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Ancient earthquake dislocations in the area of Elbrus Volcano, North Caucasus

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Abstract. New data have been obtained for the ancient, previously unknown large earthquakes that occurred during the Holocene in the central Caucasus region in the vicinity of Elbrus Volcano. The radiocarbon datings of the paleoseismic dislocations and the dating of the products of the old eruptions of the volcano suggest that at least four large eruptions of the volcano and four earthquakes with magnitudes of 6.5–7.0 had occurred during the last 7 thousand years. Although no synchronism has been found between the volcanic and seismic events, some earthquakes might have been associated with particular large eruptions.

Introduction

Natural catastrophes that take place in the densely populated territory of the North Caucasus, with its national and social problems, are fraught with serious ecological, political, and economic consequences. For this reason the study of the mechanisms that cause large earthquakes, volcanic eruptions, and the exogenic catastrophic phenomena that accompany them is an urgent scientific task. During the last decade of the 20th century the Caucasus region experienced a series of large earthquakes, this suggesting its obvious seismic reactivation. Most of the sources of the large earthquakes (Chaldyra in 1976, Paravan in 1986, Spitak in 1988, Racha in 1991, and Borisakh in 1992) were concentrated in the largest geological structure crossing the Caucasus region in the meridional direction, namely, in the Trans-Caucasus transverse rise which is a collision-associated structural feature of the continent-continent type.

The centers of recent volcanism in the Caucasus mobile region also tend to be located in the Trans-Caucasus transverse rise. The Ararat, Aragats, Kazbek, and other volcanoes, which were active in Late Quaternary time, are restricted to this zone which is transverse relative to the entire fold region. As to the central sector of the North Caucasus, repeated eruptions of the Elbrus Volcano were recorded in Late Pleistocene and Holocene [*Avdulov and Koronovskii,* 1993; *Bogatikov et al.,* 1998, 2003; *Koronovskii,* 1983, 1985; *Koronovskii and Rudakov,* 1962; *Milanovskii and Koronovskii,* 1973]. Dating of these events using various methods proved that the Neopleistocene and Holocene eruptions took place 39±5, 28±3, 23±2, ∼21, ∼9.2–9.3, ∼7.8–8.0, ∼7.2, ∼6.0, ∼4.9, and ∼4.6 thousand years ago and during the first and second centuries A.D. [*Bogatikov et al.,* 1998; *Laverov,* 2002]. Also reported in the literature are the volcanic eruptions dated approximately 1.3 and 1.0 thousand years ago [*Laverov,* 2002]. These eruptions included lava flows, hot gas ejections, ash clouds, and catastrophic lahars. The research work done in 2002–2003 proved two of these eruptions using radiocarbon dating of the paleosoil. One of these events took place about 6000 years ago and was accompanied by lahar flows. The material of one of the lahars covered the paleosoil dated 6410±100 years ago (Sample IGAN 2616) on the high terrace rising 40–50 m above the flood plain in the left side of the Baksan R. in the mouth of its left tributary, known as the Kyldybashsu R. (Figure 1, Site 2). The second volcanic eruption has been dated using the results of studying the paleosoil covered by lake deposits at the third terrace above the flood plain of the Kyzylkol River (in the upper reaches of the Malka R.). This soil horizon was dated 1780±70 years (IGAN 2591). It reflects the process of the rapid burying of the humus-rich soil under the deposits of the dammed lake which was produced by the damming of the Kyzylkol River by a lava flow in its near-mouth area. At about the same time a rock avalanche took place in the upper

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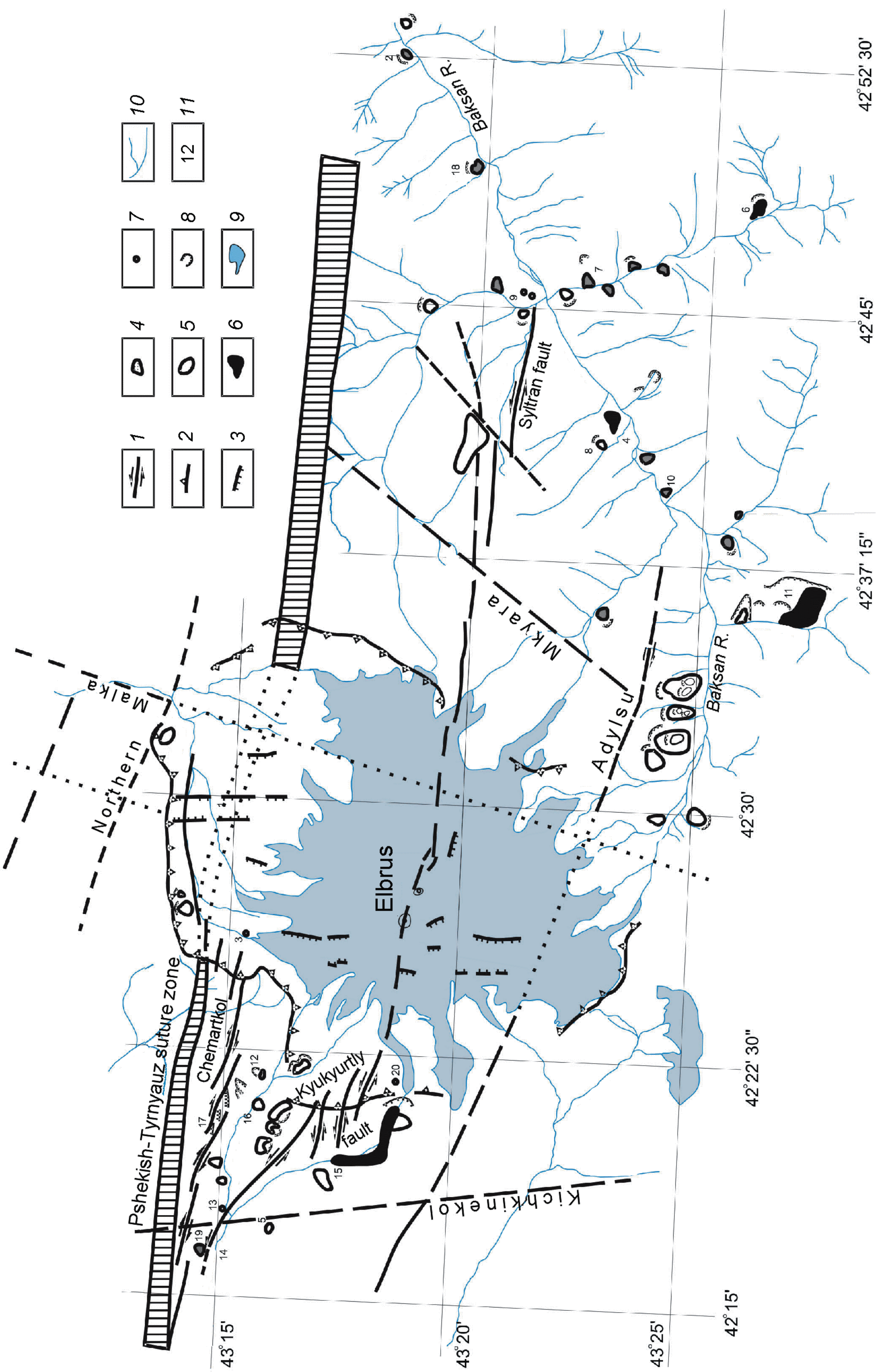

Figure 1. Paleoseismic dislocations in the Elbrus region Key: (1) Faults and displacements along them; (2) boundaries of the Elbrus caldera; (3) primary seismic dislocations; (4–6) secondary seismic dislocations: (4) avalanche, (5) landslide, (6) rock-ice avalanche; (7) seismic vibration phenomena; (8) detachment walls of secondary seismic dislocations; (9) glaciers; (10) rivers; (11) observation sites.

reaches of the Baksan R. (somewhat lower down the flow of the river, near the Elbrus Settlement). The paleosoil horizon buried under the avalanche material has a radiocarbon age of 1630±50 years (Sample IGAN 2612). It appears that this avalanche arose during the eruption of the volcano and was caused by moderate seismic movements that accompanied this eruption.

As a result of the geological, geophysical, geochemical and other observations, carried out in the recent years, a large magma chamber was discovered in the central part of the Earth crust [*Avdulov and Koronovskii,* 1993; *Laverov,* 2002]. Therefore Elbrus cannot be ranked as an extinct volcano, but can be qualified as a temporarily sleeping one [*Bogatikov et al.,* 2003; *Koronovskii,* 1985; *Koronovskii and Milanovskii,* 1960]. In other words, we have every reason to expect a new reactivation of volcanic processes in the Elbrus volcanic center (EVC).

The estimation of a seismic hazard for the Caucasus region, based on the cluster analysis of the geological, geophysical, and seismological data [*Reisner and Ioganson,* 1993], proves that the Elbrus area has a potential earthquake source (PES) with a predicted maximum earthquake magnitude of 7.2 [*Rogozhin,* 2002]. During the instrumental and historical periods of observations this source manifested itself very poorly. In essence, the Elbrus region is a large zone of seismic quiescence, where neither weak nor moderate shocks are recorded, not to mention any large seismic events. This can be explained by the fact that the melt that now fills the large magma chamber relieves the stress in the Earth crust, so that seismic shocks do not arise. At the same time the data collected by different researchers about paleoseismic dislocations suggest that very large earthquakes might have taken place there in the past [*Bogatikov et al.,* 2003; *Laverov,* 2002; *Nikonov,* 1991]. Taking into account the above information, it seems urgent to investigate the seismic and volcanic events that take place in the region of the Elbrus volcanic center. The aim of our research was to clarify whether these events accompany one another or they are unrelated in terms of the time of their occurrence.

