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GEOLOGY

Catastrophic Rock–Ice Collapse and Rapid Shove of the Kukurtli Glacier (Elbrus Volcano, Northern Caucasus) in First and Second Centuries

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Joint studies carried out by specialists from the Institute of Geology of Ore Deposits, Mineralogy, and Geochemistry (Russia); Geological Institute (Russia); Institute of Earth Physics (Russia); Institute of Volcanic Geology and Geochemistry (Russia); Geological Faculty, Moscow State University (Russia); and Geological Survey (United States) [1–6] revealed that catastrophic and extended lahars are most hazardous to the population and property in the case of probable eruptions of the potentially active Elbrus Volcano (43°20′ N, 42°27′ E, northern slope of the Main Caucasus Ridge) [3]. The two-summit and very high (5642.7 and 5621 m) Elbrus Volcano and its giant caldera [2] served as the largest glaciation center in the Caucasus. This region with a total area of present-day glaciers equal to 139 km^2 and ice volume of approximately 6 km^3 [7] continues to play such a role and provides extremely favorable prerequisites for the formation of catastrophic mudflows. Glaciers represent, however, a source of additional danger. For instance, we first interpreted in aerial photographs and then scrutinized during field works specific morphologies in valleys of the Ullukhurzuk River and right tributary of the Kuban River (Ullukam River). They were preliminarily interpreted as traces of recent large-scale rock–ice landslides and rapid shoves of the Kukurtli and Ullukam glaciers located in the western and southwestern segments of the Elbrus Volcano piedmont (figure). They begin from the spacious ice "cap" that covers the western and eastern summits of the Elbrus and the major part of its caldera [3]. The Kukurtli Glacier is located in upper reaches of the Ullukhurzuk River valley. The length of this glacier from the western summit of the Elbrus Volcano to the head located at an altitude of about 2800 m is 7.5 km. The Ullukam Glacier is ~6 km long and terminates in the valley of the right tributary of the Kuban River at an altitude of ~3050 m. The channel of both glaciers in source areas has steep (locally vertical) walls (500–1000 m) where the thickness of glaciers dissected by numerous deep fractures sharply decreases and the glaciers appear to be hanging or broken completely. In the latter case, bedrock walls are crowned by 100–200-m-thick ice.

The upper course of the Ullukhurzuk River valley is marked by fragments of a slightly undulating plain on both sides of the valley. The fragments are related to avalanches and shoves of the Kukurtli Glacier. At present, the plain is incised and partly eroded as a result of the formation of recent floodplain terraces. The depth of erosional incision amounts to 15–20 m. Prior to erosion, the plain occupied the entire valley bottom at least between altitudes of 2700 to 2400 m. Among preserved areas of the plain, the lowest one is located approximately 4.5 km away from the head of the Kukurtli Glacier (aerial photography of 1957). Hills and hillocks are mostly covered by vegetation and characterized by steep slopes. The average height of their summits is 2–3 m. Only numerous cliffs, which represent summits of giant (up to 10–15 m) tuff breccia blocks, are up to 5–10 m high. Lower parts of these brown blocks, virtually barren of soil cover, are submerged into compact rudaceous material of the hillocky plain. Large tuff breccia blocks, which were washed away from the plain, occur in both floodplain and channel zones of the Ullukhurzuk River. The coarse gravel- to boulder-sized material in tuff breccia is composed of unrounded angular fragments of dark gray dacites with abundant milky white plagioclase phenocrysts submerged into a poorly sorted mixture of inequigranular sand and aleuropelite. The sequence as a whole is dark gray to brownish gray. According to our data, tuff breccia blocks were torn out from the subvertical wall at an

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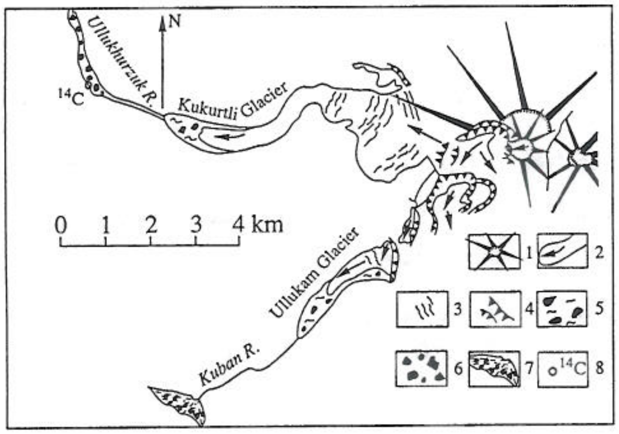

