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Radiocarbon Dating of the Dynamics of Landslides in the Upper Reaches of the Mzymta River Basin (Western Caucasus)

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Abstract—The article contains materials on the study of landslide deposits in the upper reaches of the Mzymta river basin. The results of ^{14}C analysis showed that the youngest landslides are common on the southern slope of the Psekhako Ridge and date back to less than 200 and 390 ± 90, 400 ± 70 cal. years BP and more than 770 ± 150 cal. years BP. The most ancient landslide-collapse on the northern slope of the Aibga Ridge and dates back to 1110 ± 90 cal. years BP.

Keywords: landslide, radiocarbon dating, radiocarbon age, organic matter, Mzymta River valley, Western Caucasus

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INTRODUCTION

Radiocarbon dating is widely used for the investigation of Late Quaternary landslides because the lower reliability limit of this method is 35000–38000 years and the upper limit is approximately several tens of years to 100 years (Vasil'chuk and Kotlyakov, 2000). When the radiocarbon age of a landslide is determined it is important to take the geomorphologic and stratigraphic position of the buried organic material that will be dated into consideration and its correlation with the possible time of a landslide or landfall.

It has been shown that young and old landslides are successfully dated by radiocarbon in organic remains (Hancox et al., 2013; Booth et al., 2017). This experience has been used by the authors of this article to determine the period of formation of landslides of different sizes and ages in the mountains of Western Caucasus. Radiocarbon measurements were performed in organic samples from landslides, which were taken during field work.

MATERIALS AND METHODS

We studied landslide bodies that formed in the upper reaches of the Mzymta River basin (Western Caucasus) (Slyshkina et al., 2015; Slyshkina et al., 2016). The main causes of landslide development include mountainous topography, atmospheric precipitation, and the seismic activity of the area.

During the field works of 2016, we studied and sampled four landslide bodies of different sizes. One of these was a large asequential landslide (16-C3) in the central part of the southern slope of the Psekhako Ridge located at the altitude of 1234–1207 m above sea level. Its basis is formed by the right unnamed tributary of the Mzymta River. The volume of displacement rocks was approximately 150000 m^3 (the length was ~80 m, the width was ~120 m, and the thickness of deposits varied from 0.5 m near the river valley slope to 15 m in the landslide body). The height of the main scarp reached 3.5 m. The supposed displacement surface was located in loamy crushed-stone deluvium (Fig. 1, A-3). New tension cracks are absent, which indicates temporary landslide stabilization.

Another large asequential landslide (16-C5) was revealed in the lower reaches of the unnamed tributary of the Mzymta River at the altitude of 1093–1068 m above sea level (Fig. 1, C-2). Its length along the displacement axis was 160 m, the width was 120 m, and the thickness of deposits in the landslide body was 12–15 m. The volume of rocks involved in the displacement was 250000 m^3. The landslide surface is occupied by forest, while the main scarp is washed out and is poorly pronounced in topography. The signs of modern activity are absent. Near the river valley slope, the landslide body 16-C5 is underlain by bog sediments 0.6 m thick and then by deposits of landslide 16-C6 in the lower part of the pit. The very large landslide body 16-C6 is crossed by an unnamed tributary of the Mzymta River, which indicates long-term stabilization of the landslide deformations. The volume of displacement rocks is approximately 1.2 million m^3.