Formulation of the Problem

Considering the urgent character of this problem, field investigations were arranged to study the geology and geomorphology of the Elbrus region for the purpose of finding the traces of old unknown large earthquakes, that is, any paleoseismic dislocations [*Solonenko,* 1973]. The existence of paleoseismic dislocations that had been produced in the Greater Caucasus region by large earthquakes of the past has been proved by many researchers in other regions: in the Northwest Caucasus [*Rogozhin et al.,* 2002], in the West Caucasus and in Svanetia [*Khromovskikh et al.,* 1979], in Mountainous Dagestan, and in North Osetiya [*Nikitin,* 1987]. Therefore, the finding and study of ground surface disturbances, that remained from ancient earthquakes, in the Central Caucasus region seemed to be promising. The authors of this paper intended to study both primary (seismotectonic) and secondary (gravitation and vibration) deformations. In the course of studying these objects we intended to collect samples of the material that had been buried during the operation of the respective processes, which was expected to contain organic matter suitable for dating the seismic dislocations and, hence, for timing the earthquakes that had produced them. The resulting rock samples were dated using the radiocarbon (^{14}C) method at the pertinent laboratory of the Institute of Geography, Russian Academy, by a group of researchers headed by O. A. Chichagova. The comparison of the numerous dating results for seismic dislocations of different origins allowed the more reliable reconstructions and timing of old earthquakes as compared to the dating of individual dislocation types. The resulting age values were used to correlate the periods of large earthquakes with the known periods of the volcanic eruptions.

Results of the Study

The field study of the traces of the large earthquakes that had occurred during the prehistoric past in the Elbrus volcanic center, namely, in the Baksan R. basin, in the valleys of the Biitik-Tebe and Kyukyurtly Rivers (Kuban R. upper reaches), and in the upper reaches of the Malka River, resulted in locating paleoseismic dislocations of both primary seismotectonic origin, and of secondary seismogravitational and vibration origin (Figure 1).

The primary seismic dislocations include the en-echelon system of the paleoseismic faults of the meridional, Trans-Caucasus orientation, complicating the sides and the surface of a small (0.6×1.4 km^2) flat graben-shaped basin of a Second World War airdrome, known as the Irakhik-Syrt area, on the northern slope of the volcanic cone (Figure 1, Site 1). The total length of the fault system exceeds 5 km, some individual faults being traced for distances of 800–1000 m. The faults (left-lateral normal faults) break the Paleozoic bedrocks in the zone of the Pshekish-Tyrnyauz Fault and the moraine-covered surface of the late Pleistocene (40–45 thousand years) Kyzylkol dacite lava flow and produce steps in the topography of the ridges and around the "Aerodrom" Plateau. The breaks in the plateau surface are accompanied, throughout their lengths, by narrow linear pockets of abnormally thick paleosoil (as thick as 1 m with the normal thickness of the modern soil being 5–15 cm), the base of which includes angular fragments of dacite which composes (in its bedrock position) the relatively upthrown western limb (Figure 2). The total magnitude of the modern vertical normal-fault displacement along this system of faults may be 1.5–2.0 m, being as large as 50–100 m for the recent history. The pulse-type normal fault movement of about 1 m might have occurred somewhat earlier, about 2280±90 years ago, as follows from the radiocarbon dating of the lower paleosoil layer from a near-fault pocket (Sample IGAN 2592). Approximately at the same time, 2520±60 years ago (Sample GIN 9114), a gravitational avalanche of a huge rock mass took place in the upper reaches of the Biitik-Tebe R. [*Laverov,* 2002] (Figure 1, Site 5), obviously provoked by some ancient earthquake.

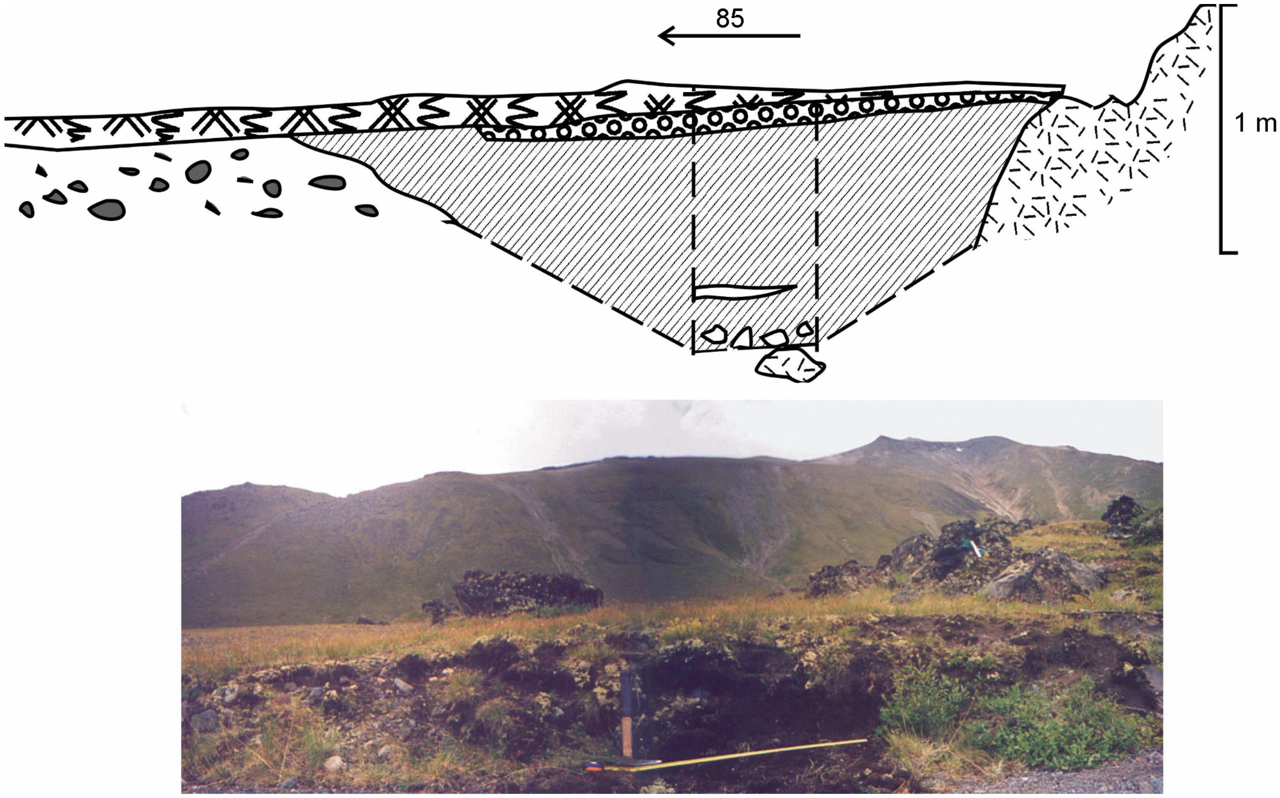

Figure 2. A pocket of abnormally thick paleosoil (Irakhik-Syrt area). Log of cleaned outcrop wall (top) and photo of the wall (bottom).

The western slope of the Elbrus Mt. shows another series of active faults expressed as a series of steep meridional scarps. Similar scarps also frame the Ulluchiran Glacier (Figure 1, Site 3) and can be traced southward from the tongue of the latter. It appears that these topographic forms are normal faults of earthquake origin.

A Chemartkol active fault zone of a nearly latitudinal strike extends in the middle of the slope in the right side of the Biitik-Tebe Valley (Figure 1, Site 12). This fault enters the zone of the Pshekish-Tyrnyauz old crustal fault, being located in its southern part. The fault is represented by a series of en-echelon faults totaling 1–3 km in length and having a WNW trend.

The system of the Chemartkol faults can be used to follow the traces of recent intensive right-lateral shear faults. They are expressed as the high asymmetry of the counterforts of the northern sides of the Biitik-Tebe and Ullukhurzuk river valleys. The eastern slopes of these counterforts are rectilinear and are oriented across the strikes of the river valleys and the Sadyrlyar Range. At the same time, the western slopes of the counterforts are highly curved in map view and acquire a NE and even a nearly latitudinal strike up the slope. This results in the highly asymmetric structure of the counterforts. The lower parts of the latter are displaced 250–300 m westward relative to the upper parts, this displacement being restricted to the narrow zone of the Chemartkol fault which is expressed in the topography as a chain of saddles.

This fault has been traced over a distance of about 15 km from the Burukhtysh Pass at the NW slope of Elbrus to the right sides of the Biitik-Tebe R. and Ullukhurzuk R. valleys in the WNW direction (along the azimuth of 280°) and forms, in the topography of the slope, a clearly expressed saddle 100–200 m wide, which complicates the steep northern side of the Biitik-Tebe R. Valley (Figure 3). A trench dug across the saddle by the geologists of the Koltsovo Expedition in the 1960s (Figure 1, Site 17) showed that the bedrock consisting of Late Paleozoic granite was close to the ground surface. The crystalline rocks are overlain there by a thin deluvium detrital apron with the elements of the weathering crust (red arcose grus) and a thin present-day soil 10–20 cm thick. Along the edges of the saddle, near the faults limiting it, the modern soil is underlain by paleosoil lenses 15–20 cm thick. A sample was collected from the northern lens bordering the fault for the purpose of radiocarbon dating. The age of the buried paleosoil was found to be 2350±40 years (IGAN 2827). It is important to note that this age value almost coincides with the age of the buried paleosoil from a fault wedge at the Irakhik-Syrt Plateau (see above).

