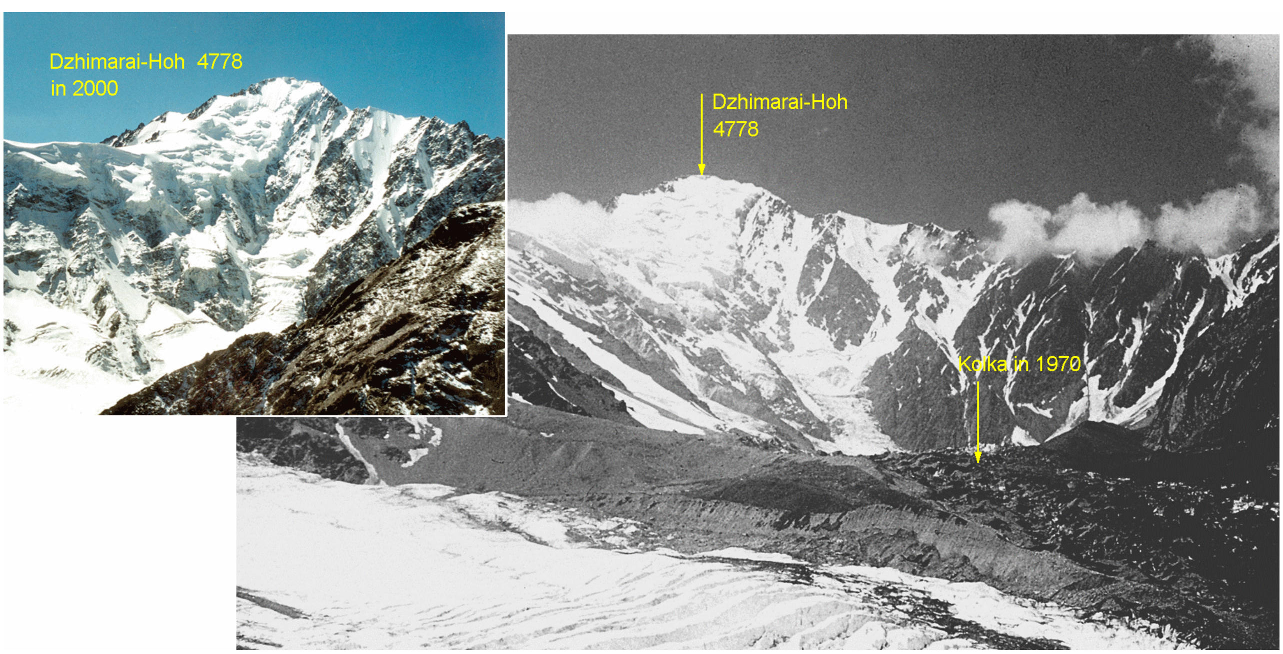

Figure 29. Dzhimarai-Hoh firn fields in 1970 and 2000.