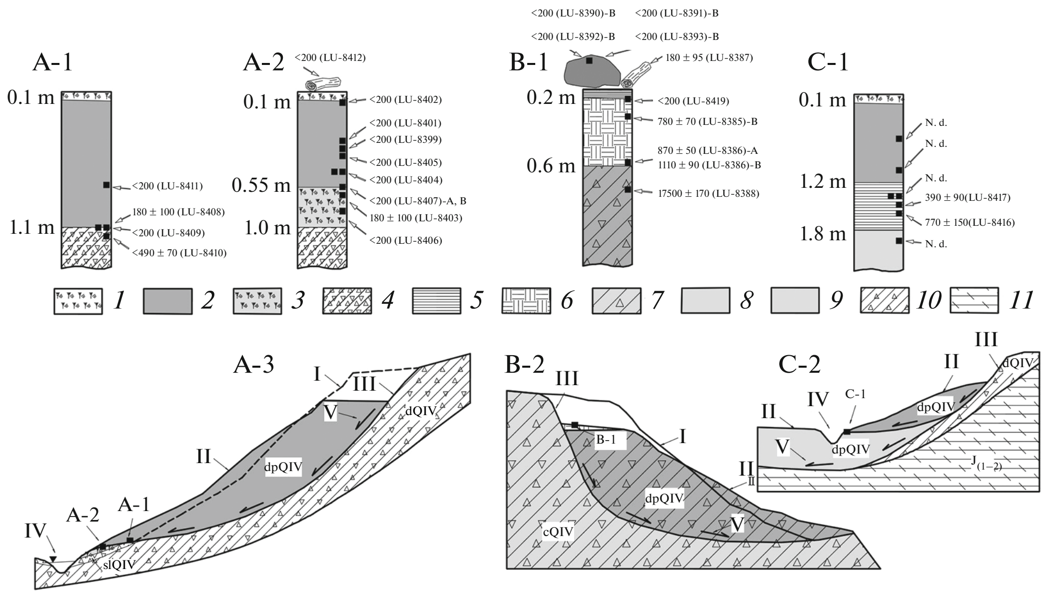

Fig. 1. Schematic cross-sections of landslides indicating the locations of sampling of organic matter: A-1, lithological column of deposits in the body of landslide 16-C3; A-2, the lithological column of deposits in the toe of landslide 16-C3; A-3, schematic crosssections of landslide body 16-C3; B-1, lithological column of deposits in the head of landslide 16-C4; B-2, schematic cross-section of landslide body 16-C4; C-1, lithological column of deposits on board of landslides 16-C5 and 16-C6; C-2, schematic crosssections of landslide bodies 16-C5 and 16-C6. On the lithological columns are indicated the sampling sites (black squares); laboratory numbers and age determined by radiocarbon approach are given in brackets (A, obtained on cold extract from humic acids and B, according to hot extract from humic acids). (*1*) soil; (*2*) modern landslide deposits (dpQIV); (*3*) humus horizon (in situ); (*4*) fragments of debris cones (slQIV); (*5*) bog sediments; (*6*) brown mountain-forest soils; (*7*) collapse deposits (dpQIV); (*8*) landslide-collapse deposits (cQIV); (*9*) ancient landslide deposits (dpQIV); (*10*) deluvial deposits (dQIV); (*11*) bedrocks, argillites (J1es); I, initial morphology of slope; II, modern morphology of slope; III, the main scarp; IV, water level of stream; V, direction of displacement.

A very large block landslide 16-C4 (Fig. 1, B-2) was studied in the central part of the northern slope of the Aibga Ridge (near the Krasnopolyansk fault) at an altitude of 904–782 m above sea level. The landslide deposits include coarse, poorly-rounded, and unsorted material. These are dominated by porphyrite boulders (5–6 m and more in diameter), while fragments of tuff breccia and sandstone sometimes occur. The main scarp is represented by a steep cliff ~60 m high and ~260 m width covered by a layer of deluvial-colluvial deposits overgrown by rare bushes and trees. Boulders with clay loam aggregate are revealed in the main scarp, which indicates that landslide 16-C4 was formed in collapse deposits transported into the Mzymta River valley earlier. The volume involved in the displacement was ~3.5 million m^3 (the length of landslide 16-C4 was ~290 m, the width was ~270 m, and the thickness of deposits was ~90–120 m). The block landslide is partially covered by colluvial deposits and large boulders transported from the main scarp. The landslide surface is overgrown by 200–250-year-old trees and bushes. This all indicates that the landslide occurred one time long ago.