The modern topography of the Biitik-Tebe and Ullukhurzuk river valleys began to form since the Middle Pleistocene, when the river cut across the old glacier trough. At the present time the sides of the valleys show the remnants of this trough, having the form of high terraces. In this connection, the system of the counterforts and the valleys separating them was being shaped, to achieve their

Figure 3. A chain of saddles marking the Chemartkol Fault zone (shown by an arrow).

modern shapes, during about 100 thousand years. This means that the average rates of the right-lateral displacements were 2.5–3.0 mm/year. Generally, those were mostly creeplike, slow geological movements. At the same time, the fault zone shows the traces of old earthquakes in the form of the segmented system of primary seismic breaks (Figure 4). These breaks are expressed as scarps, up to 1.2 m high, oriented along the slope of the valley. Some segments are as long as 1 km, the total length of the system traced being about 5 km. The swells and the seismic breaks that accompany them are roughly latitudinal, with the strike azimuth of 70°–90°.

The structure of the seismic break is especially well seen in one place where it was studied in a trench specially dug across the break strike (Figure 1, Site 17, and Figure 2). The trench has a length of 3.5 m and a depth of 1.5 m (Figure 5). It intersects the northern slope of the swell and a narrow earthquake-produced trench bordering it in the north. The trench has a strike of 75°ENE. The surface of the rampart is almost devoid of any humic material of the modern soil. The exposed material is represented by reworked and weathered bedrock granite, covered by meager grass vegetation. On the contrary, the earthquake produced trench exposed a thick modern soil, covered by a rich dense grass vegetation with a humus layer, up to 30 cm thick, and two layers of buried paleosoil. The upper layer is composed of black good soil up to 35 cm thick, the lover layer being lass than 25 cm thick and being composed of gray poor soil with scattered nests enriched in organic matter. The total thickness of the soil layers amounts to 90 cm. The southern segment of the trench exposed an earthquake-produced scarp with upward vertical displacements measuring 1.5 m. The lower part of the bench includes a two-level colluvium wedge. The upper part of the wedge is composed of coarse-clastic gravelly rock mass of

Figure 4. An earthquake produced break in the zone of the Chemartkol Fault. The arrow shows the place of a trench (Figure 5).

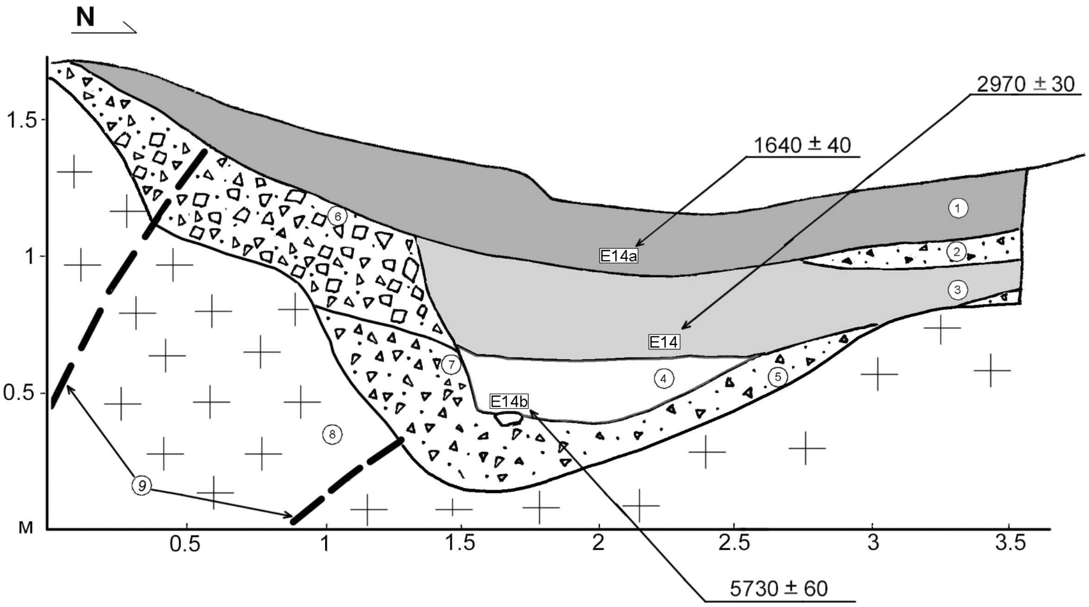

Figure 5. The structure of the earthquake exposed rock sequences in the Chemartkol Fault zone: (1) modern soil; (2) gravel-sand deluvium; (3) black humus-rich paleosoil; (4) gray paleosoil, poor in humus; (5) buried gravel-sand deluvium; (6) upper colluvium wedge; (7) lower colluvium wedge; (8) bedrock granite; (9) fault lines. E14, E14a, E14b – Sampling sites for radiocarbon dating and ages of the samples.

arcose composition, and the lower, older part consists of a finely broken grus of the same composition. The bottom of the trench exposed a coarse arcose gravel mass, the lower, older wedge being composed of a finely crushed grus of the same composition. Exposed in the floor of the trench was a colluvium-deluvium detrital apron composed of gravels and sand. Samples were collected from the lower part of the modern soil and from two paleosoil beds for the purpose of radiocarbon dating.

The rock sequence described seems to be the product of three earthquake events. The abnormally thick paleosoil horizons had been formed in a narrow valley, which marked the downthrown limb of a fault. It appears that each cycle of soil formation in this trench began after each successive pulsed movement along the fault. The lower horizon of the oldest paleosoil (Horizon 4 in Figure 2) has a radiocarbon age of 5730±80 years (IGAN 2826). This date correlates well with the seismic event that took place approximately 5500–5700 years ago. The younger paleosoil (Horizon 3 in Figure 2) has a radiocarbon age of 2970±30 years (IGAN 2824). At the same time there is an obvious indication for an older earthquake which occurred 3900 years ago. It can be supposed that this horizon was formed after this seismic displacement. Both events caused large rock avalanches and the formation of dammed lakes in the Baksan Valley and are discussed in detail here somewhat later in the section devoted to dammed lakes.

The bottoms of the modern soils (Horizon 1 in Figure 2) have a radiocarbon age of 1640±40 years. This soil "seals" the fault, which may indicate that it had ceased to be active after the time of 1600 years. It is significant that this date correlates well with the time of the last Elbrus eruption, 1800 years ago [*Laverov,* 2002]. It is possible that the last seismic movement was associated with this event. On the other hand, the arc-shaped subsidence of a modern soil horizon in the central part of the paleoseismic trench suggests that the slow upthrust movements continued throughout that period of time.

To sum up, the study of the seismic rupture in the trench resulted in finding the traces of two old earthquakes which had taken place about 5500–5700 and about 3900 years ago, which produced a two-stage colluvial wedge and two buried paleosoil horizons. Another interesting result is the indication that the Elbrus eruption that took place about 1800 years ago was accompanied by seismic activity.

The other fault studied in the northwestern Elbrus region was named the Kyukyurtly Fault. It has a WNW strike (310°–290°). It has been traced at the right side of the Kyukyurtly R. in the southeastern direction as far as the northern slope of the Kyukyurtly Glacier. It is traceable in the NW direction as far as the northern slope of the Kyukyurtly Glacier and the same NW direction into the area, where the Kyukyurtly and Biitik-Tebe rivers flow together, and to the right side of the Ullukhurzuk R. Valley. In some areas the studied segment of this fault zone has an expression of an earthquake produced trench filled by a lenticular body of abnormally thick soil. The radiocarbon dating of a sample taken from this soil yielded its age to be 1660±40 years (IGAN 2822). In other segments the fault is marked by an earthquake scarp and by mineral and fresh water springs (Figure 1, Site 13). In the upper reaches of the Ullukhurzuk River, in its right-hand side, the fault is represented by an en-echelon series of active faults demonstrating left-lateral shear displacements. The fault displacement magnitude was