Location of the Kukurtli and Ullukam glaciers. (*1*) Volcanic edifices and their craters; (*2*) glaciers (arrows indicate direction of their movement); (*3*) ice fall; (*4*) subvertical wall of bedrocks; (*5*) young (presumably the middle of the 19th century) moraines; (*6*) fragments of avalanche-related hillocky plain of first and second centuries; (*7*) late Holocene glacial–mudflow fan in upper courses of the right tributary of the Kuban River; (*8*) sampling sites for ^{14}C dating

altitude of 4200–4900 m in the feeding area of the Kukurtli Glacier and then transported over a distance exceeding 10 km.

The area between bases of valley walls and lateral edges of the hillocky plain locally bears signs of old shorelines left by impounded lakes. Judging from their altitude, the lakes were initially several dozens of meters deep. Then, their levels fell down to approximately the surface of the hillocky plain, and peat started to accumulate in the lake bottom. The present-day thickness of peat is 50–60 cm.

The basal (5–6 cm) peat sequence was sampled for ^{14}C dating. The obtained radiocarbon age of 1750 ± 30 ^{14}C yr B.P. for Sample GIN-11983 corresponds to the calendar age of ~290 A.D. according to the calibration method [8]. Taking into consideration the peat accumulation rate, its formation commenced in 200–250 A.D. It is remarkable that the age estimate of the peat base is consistent with the date obtained for the soil horizon (GIN-9307, 1770 ± 60 ^{14}C B.P., calendar age 290 A.D.) overlying the tephra layer related to the last eruption (among thus far registered ones) of the Elbrus Volcano at the beginning of the current era [2].

Hills and cliffs are chaotically distributed on the plain surface. Therefore, we cannot assign them to moraines of the Kukurtli Glacier, which are characterized by arcuate ridges and well-developed lateral moraines. In terms of the surface topography, the hillocky plain also differs from typical landslide relief of volcanic areas [9, 10]. It was assumed, therefore, that this hillocky plain formed as a result of the rock–ice fall combined with rapid shove of the Kukurtli Glacier. A similar situation was observed in upper courses of the Genaldon River valley (North Ossetia, Northern Caucasus) where the rock–ice fall induced by the collapse of the pulsating Kolka Glacier (September 20, 2002) started to move along the valley with an enormous speed, destroying everything on its way and claiming human victims.

Remnants of a similar, although less manifested and smaller, hillocky plain are also observed at the bottom of the right source of the Kuban River downstream of the Ullukam Glacier head. This is probably related to the narrow (locally canyon-shaped) form and significant depth of the valley segment that served as a channel for the transportation of the major mass of rock–ice material to form a spacious fan at the confluence of the Kuban River source with the right tributary of the Ulluzen River (figure). The surface of the fan is protruded by 5- to 6-m-high upper parts of large cliffs of dacitic tuffaceous breccia (product of the Elbrus Volcano) and Paleozoic granites. Unfortunately, the age of this event is unknown.

In order to more reliably identify the studied plain with genetically analogous topographic forms and test the proposed hypothesis, Melekestsev interpreted aerial photographs of the Kazbek Volcano area and northern Genaldon River valley where rock–ice falls and rapid glacier shoves occurred repeatedly during the historical time in the geological–geomorphological settings similar to the Elbrus one [11, 12, and others]. The most catastrophic events were registered in the Genaldon River valley in 1834, 1902, 1969, and 2002. This area hosts the Kolka and Maili glaciers with an area of 2.47 and 6.81 km^2, respectively [11]. They are similar to the Ullukhurzuk and Ullukam glaciers of the Elbrus Volcano in terms of morphology and feeding peculiarities.

Interpretation of aerial photographs of 1958 and 1960 showed that imprints of events in 1834 and 1902 are still well manifested in topography as longitudinal abrasive furrows and grooves on slopes of the Genaldon River valley at 100–140 m above its present-day water level. They are also registered as accumulative structures, e.g., downstream-oriented bands (gouges) of rudaceous material on slopes of the valley and hillocky plain segments with abundant bedrock fragments and huge blocks in channels of the valley. The largest segments of plains are observed opposite of the Tmenikau Village and, particularly, in the mouth of a canyon crossing the Skalistyi Ridge. In aerial photographs, hillocky plain segments in the Ullukhurzuk (Elbrus piedmont) and Genaldon river valleys are almost identical, which indicates their similar origin.