Sampling Technique

When the activation period of a landslide body is determined by single samples of organic matter the reliability of the data decreases because the samples may be contaminated by carbon-bearing material of lesser or greater age (Vasil'chuk and Vasil'chuk, 2017). This is especially true for mountain areas with considerable differences in elevation, large amounts of precipitation, and high intensity of slope processes. During field works, the authors used the approach of series sampling of organic material from different elements of the landslide body. This is based on the age variability within groups of organic material and enables one to increase the reliability of the age determined for the landslide event.

The samples of the large landslide 16-C3 were taken from its surface, body, and toe, which were considered as the main elements for age determination. The landslide body was studied in two natural outcrops formed by lateral erosion by the right tributary of the Mzymta River. The landslide body there was classified into the following layers: (1) soil (from 0.0- to 0.1-m-thick); (2) landslide coarse (fine) gravel with clay loam (from 0.1- to 1.1-m-thick); and (3) loams are boulders-cobbles with abundant inclusions of wood debris (from 1.1- to 1.9-m-thick), as fragments of debris cones. In the adjacent cross-sections in the toe of the landslide body, the following layers are distinguished: (1) soil (from 0.0- to 0.1-m-thick); (2) coarse (fine) gravel with clay loam (from 0.1- to 0.55-mhick); (3) the humus horizon, representing the buried organic material in situ (from 0.55- to 1.0-m-thick); and (4) fragments of debris cones (from 1.0- to 1.6-m-thick) – loams are boulders-cobbles with numerous inclusions of wood debris. Organic matter was sampled from all the exposed horizons.

The very large landslide body 16-C6 (Fig. 1, B-2) was characterized by its ancient surface, which was chosen as a basic element for radiocarbon dating. Landslide covered by bog sediments and a younger landslide, 16-C5. Organic material was sampled from deposits accumulated on the ancient landslide surface. The following layers were distinguished in the deposit: (1) soil (from 0.0- to 0.1-m-thick); (2) modern landslide deposits (from 0.1- to 1.2-m-thick) represented by crushed-stone ground with loamy aggregate; (3) bog sediments represented by gray brown firm clay with inclusion of organic matter (from 1.2- to 1.8-m-thick); and (4) ancient landslide deposits represented by crushed-stone solid loam with rare boulders (the exposed layer is from 1.8- to 2.6-m-thick). Organic material was sampled from all the horizons.

The surface and the body of the very large landslide 16-C4 were chosen as the main elements for its dating. A pit was made in its rear part, where peat, soils, or organic remains are most often accumulated. The layer included: (1) bog sediments presented by silty gray-green stratified light loam (from 0.0- to 0.2-m-thick); (2) brown mountain-forest soils (from 0.2- to 0.6-m-thick); and (3) landslide collapse deposits presented by boulders with loamy aggregate (from 0.6- to 2.6-m-thick).

Samples from medium and small landslide bodies 15-C1 and 15-C2 were taken in 2015 (Vasil'chuk and Slyshkina, 2017).

Dating Method

Radiocarbon dating of organic matter sampled from all landslide bodies was performed with a Quantulus-122 ultralow-background liquid-scintillation spectrometer at the Laboratory of Geochronology of the Quaternary Period of the Institute of Earth Sciences, St. Petersburg State University (the director of the laboratory is professor Kh.A. Arslanov).

RESULTS AND DISCUSSION

The studies performed in the upper reaches of the Mzymta River in 2015 and the determined calibrated radiocarbon age of landslides 15-C1 and 15-C2 (Table 1) show that they were active less than 200 (LU-8105) and 400 ± 70 (LU-8106) cal. years BP.