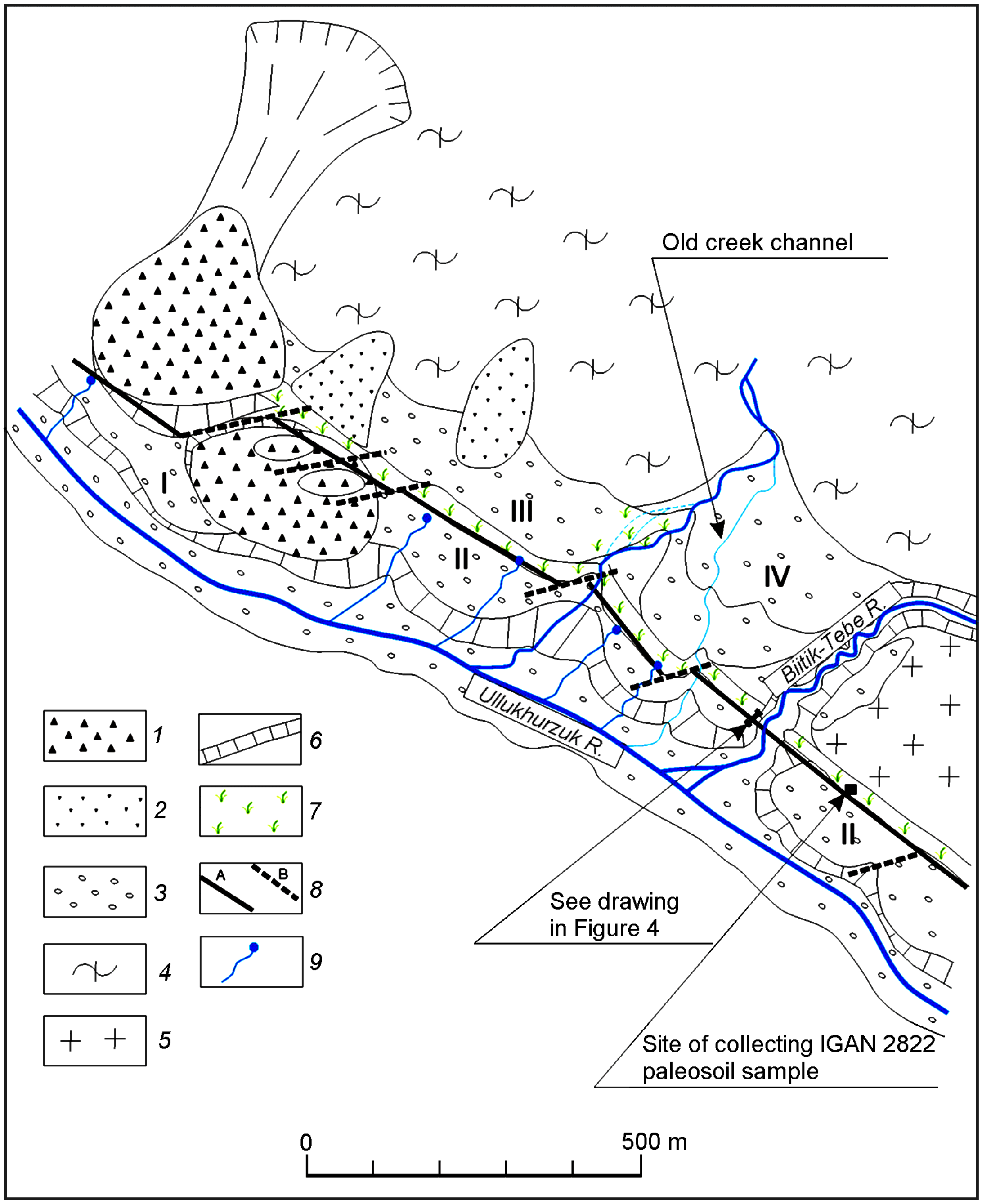

Figure 6. The layout of the Ullukhurzuk R. Valley demonstrating the displacement of the avalanche body and watercourses in the zone of the Kyukyurtly Fault: (1) colluvium of an old avalanche body; (2) colluvium of the younger avalanches; (3) alluvium of the flood plain and of the terraces above it; (4) Proterozoic–Early Paleozoic granite gneiss; (5) Late Paleozoic granite; (6) scarp; (7) swamping; (8) Kyukyurtly Fault zone (A) and feathering ruptures (B); (9) water springs.

estimated, using the displacement of an old avalanche body, found at the right side of the Ullukhurzuk River 1 km higher upstream from the area where its left tributary (Kichkinekol) flows into this river. Here, an avalanche body composed of large granite gneiss blocks is displaced over a distance of 200–250 m in this fault zone (Figures 6 and 7). This body rests on the Pleistocene 2nd and 3rd terraces above the flood plain and is cut by a fault trench. This avalanche can be dated Late Pleistocene (40 000 years). Consequently, the average displacement rate can be estimated roughly to be 5–6 mm/year. The same area shows the interception of the valley of the left unnamed tributary of the Ullukhurzuk

Figure 7. Displacement of an avalanche body (shown by arrows) in the Kyukyurtly Fault zone.

River in the third terrace above the flood plain near the place where the Biitik-Tebe and Kyukyurtly rivers flow together. The displacement and interception of the creek had been caused by the left-lateral movements along the faults feathering the Kyukyurtly Fault. Moreover, where the creeks are crossed by the breaks feathering the fault, some of their courses show individual knee-shaped curves of their channels. These curves can be traced linearly from one creek to another and have a left-lateral pattern with the magnitudes of the displacements of the main water channel measuring 10 to 30 m.

This fault zone shows the earthquake displacement of the Quaternary rewashed tuff (tephra) and the overlying alluvial deposits of the 3d terrace above the flood plain in the right bank of the Biitik-Tebe R. 150 m up the stream from the area where it flows into the Kyukyurtly River. The earthquake displacement has a normal fault character: the southern limb of the fault dipping steeply to the south (at an angle of 80°) with the formation of colluvial wedge >2 m thick (Figure 1, Site 13; Figure 8). The magnitude of the vertical displacement is about 3 m. The downthrown segment was the south-western limb. This displacement seems to have occurred in the Holocene, yet not later than 1600–1700 years ago.

As follows from the above description, both of the active faults of the Caucasus orientation, mapped in the area northwest of Elbrus, namely, the Kyukyurtly and Chemartkol ones, are still active in terms of geologic and seismic activity. Both faults show both horizontal displacements (right-lateral in the former case and left-lateral in the latter and also vertical movements (upthrust in the former case and downthrust in the latter).

Where the faults intersect the Elbrus caldera [*Bogatikov et al.,* 1998], their structure grows more complicated, and they are marked by broad (2–3 km) zones of en-echelon ruptures (Figure 1). The Chemartkol Fault joins the Kyzylkol Fault in the east, and the Kyukyrtly Fault joins the Syltran Fault in the southeast. So, the faults of the Caucasus strike are kind of get inscribed into the given young concentric structural pattern. The Adylsu Fault, extending in the southern part of the Elbrus caldera for a distance of about 30 km, is also of earthquake origin. In terms of its structure this is a typical earthquake trench. Its modern horizontal movements are typical right-lateral displacements. Earthquakes seem to have occurred repeatedly causing landslides and rock falls and producing dammed lakes in the Baksan R. area. It appears that this fault had been reactivated 300–400 and about 5500 years ago.

The secondary paleoseismic dislocations include numerous landslides of loose slope deposits, block-type bedrock landslides, found everywhere on the slopes of the volcanic edifice and in the valleys of the left and right tributaries of the Baksan River, in the source areas of the Malka and Kuban rivers, the bodies of ancient rock avalanches in the valleys of the Baksan R. (Figure 1, Sites 2, 8, 10, and 18), Irik R., Yusenga R. (Figure 1, Site 11), and Adyrsu R. (Figure 1, Sites 6 and 7), and the neptunian dikes in loose tuffaceous and alluvial deposits, in lake sands, and in an old lahar layer. The volumes of some gravitational slope deposits are as great as 15–17 million cu. m. In the past the largest of them covered wholly the valleys of the Baksan R. and its tributaries (Adyrsu, Adylsu, Syltran-Su, Kyrtyk, Irik, and Yusenga), this having caused the formation of dammed lakes. Later, these dams were breached by the river currents, and the lakes were drained off. The sediments of these lakes are preserved on the tops of the terraces. The landslide garlands (Figure 1) observed on the slopes of the Baksan R. Valley, as steep as 30°–40°, originated a long time ago as a result of a single-act pulse-type movement of high intensity, and have not been displaced since that time (Figure 9). They sort of hang on the slopes, as can be clearly seen in the left side of the Baksan R. Valley over an area from the Terskol R. inflow to that of the Yusenga R. inflow. This proves the seismic origin of the gravity anomalies. The neptunian dikes discovered in the Quaternary loose deposits suggest the protrusion mechanism for the liquefied sand intrusion into the overlying rocks under the compression effect of the propagating seismic wave. These phenomena are widespread in the epicentral zones of modern large earthquakes of magnitudes 7, 8, and higher [*Obermeier,* 1995].

There are at least two generations of secondary slope earthquake dislocations. The older rockfalls and landslides show smooth surfaces, the large blocks in their clastic material are covered by a desert varnish, are overgrown densely with desert lichen, and a thick modern soil has been formed. The samples of these modern soils, collected in different localities of this region have been dated (^{14}C) 110±30 (IGAN 2620), 180±30 (IGAN 2621), and 210±30 (IGAN 2617) years. The bodies of these landslides and rock falls rest on the low, 10- and 20-meter Late Pleistocene terraces of the Baksan R. flood plain [*Reisner and Bogachkin,* 1989]. At the same time they are covered by the alluvium and proluvium material transported from the valleys of the side tributaries. Proceeding from the radiocarbon dating of the coals from an earthquake avalanche body in the lower course of the Adyrsu R. (Site 7 in Figure 1), which yielded an age of 2810±70 years (IGAN 2586), and from the earlier radiocarbon dating of the paleosoil from under an earthquake produced avalanche body measuring 3.5×10^6 m^3 in the source area of the Biitik-Tebe River (Site 5 in Figure 1) with a radiocarbon age of 2520±60 years [*Laverov,* 2002] (IGAN 2586), the earthquake that produced these avalanches might have occurred roughly 2300–2400 years ago.