Shteber [12], who visited the Genaldon River valley one month after the catastrophe, made an excellent description of this event in 1902. Based on his own observations and evidence of local residents, he reconstructed the event in the following way. On July 3, residents heard a rumble produced by rock fall; an extremely strong hurricane saturated with dust and ice particles swept along the valley; and a black mass of rocks and ice broke out of the canyon with an incredible sound and passed over a distance exceeding 7 km in 5 or 8 min. The second rock fall of July 6 overlapped the first one, passed down an additional 0.5 km, and came to a rest. The ice mass was saturated with detrital material and resembled "a real glacier but without lateral moraines." According to Shteber's estimate, its volume was $\sim 54 \cdot 10^6$ m^3. The weight of the largest transported blocks amounted to 32–48 t. According to other data [11], the avalanche transported 74.5 or even $100–110 \cdot 10^6$ m^3 of ice and detrital material beyond the Kolka Glacier limits. According to Shteber, the catastrophe was mainly provoked by the collapse of hanging glaciers with steep (40°–60°) channels. Rock–ice masses, accumulated at an altitude exceeding 4500 m, collapsed on the Kolka Glacier, lying at 3300–3000 m, and set it in motion.

In the 1920s, this ice mass, with abundant rock fragments of different sizes deposited in the Genaldon River valley in 1902, melted [11], and the released unsorted detrital material formed a hillocky plain similar to that in the Ullukhurzuk River valley.

The larger catastrophe of September 20, 2002, was widely discussed by mass media. It demonstrated the mechanism of impounded lake formation. Based on the duration of registered signals, the glacier collapse commenced at 20:08–20:09 MT and continued 3–4 min. Precisely at that time, the hanging glacier (or glaciers) was torn off the steep northeastern slope of Mount Dzhimara (4780.1 m) from an altitude of ~4300 m. The ice mass instantly negotiated ~1100 m by air, collapsed on the Kolka Glacier, and set it in motion. The ice with detrital material, which was captured both from the slope and pathway, rushed along the Genaldon River valley with a speed of ~150 km/h. In so doing, it tore off giant rock blocks and trees. Locally, it made deep incisions on valley walls. The rock–ice mass collapse followed an extremely strong whirlwind. The mixture of ice and rock fragments, $\sim 150 \cdot 10^6$ m^3 in volume, was transported over a distance of 19 km and stopped at ~1200 m near the mouth of a canyon cut by the Genaldon River in the Skalistyi Ridge. The glacial mudflow passed farther downstream of the tunnel. The rock–ice mass, up to 100 m thick, extended along the Genaldon River valley over more than 4 km and impounded lateral streams, resulting in the formation of deep lakes along both sides of the valley. Traces of precisely such lakes were observed in the Ullukhurzuk River valley.

The factors responsible for the collapse of hanging glaciers in 1902 and 2002 are ambiguous at present. L.A. Vardanyants believed that glacier collapses and subsequent catastrophic events were stimulated by neotectonic movements related to "squeezing out" of the sublatitudinal block of two anticlines and sandwiched syncline bordered by faults on the south and north. Most researchers assume that the collapses were probably caused by anomalous meteorological conditions: unusually high summer temperatures, high precipitation, and heavy showers. In principle, the same can also be assumed for the Kukurtli Glacier in Elbrus at the beginning of the current area. Nevertheless, other factors such as, for instance, strong local earthquakes occurring prior to and during volcanic eruptions, as well as uplift and deformations of near-summit parts of volcanoes during the ascent of viscous dacitic magma are not inconceivable. It should be remembered that the dated Elbrus eruption occurred approximately at that time [2].

The aforesaid allows the logical assumption that catastrophic rock falls and rapid glacier shoves can occur in the Elbrus Volcano in the future as well. In the case of eruptions of this volcano, the above processes may be accompanied by powerful lahars. In order to minimize the number of victims and potential damage related to these and other catastrophic events in the Elbrus region and Ossetian Mountains, the permanent complex monitoring of potentially active Elbrus and Kazbek volcanoes should be organized as soon as possible.

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