Radiocarbon dating of landslide body 16-C3 indicates the modern age of the event (Table 1). A wood fragment (LU-8404) and other samples of organic matter (LU-8412 and others) taken from the landslide body are assigned to two time periods: 1956–1958 and 1988–1995, because of the excessive content of radiocarbon. These data are strongly confirmed by the age of the humus horizon determined in situ (LU-8407, LU-8406) covered by the landslide toe. The dating of wood remains from bog sediments that underlie the landslide (Fig. 1, A-1, A-2) indicated activation at less than 200 and 500 years BP.

The dating of landslide bodies 16-C5 and 16-C6 (Table 1) indicates the probable activation of landslides less than 400 years BP and more than 800 years BP, respectively (Fig. 1, C-1). The age of wood from bog sediments above and below the landslides is 390 ± 90 cal. years BP (LU-8417) and 770 ± 150 cal. years BP (LU-8416). The data were in good agreement and showed a monotonic increase in age with depth.

The radiocarbon analysis of organic matter samples from different elements of block landslide 16-C4 showed the activation of the process (Fig. 1, B-1) approximately 1100 years BP. The youngest data, that is, less than 200 years BP, were obtained for tree leaves from bog sediments (Table 1) accumulated in the rear part of the block landslide. The age of the undisturbed top part of the brown mountain-forest soils accumulated on the surface of the block landslide is 780 ± 70 cal. years BP (LU-8385), while the age of the same soil sampled from the foot is 870 ± 50 cal. years BP (according to the cold extract from humic acids) and 1110 ± 90 cal. years BP (according to hot extract from humic acids). The most ancient age of wood remains from the landslide body is 1750 ± 170 cal. years BP.

Based on the analysis of radiocarbon dating of landslide deposits and the catalog of earthquakes of the Caucasus (Godzikovskaya, 2001) we presume that seismicity was a trigger mechanism of activation of some landslides (which were probably prepared for a displacement by other processes) on the southern slope of the Psekhako Ridge, in addition to atmospheric precipitation. As an example, the latest series of earthquakes (M = 4.0–4.4, H = 3–6 km) with force of up to 7–8 (Anan'in, 1977), which took place 20 km to the southwest of the Psekhako Ridge in 1955–1956, could have caused the activation of the large landslide body 16-C3 that was dated to the 1956–1958 period.

Traces of a paleoearthquake (M ~ 7.2 and magnitudes of up to 9–10) were revealed by V.S. Khromovskikh et al. near the epicenter of the Bzyb' earthquake; they determined its age in the interval of 200–400 years BP (Khromovskikh et al., 1979). It may be assumed that the described paleoearthquake caused the activation of one of the series of landslides: 15-C1 and 16-C5 (less than 200 years BP) or 15-C2 and 16-C5 (less than 400 years BP).

The approach of radiocarbon dating was used by A.N. Ovsyuchenko and collaborators during the study of seismic activity and related landslides in the upper reaches of the Mzymta River basin. Based on single samples of soil and humus, they determined the activation period of 1055–1183 years BP for a block land-

Table 1. Radiocarbon age of organic matter from landslide bodies on slopes of the Psekhako and Aibga Ridges