The younger seismogravitational dislocations are distinguished by a relatively more fresh appearance of the rockfall and landslide masses, by the absence of desert varnish on the large fragments and by a thin modern soil. They cover the 5- and 6-meter Holocene terraces of the Baksan River [*Reisner and Bogachkin,* 1989] and even extend as far as the flood plain. Some bodies of these avalanches are covered by the proluvial material of the alluvial fans of the side tributaries. The radiocarbon dating of the paleosoil, covered by the earthquake produced avalanche material at the right bank of the Baksan River (Figure 1, Site 10) opposite Elbrus (400±70 years ago, IGAN 2590), suggests that that another younger earthquake took place about 300–400 years ago, which provoked the reactivation of these catastrophic gravitational slope activities.

In some areas the older collapse material is covered by the later ones, where the paleosoil is hidden under the avalanche rock masses of the latter. It appears that there had been even older avalanches and landslides, though their traces have not been found thus far.

In the course of this study we found a few sequences of lake deposits resting on the old alluvial terraces in the Baksan and Adyrsu river valleys. It appears that these lakes had been of dam origin and were formed as a result of old avalanches which dammed the river courses. We found four generations of these paleolakes. Our dating of coal and paleosoil from the basis of the lake deposits crowning a 40–50-meter terrace above the flood plain in the left side of the Baksan R. Valley suggested that a dammed lake had existed there near the mouth of the Kyldybashsu tributary during two periods of time. (Figure 1, Site 17). The first lake originated 6410±100 years ago (IGAN 2616), the second, about 5510±40 years ago (IGAN 2610). Somewhat earlier than the time when this second lake was filled with water (6170 years ago) and after its existence (4900 years ago) catastrophic lahars descended down the Baksan R. Valley over a distance of 70 km from the volcanic cone [*Laverov,* 2002], the formation of which was associated undoubtedly with the volcanic activity which caused the rapid melting of the glaciers. This provides an example of the distinct alternation of volcanic and seismic activities in time.

The two other ancient lakes have been reconstructed in the Baksan R. Valley, in the area of the Elbrus Settlement (Figure 1, Site 4) and slightly higher up the river from the Tyrnyauz Settlement (Figure 1, Site 2) based of the analysis of the ages of the paleosoils covered by the lake deposits. These two lakes, spaced 20–25 km from one another, had been formed almost simultaneously. One of them originated 3870±90 years ago (IGAN 2613), the other, 3840±50 years ago (IGAN 2588).

As follows from the ^{14}C dating of the buried coals from the lake deposits (IGAN 2589) resting on the terrace rising 20 m above the flood plain in the left side of the Baksan R. Valley in the southern outskirts of the Neutrino Settlement (Figure 1, Site 8), the next lake (in terms of the time of its origin) was formed 2320±70 years ago. Its origin seems to have been associated with the collapse at the right side of the Baksan R. Valley of a huge rock avalanche composed of granite blocks, varying in size, from the right side of the Baksan Valley. The body of this avalanche, known as the Tyubele Swell [*Koronovskii and Milanovskii,* 1960; *Nikonov,* 1991] was had been spread over the terrace, overlapped the deposits of an old moraine, and dammed the Baksan Valley, obviously having dammed the river (Figures 10 and 11). The detachment zone of the collapsed block of crystalline rocks, well seen from the motor road, proves the avalanche origin of the Tyubele Swell.

A few dammed lakes originated in different places of the Elbrus region comparatively recently. For instance, one of the low terraces above the floodplain at the right bank of the Baksan River, slightly up the Tyrnyauz Town (Figure 1, Site 11), was found to contain lake deposits from which ancient coals were collected. Their ^{14}C age was found to be 490±30 years (Sample IGAN 2611). A lake was also formed in the upper reaches of the Adyrsu R. (Figure 1, Site 6) as a result of damming the river by a huge rock avalanche in the area of the present-day Dzhailyk Camp of alpinists. The paleosoil overlain by the lake deposits was dated 430±60 years (Sample IGAN 2619). Lake sediments with occasional charcoal remains were found in the area of the Elbrus Settlement (Figure 1, Site 4) on the first terrace of the Baksan R. left side. The radiocarbon age of this coal was found to be 340±150 years (Sample IGAN 2585). The paleosoil covered by the lake deposits has been dated 530±30 years (Sample IGAN 2618). To sum up, at least three lakes had existed almost simultaneously in the time interval of 400–500 years ago.

The neptunian dikes can be classified into two generations. The older generation includes the thin (0.5–1.0 cm) inclined dikes developed in the sand lenses and interlayers in the alluvial deposits of the high, 100- and 70-meter terraces in the Baksan R. Valley, where the left Kyrtyk tributary of the Baksan River flows into it (Site 9 in Figure 1 and Figure 12). As reported by *Reisner and Bogachkin* [1989], this terrace is of Early or Middle Pleistocene age. An in-

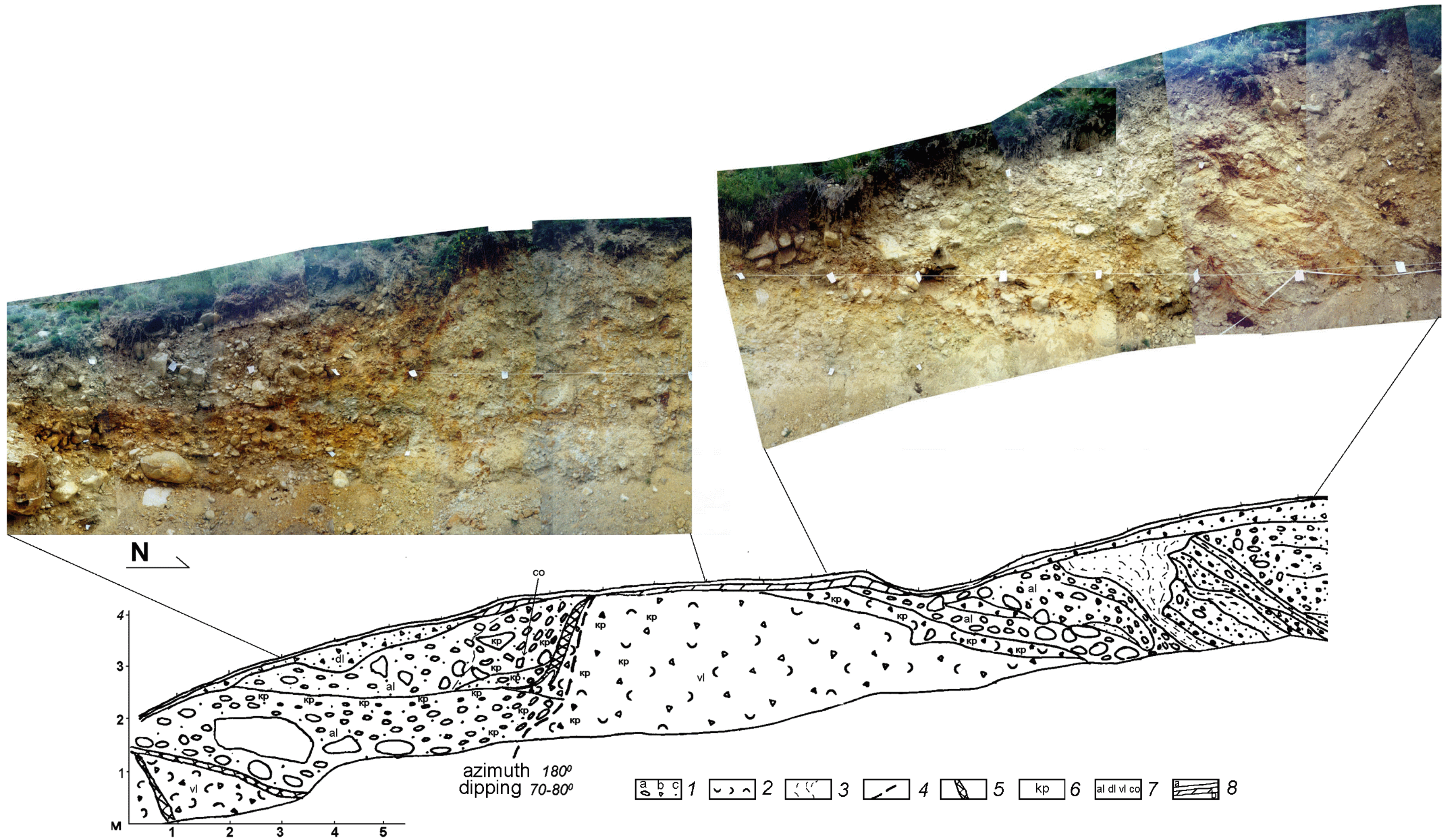

Figure 8. The photo (top) and drawing (bottom) of an outcrop from the Kyukyurtly Fault zone: (1) clastic rocks: (a) rounded, (b) unrounded, (c) sand and gravels; (2) tephra (rewashed tuff); (3) ripple mark directions in the protruded sand; (4) fault plane; (5) limonitization zone; (6) dispersed limonitization; (7) genetic types of Quaternary deposits; (8) soil: (a) modern, (b) old.