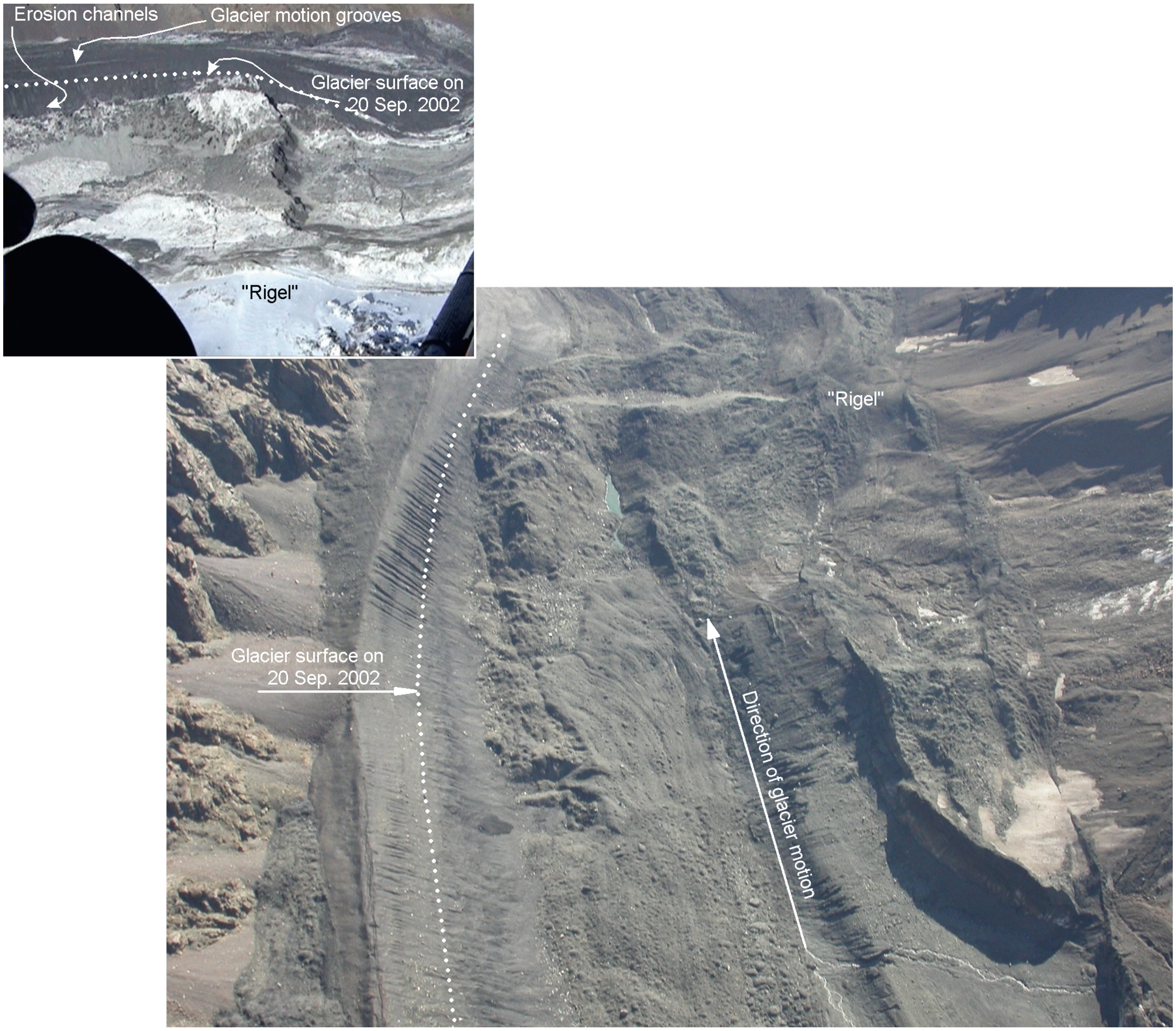

Figure 30. Transverse ice-stone formation at the lower boundary of the Kolka glacier bed.

ternal, and bottom melting of the enclosing ice. At the lower levels of the glacier, the content of the lithogenic material attains the level where plastic deformation declines and later vanishes. The ice acquires a rock skeleton. It follows that the glacier locks itself in the zone of predominant nutrition. Under the conditions of normal accumulation (typical of the Kolka Glacier) the glacier stability is controlled by the strength of the dam created by the glacier itself until this strength is sufficient.

[76] Turning to Figure 29, it should be noted that the Dzhimarai-Hoh firn fields are obviously unrelated to the Kolka Glacier motion in 1969–1970, yet, the latter did occur. The different character of the Kolka movements in the two latter cases can be explained by the difference in the systems and mechanisms of fault formation in the glacier body, as the restrictive forces of a critical level accumulated in it.

[77] It appears that the "pulsation", or to be more exact, the tendency of the Kolka Glacier to lose periodically its rigidity is controlled by its ability to form a zone with a high content of a stone material in the lower level of its body. The high strength of this formation is undoubtful: "Rigel" withstood this catastrophe and survived (Figure 30).

Conclusion

[78] The Karmadon catastrophe is not a scientific puzzle, in spite of its unique character. The preliminary study of the conditions for the development of a catastrophic process in the Genaldon Gorge was multisided. Each natural factor which might affect the glacier was studied. However, using any combination of the external factors, this avalanche is classified as an exogenic motion of a catastrophic level, that is, as a slope process. Yet, the level of the scientific problems produced was extremely high. To avoid the repetition

of any tragedy in future, the Kolka Glacier area must be controlled by several services simultaneously. The meteorologic monitoring should be accompanied by a topographic one. The results of geothermal, meteorologic, and seismic observations should be correlated with the plastic deformation rate of the glacier, determined using high-accuracy instruments. This will enable the calculation of the integral values of the changing physico-mechanical properties of the active body automatically in the field conditions. In the case of the declining glacier stability to a dangerous level, special active measures need be developed to provoke its descent.

[79] **Acknowledgments.** I thank I. V. Galushkin (InfoTERRA, Vladikavkaz), L. V. Desinov (Institute of Geography, Russian Academy), G. A. Dolgov (the Respublican Center of North Osetian Geoecologic Monitoring), A. A. V'ukhin (RSO-Alaniya National Park), E. T. Manukyants (Vladikavkaz), S. S. Chernomorets, and O. V. Tutubalina (Moscow University Center of Enginering Geodynamics and Monitoring).

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