Laboratory ID	Field ID	Sampling depth, m	Description	Radiocarbon age, year BP	Calibrated age (calendar), cal. years BP
Landslide body 15-C1*					
LU-8105	SL-1	2.1	Wood	180 ± 50	≤200
Landslide body 15-C2*					
LU-8106	SL-2	1.9	Wood	35 ± 60	400 ± 70
Landslide body 16-C3					
LU-8399	SB-26	0.35	Tree branch	$\delta^{14}C^{**} = 6.64 \pm 1.17\%$	1956–1957 (3.7%); 2001–present (91.7%)
LU-8400	SB-31	0.5	Tree branch	30 ± 75	<200
LU-8401	SB-25	0.3	Tree branch	$\delta^{14}C^{**} = 0.56 \pm 1.2\%$	1676–1767 (29.5%); 1771–1778 (1.0%); 1799–1941 (63.1%); 1954–1956 (1.8%)
LU-8402	SB-24	0.1	Tree branch	$\delta^{14}C^{**} = 17.59 \pm 1.15\%$	1957–1959 (19.9%); 1985–1990 (75.5%)
LU-8403	SB-29	0.6	Wood	200 ± 50	180 ± 100
LU-8404	SB-28	0.5	Wood	$\delta^{14}C^{**} = 14.52 \pm 1.22\%$	1957–1958(8.7%); 1988–1995 (86.7%)
LU-8405	SB-27	0.4	Wood	$\delta^{14}C^{**} = 6.73 \pm 0.97\%$	1956–1957 (2.7%); 2001–present (92.7%)
LU-8406	SB-30	0.7	Tree branch	$\delta^{14}C^{**} = 20.92 \pm 1.15\%$	1958–1961 (29.4%); 1983–1987 (65.9%)
LU-8407 (A)	SB-32	0.55	Humus	$\delta^{14}C^{**} = 14.2 \pm 1.39\%$	1957–1958 (8.3%); 1988–1996 (87.1%)
LU-8407 (B)	SB-32	0.55	Humus	$\delta^{14}C^{**} = 13.4 \pm 1.28\%$	1957–1958 (6.6%); 1989–1997 (88.8%)
LU-8408	SB-33	1.1	Tree trunk	200 ± 50	180 ± 100
LU-8409	SB-34	1.1	Tree trunk	155 ± 55	<200
LU-8410	SB-35	On the surface	Tree branch	460 ± 60	490 ± 70
LU-8411	SB-36	0.65	Tree branch	$\delta^{14}C^{**} = 11.91 \pm 0.83\%$	1957–1958 (5.4%); 1993–1998 (90.0%)
LU-8412	SB-37	1.2	Wood	$\delta^{14}C^{**} = 11.4 \pm 1.08\%$	1957–1958 (4.9%); 1993–2000 (90.5%)
Block landslide 16-C4					
LU-8419	SB-8	0.2	Tree leaves	$\delta^{14}C^{**} = 6.41 \pm 1.77\%$	1956–1957 (5.5%); 1999–present (89.8%)
LU-8385 (B)	SB-9	0.35	Mountain-forest soil	840 ± 70	780 ± 70
LU-8386 (A)	SB-10	0.6	Mountain-forest soil	970 ± 50	870 ± 50
LU-8386 (B)	SB-10	0.6	Mountain-forest soil	1190 ± 90	1110 ± 90
LU-8388	SB-15	0.8	Wood coals	1810 ± 150	1750 ± 170
LU-8387	SB-13	On the surface	Wood	210 ± 25	180 ± 95
LU-8390 (B)	SB-65	On the surface	Mountain-forest soil	$\delta^{14}C^{**} = 6.03 \pm 1.31\%$	1956–1957 (4.3%); 2002–present (91.1%)

Table 1. (Contd.)

Laboratory ID	Field ID	Sampling depth, m	Description	Radiocarbon age, year BP	Calibrated age (calendar), cal. years BP
LU-8391 (B)	SB-67	On the surface	Mountain-forest soil	δ^{14}C** = 13.02 ± 0.98%	1957–1958 (6.1%); 1990–1996 (89.3%)
LU-8392 (B)	SB-66	On the surface	Mountain-forest soil	δ^{14}C** = 11.56 ± 1.12%	1957–1958 (5.3%); 1992–2000 (90.1%)
LU-8393 (B)	SB-11	On the surface	Mountain-forest soil	100 ± 50	<200
Lacustrine deposits between two landslide bodies 16-C5 and 16-C6					
LU-8417	SB-56	1.6	Tree branch	350 ± 80	390 ± 90
LU-8416	SB-59	1.7	Wood	800 ± 170	770 ± 150