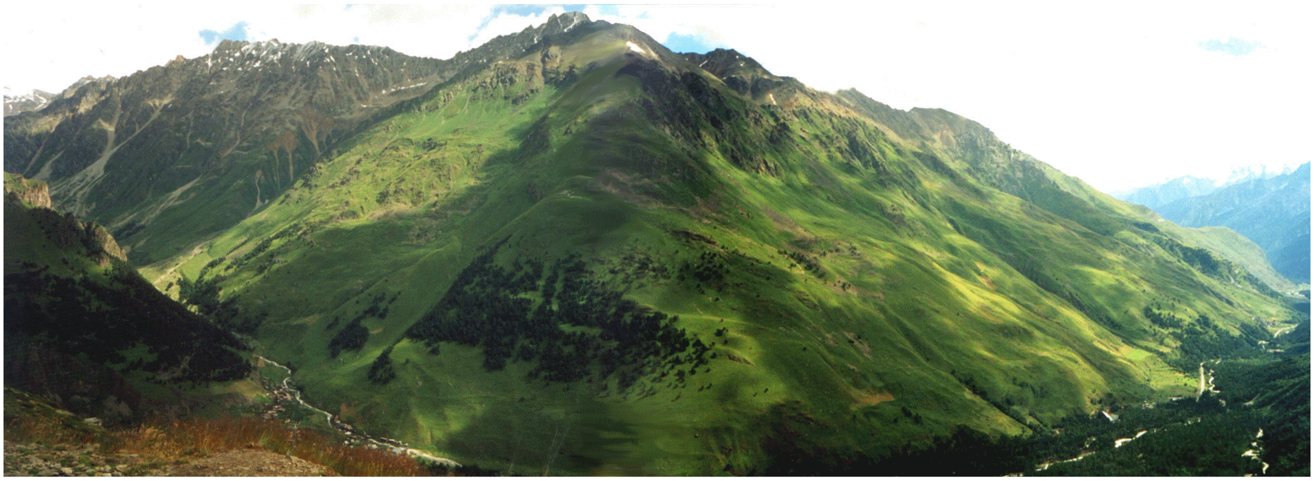

Figure 9. Block slides on the slopes of the Baksan R. Valley.

teresting fact is that the sand in the alluvium of the higher terraces (200 or 300 m) does not include neptunian dikes of this kind in this place. Younger dikes have been found on the northern slope of Elbrus near the end of the Ulluchiran Glacier (Site 3 in Figure 1; Figures 13 and 14). Here, the stratified sequence of fluvioglacial volcanomictic sand and the lahar deposits overlying it show numerous fissures, gently inclined to the south, many of which had been filled with liquefied sand in the past. Clearly seen there are the traces of the turbulent sand flow inside the dikes. The widths of these dikes vary from 2 to 5 cm. One can see the relative upthrust-overthrust displacements of the layers along these sand-filled fissures. This means that the sand was injected into these fissures under the conditions of the nearly horizontal compression of the layered rock sequence. The relative displacement of the fold limbs amounts to 2–3 cm. The stratified sand sequence and the lahar deposits are overlain unconformably by the coarse-clastic material of a modern moraine. It appears that the age of these vibration products is Holocene. In view of the fact that the age of these lahar deposits has been estimated to be 6–7 thousand years [*Laverov,* 2002; *Rogozhin et al.,* 2001], they must have experienced seismic shaking and the injection of liquefied sand somewhat later. It appears that the period of time from the accumulation of the fluvioglacial rock sequence with the lahar deposits on its top to the intrusion of the neptunian dikes could not be very large, otherwise under the conditions of the active high-mountain topography this rock sequence must have been rapidly dismembered and must have lost its water, necessary to liquefy the ground in response to seismic oscillations. It is more likely that these dikes were emplaced in connection with the earthquake that took place in the Elbrus area about 5700 years ago.

The neptunian dikes of the second, younger generation have been found on the western slope of the volcanic cone, in the upper reaches of the Kyukyurtly R., and in the area where it flows to the Biitik-Tebe River (Figure 1, Site 13, and Figure 15). Found in two localities of the Kyukyurtly fault zone were the traces of the old liquefaction of the water-saturated sand protruded as neptunian dikes and diapirs into the overlying alluvial or tuffaceous rocks. These phenomena were found in the area where the Biitik-Tebe and Kyukyurtly rivers flow together (this site was studied in an artificially cleaned outcrop, Figure 8). Here, found in the Late Quaternary deposits was a mashroom-shaped diapir body of light-color compact quartz and volcanomictic sand, intruded through a sequence of lake sand and alluvial pebble. The dike was found in the direct vicinity of a normal seismic fault, where the vertical displacement of the late Pleistocene and Holocene deposits was about 2 m. As has been mentioned above, the southwestern limb of this fault includes a thick colluvial wedge. This normal fault and the neptunian dike extend parallel to the Kyukyurtly Fault in the WNW direction. The age of these neptunian formations is obviously Holocene, but not younger than 1600 years, because farther southeast the fault zone is covered by a layer of undisturbed thick, fat soil. The radiocarbon age of its bottom was found to be 1660±40 years (Sample IGAN 2822).

Neptunian dikes up to 5 m long and 10–20 cm wide have been found and documented in the right, northern side of the Kyukyurtly Glacier trough (Site 20 in Figure 1). They intersect a tuff sequence covered by a moraine. The material filling the dikes is a sand and clay mixture of alluvial-limnic origin, composed of a rewashed volcanic material. In one place a dike of this kind was found to displace an alluvium interlayer, like a normal fault, over a distance of about 2 m. It should be noted that the dikes here have a submeridional strike, that is, transverse relative to the strike of the Kyukyurtly Fault. The age of the dikes was not determined.

Discussion of the Results

As seen from the above material, various topographic disturbances, such as active seismic breaks, avalanches, rock falls, dammed lakes, and neptunian dikes, acted repeatedly

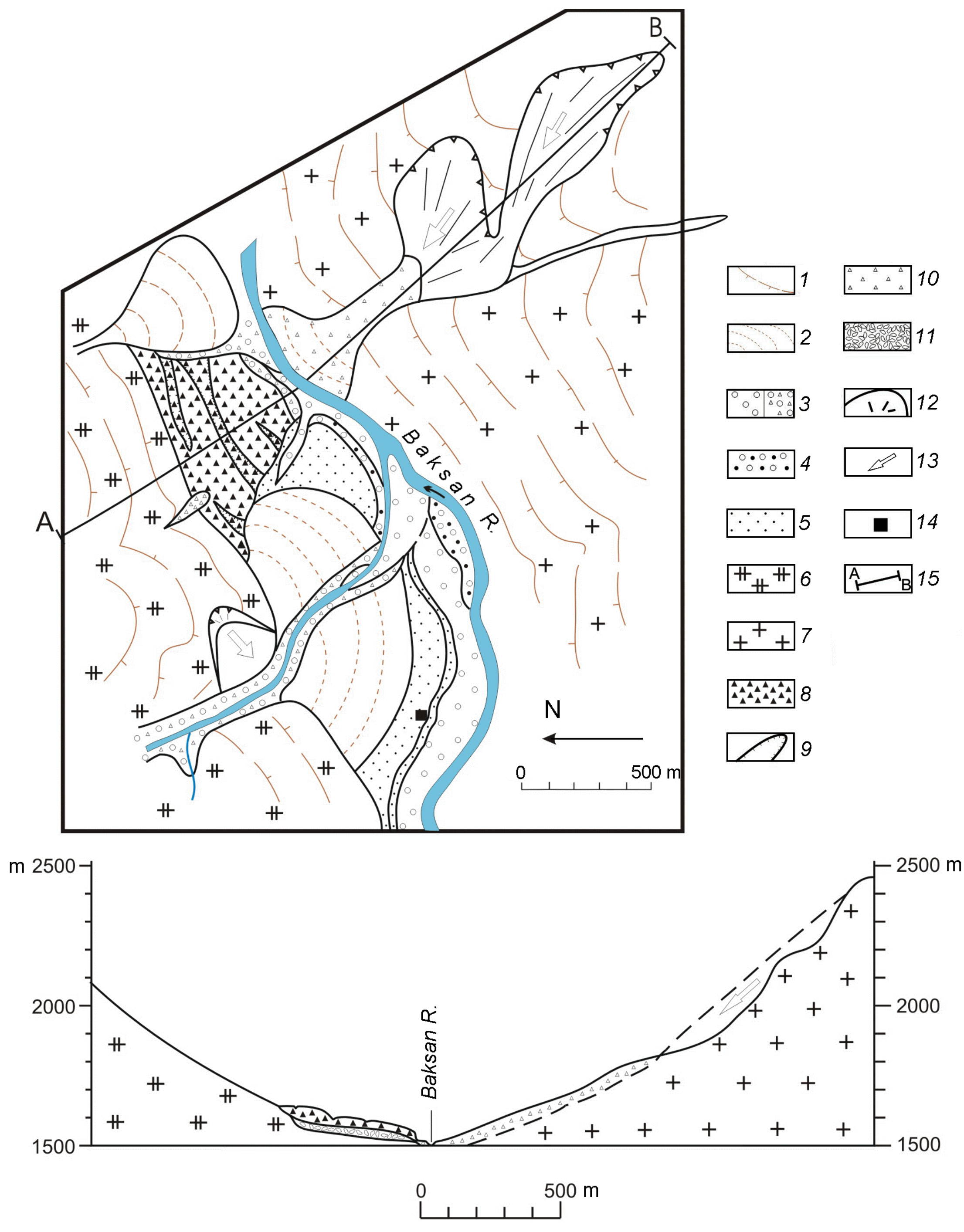

Figure 10. The map view and section across the rock avalanche which produced the Tyubele Swell at the left bank of the Baksan River (Site 8 in Figure 1). (1) Conventional contour lines on the slopes; (2) conventional contour lines for the alluvial fan; (3) alluvial (a) and alluvial-proluvial (b) Holocene deposits; (4) alluvial deposits of the lower river terrace; (5) lake deposits; (6–7) granitoids of various types; (8) colluvial formations of the Tyubele Swell rock avalanche; (9) linear lows in the Tyubele Swell body; (10) colluvial-proluvial deposits; (11) moraine deposits; (12) stone avalanche detachment circus; (13) direction of the stone avalanche fall; (14) site of sampling chare coal for ^{14}C dating; (15) section line.

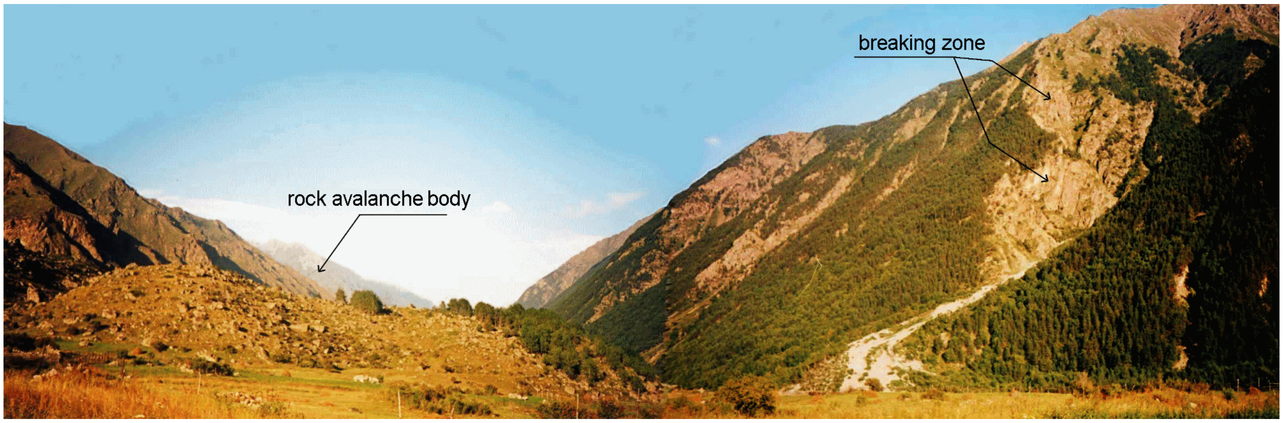

Figure 11. General view of the Tyubele Swell.

during short periods of time, sometimes almost in a synchronous manner, in different areas of this mountainous zone in the course of its Holocene evolution (Figure 6). These intervals were separated by the periods of time when no such processes developed. It appears that the short periods during which the young rock sequences and the topography were violated can be confidently identified with the moments of large earthquakes. This is undoubtedly true for the cases of finding seismic breaks and ground liquefaction structures (Figures 2, 4, 6). In the case of gravitational slope structures and dammed lakes, their seismic origin can be proved by the coincidence of the time of their formation with the time of the origin of primary seismic dislocations or vibration marks.

An additional confirmation of the seismic origin of the three dammed lakes discovered in this study (the upper course of the Adyrsu R., the left side of the Baksan R. Valley in the area of the Elbrus Settlement, and the right side of the Baksan R. Valley, somewhat higher than the Tyrnyauz Town) is the fact that they originated synchronously in different areas, situated far from one another, this procedure having been repeated two times. The deposits of these lakes differ in lithology and have different thicknesses. Yet, there exists one property which is common for all of them. Each rock sequence includes two horizons of buried paleosoil or coalified organic matter found at the same stratigraphic levels: at the base and in the upper third of the sequence. We collected samples from all of them for the purpose of their radiocarbon dating which proved that their ages in all three sites turned out to be very close for each horizon, respectively. Moreover, the ages of upper horizon correlate well with the Terek earthquake which took place in 1688±1 year [*Kondorskaya and Shebalin,* 1977]. Most of the very large earthquakes showed an independent character, yet, in some cases seem to have occurred shortly before or accompanied the large eruptions of the volcano.

Figure 12. Neptunian dike in the alluvial deposits of the Kyrtyk R. area.

As follows from the paleoseismogeological and other data, discussed above, the periods of seismic reactivation can be dated roughly 5500–5700, 3900, 2300, and 300–400 years ago (Figure 16).

The first earthquake was accompanied by the rising of an earthquake source to the ground surface in the form of an earthquake break in the zone of the Chemartkol Fault with the formation of the lower colluvial wedge (see Site 16 in Figure 1 and Figure 5), and by the origin of a dammed lake in the Baksan Valley near the mouth of the Kyldybashsu River. This earthquake seems to have caused the emplacement of numerous neptunian dikes which can be observed in the layered sequence of the fluvioglacial volcanomictic sand at the northern slope of Elbrus near the end of the Ulluchiran Glacier (Site 3 in Figure 1; see also Figures 13 and 14).

The second seismic event was also accompanied by the formation of two dammed lakes in the Baksan R. Valley: in the area of the Elbrus Settlement and higher upstream from the Tyrnyauz Town (Figure 1, Sites 2, 4, and 11). It appears that at least two natural dams were formed in the Baksan R. Valley.

The third earthquake was accompanied by the emergence of a break in the Chemartkol Fault zone with the formation of an upper colluvial wedge and a buried soil lens (Figure 1, Site 16, and Figure 5). This earthquake also produced a meridional break in the flat surface of the Irakhik-Syrt Plateau (also known as the Aerodrom Plateau) on the northeastern slope of the volcanic cone (Figure 1, Site 1) and

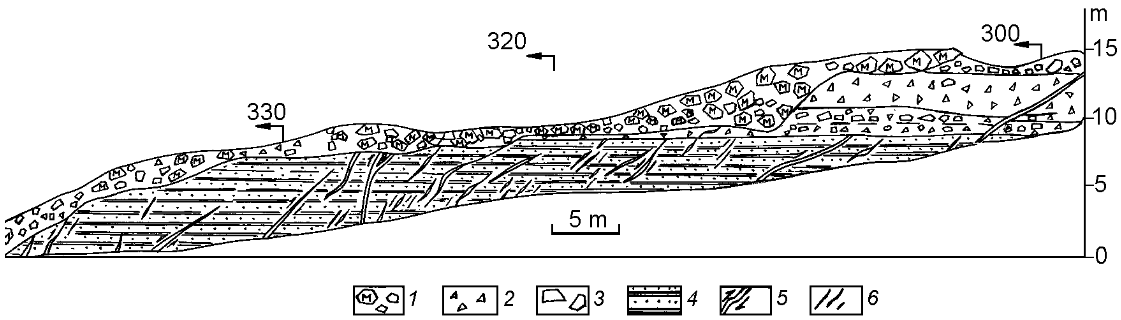

Figure 13. Neptunian dikes in the loose fluvial-glacial, lacustrine sand, gravel and in the lahar horizon on the northern Elbrus slope near the end of the Ulluchiran Glacier (Site 3 in Figure 1): (1) moraine; (2, 3) lahar material: (2) fine clastics, (3) large blocks; (4) bedded fluvioglacial sand and gravel; (5) large neptunian dikes in fissures and the direction of the displacement of the layers along the fissures; (6) neptunian dikes in thin fissures.

caused avalanches in the lower course of the Adyrsu River, in the Tyubele Swell, and in the source area of the Biitik-Tebe River (Sites 7, 8, 5, and 12 in Figure 1).

Finally, the fourth seismic event was accompanied by large collapses in the upper reaches of the Adyrsu and Yusenga rivers and in the Baksan R. Valley east of Elbrus Settlement (Sites 6, 4, 10, and 11 in Figure 1), which caused the formation of several dammed lakes (in the area of the present-day Elbrus. Settlement, in the upper reaches of the Adyrsu River, and in the area of the Baksan River higher than Tyrnyauz Town).

The magnitudes of these three reconstructed paleoearthquakes, which had occurred in the Elbrus region about 2300, 3200, and 5500 years ago, can be estimated from the magnitudes of the earthquake produced displacements in the zone of the reactivated seismic fault, and from the areas involved in the primary and secondary (gravitation and vibration) dislocations. For instance, the magnitude of the vertical earthquake-related displacement in the Chemartkol fault zone was about 30 cm in the first case and about 50 cm in the second and third events. Using the known relationships between the size of an earthquake displacement and the magnitude of the earthquake that caused it, the latter can be estimated as 6.3–6.6 [*Wells and Coppersmith,* 1994]. The dislocations produced by the paleoearthquakes that took place about 2300 and 3200 years ago were found in an area of about 45×20 km^2. The source area of this kind is typical of earthquakes with magnitudes of 6.5 to 7.0.

There is historical evidence that a large earthquake occurred on the northern slope of the Greater Caucasus in the year of 1688±1, that is, more than 300 years ago [*Kondorskaya and Shebalin,* 1977]. This earthquake is known as a Terskii event and, as follows from the catalog data, had the coordinates of 43.7°±1°N and 44.7°±1°E, a magnitude of 5.3±0.7 and an intensity of 7±1. The Terskii earthquake caused the destruction of buildings. It cannot be ruled out that this earthquake generated the above mentioned young seismic dislocations in the Baksan R. and Adyrsu R. valleys, the coordinates of which are given in the catalog mentioned above. At the same time the evidence given in the catalog about the position of the epicentral

Figure 14. Neptunian dike near the end of the Ulluchiran Glacier.

Figure 15. A neptunian dike in the tuffaceous rocks (Kyukyurtly R. upper reaches).

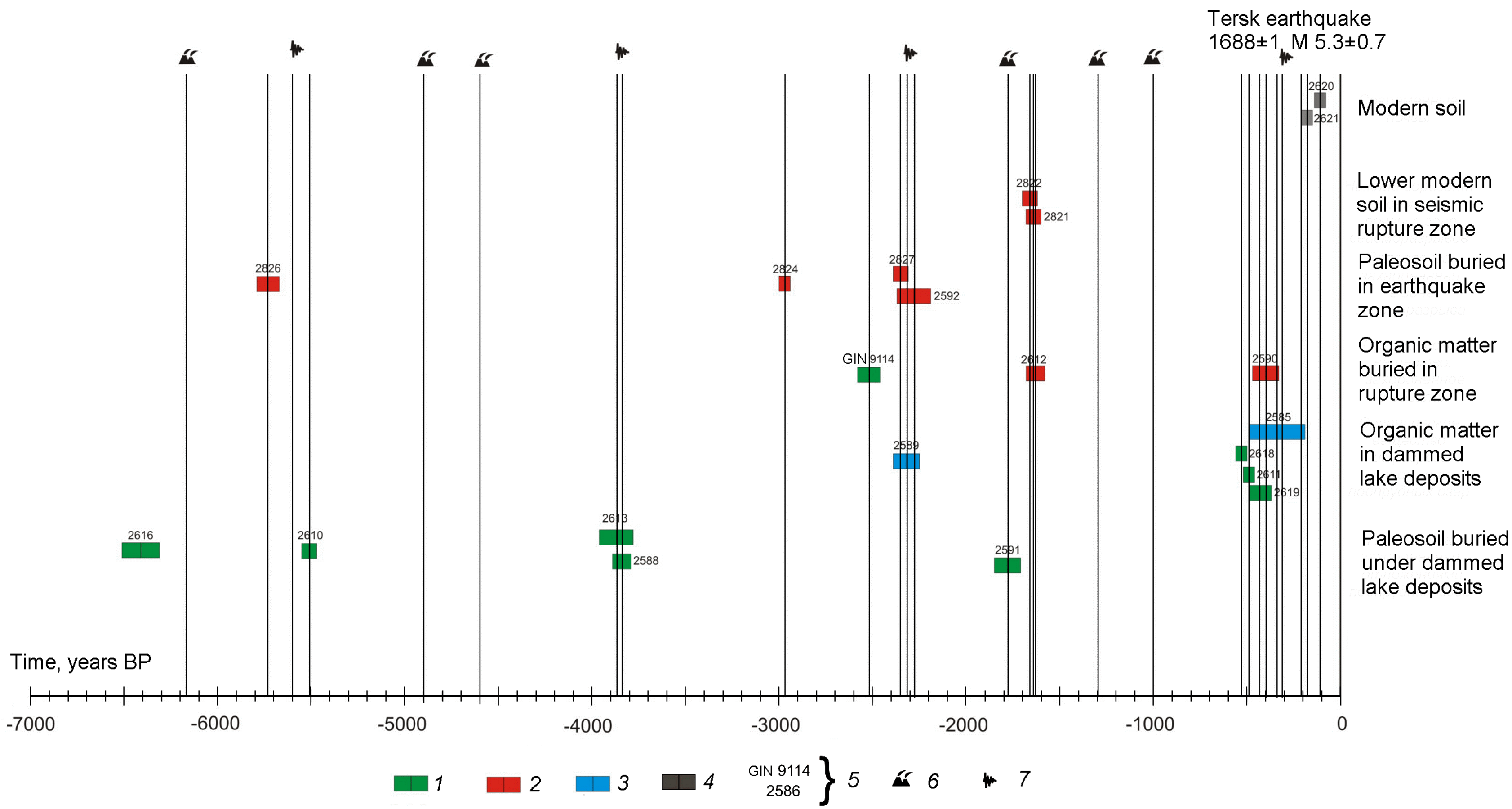

Figure 16. The distribution of the different types of the paleoseismic dislocations in time: (1–2) results of ^{14}C dating at the Radiocarbon Laboratory of the Institute of Geography and Geological Institute (GIN), Russian Academy of Sciences: (1) lower age boundary of seismic event; (2) age of earthquake dislocations; (3) upper age limit of seismic event; (4) modern soil sample (the size of the rectangle agrees with the size of the error); (5) numbers of samples used in radiocarbon analysis; (16) age of volcanic eruption; (17) age of seismic event.

region of this seismic catastrophe and its magnitude is obviously highly approximate. In reality, the earthquake source might have been located somewhere in the Elbrus region, and its magnitude might have been higher than 6.5.

By and large, the seismic dislocations, varying in age and nature, that manifested themselves in the Elbrus region, form an oval area in map view (Figure 1) with the Elbrus Volcano residing in its western part, the long axis of which is oriented in the Caucasian, WNW, direction and coincides almost wholly with the Syltran magma-controlling fault. Restricted to this fault zone are the main volcanic apparatuses of Elbrus, the Syltran volcanic cone, and a series of necks in the source areas of the Kyukyurtly and Ullu-Kam rivers. The northern boundary of this area extends along the northern limb of the Pshekish-Tyrnyauz Fault, the southern boundary extending in the middle courses of the Adylsu R. (Shkhelda R. mouth) and the Adyrsu R. (in the area of the Novyi Dzhailyk Camp of alpinists). The western boundary of this "oval" can be traced in the upper part of the mountainous segment of the Kuban R. Valley, and the eastern one does not extend beyond the Tyrnyauz Town meridian. Consequently, the length of the area of the paleoseismic dislocations of all ages is about 50 km, its width being 20–25 km. This area coincides roughly with the potential earthquake source (PES) located by a seismotectonic method. The size of the seismic dislocation zone generally corresponds to the size of the pleistoseist region of an earthquake with a magnitude of 7.0 and the crustal position of its source [*Wells and Coppersmith,* 1994]. Outside of this oval region, neither primary seismic dislocations nor gravitational slope structural features (seismic or aseismic) have been found over the distances of dozens of kilometers.

The comparison of the periods of seismic reactivation, proved by the paleoseismological data mentioned above, with the periods of the Holocene volcanic activity of Elbrus [*Laverov,* 2002; *Rogozhin et al.,* 2001] shows that these two forms of endogenic activity replaced periodically one another in time. The repetition period of large earthquakes was 1500–1900 years, and that of volcanic eruptions, 1000-2000 years. Moreover, there is no coherence in the manifestations of these two natural catastrophes, even though volcanic eruptions can be accompanied by a moderate earthquake activity.

This relationship between two different forms of catastrophic endogenic activity can be explained by the geodynamic position of the Elbrus caldera in the system of the active faults in this region. The oval caldera, slightly elongated in the meridional direction, is bordered in the north by a system of active faults in the Pshekish-Tyrnyauz crustal disjunction zone, namely by the Chemartkol and Kyzylkol right-lateral strike-slip faults (Figure 1). In the south the caldera is cut also by the Adylsu active right-lateral fault. In response to the right-lateral seismic impulse-type and geological creep-type displacements along the northern and southern surroundings, the caldera area and the Syltran WNW trending left-lateral fault intersecting it in its central part happen to be in the environment of nearly latitudinal extension and basement subsidence in the manner similar to pull-apart basins. The environment of a nearly latitudinal extension is typical of the meridional structural features in the Trans-Caucasus transverse uplift. The Ararat and Aragats volcanic cones in the Minor Caucasus region are associated with similar types of uplifts. In particular, extension in the Elbrus Caldera is caused by meridional active normal faults.

The active seismogenic movements along the faults in the northern and southern surroundings of the caldera produced channels in the crystalline basement for the magma flowing from the middle to the upper crust, namely to a volcanic chamber. During this procedure the magma heats the crust in the volcanic area, this relieving the tension capable of producing large earthquakes. After the volcanic eruption the lithosphere cools off, looses its plastic state, and starts to accumulate elastic stress again. The magma flow channels become healed. As seismic movements renew, the whole procedure repeats itself from the very beginning.

Conclusion

This study proved that the Elbrus volcanic center is also dangerous in terms of earthquakes. Seismic and volcanic activities took place there repeatedly both during the Holocene and the Late Pleistocene. The long repetition periods (many hundred and even a few thousand years) of high-magnitude earthquakes characteristic of the Caucasus region as a whole [*Khromovskikh et al.,* 1979; *Rogozhin,* 2002; *Rogozhin et al.,* 2002; *Solonenko,* 1973], as well as catastrophic volcanic eruptions [*Bogatikov et al.,* 1998, 2003; *Laverov,* 2002; *Rogozhin et al.,* 2001] cause the seeming quietness of Elbrus at the present time. The seismic quiescence of the present time can be associated with the particular rheologic conditions of the Earth's crust necessary for the formation of a large earthquake source. At the same time the absence of modern earthquakes can be indicative of the growing danger of a large volcanic eruption of Elbrus in the near geological future.

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