*Previously studied landslide bodies (Vasil'chuk and Slyshkina, 2017). The calendar age is given according to the OxCal 4.2 calibrating program (IntCal 13 (Reimer et al., 2013) and Bomb13 NH1 (Hua et al., 2013) calibrating curves) ChristopherBronk Ramsey (https://c14.arch.ox.ac.uk). Data designated by A were obtained by cold extract from humic acids and data designated by B were obtained by hot extract from humic acids. δ^{14}C** is the content of excessive radiocarbon above the modern standard, which corresponds to two time periods on the Bomb13 NH1 calibrating curve; 1957–1958 (8.7%) and 1988–1995 (86.7%) are the probability intervals of the calibrated age.

slide (Sh-16) on the right slope of the Mzymta River valley, near the mouth of the Pslukh River, and 1102–1140 cal. years BP for a large block landslide (Sh-14) on the northern slope of the Aibga Ridge (Ovsyuchenko et al., 2016). The period of displacement of block landslide 16-C4, that is, 1110 ± 90 cal. years BP, was determined near these landslides (Sh-14 and Sh-16). It may be assumed that the three events were simultaneous as a response to a strong paleoearthquake.

The ages of single samples of the soil covering the surface of the insequent landslide (Sh-9) on the left slope of the Mzymta River valley (the interfluve of the Monashka and Beshenka rivers) and of the soil accumulated on the surface of the insequent landslide (Sh-8) on the watershed of the Mzymta and Pslushenok rivers (Ovsyuchenko et al., 2016) have been compared to the age of wood from the bog sediments that cover the landslide 16-C6 on the southern slope of the Psekhako Ridge. The obtained data are similar: 645–795 (IGAN-3554), 636–685 (IGAN-3879) and 770 ± 150 cal. years BP (LU-8416) and indicate the lowest age of the events. The single sample of paleosoil taken by A.N. Ovsyuchenko with coauthors from the base of landslide deposits (Sh-10) on the right slope of the Monashka River valley (the part near the watershed top) is dated at 697–798 cal. years BP and indicates the maximum age of the event. This data series in the range of 650–800 years BP may be a result of seismic activity.

We hypothesize that the approximate scenario of formation of landslide body 16-C4 is as follows (Fig. 2B): approximately 1 800 years BP, a huge fall occurred (the transit area was 450 m high and approximately 1000 m wide), which could be caused by a strong paleoearthquake. Trees on the slope could be buried in the body of this fall. We dated their remains at 1750 ± 170 cal. years BP. Next, 600–700 years later, a block landslide included the upper body of the huge fall, which was approximately 270 m wide and 290 m long and shifted downhill by approximately 122 m. Its activity was probably related to heavy rains that resulted in excessive moistening of material in the upper part of the huge fall. This moist material could begin to move even as a result of moderate seismic vibrations in the Krasnopolyansk zone near the fault. After the block landslide shifted, a swamp remained on its surface; the formation of brown mountain-forest soils started there in the period from 1110 until 780 years ago. At the final stage, this soil massif underwent a secondary flood and was partially covered by bog clays with a high content of plant remains (dated to the present time).

On the basis of radiocarbon dating of organic material and of historical seismic events it may be assumed that there were three material movements near landslide 16-C3 (Fig. 2A). Two mudflows 490 ± 70 and 180 ± 100 cal. years BP were caused by heavy rains and moved in the valley across the local landslide slope. Fragments of debris cones are exposed in the stream valley at the foot of large landslide body 16-C3. Seismic processes of 1955–1956 resulted in activation of the landslide (120 m wide and 80 m long). The large landslide was related to heavy rains, which resulted in excessive moistening and worsening of physical-mechanical properties of clay soils. The active landslide body displaced down the slope and partially covered two fragments of debris cones and the humus horizon over them, whose age is approximately 60 years according to the radiocarbon analysis.

Large landslide 16-C6 (1.2 million m^3 in volume) occurred approximately 800 years BP. Its movement was obviously related to seismic activity in that period (Ovsyuchenko et al., 2016). A huge amount of material was displaced down the slope and formed a leveled

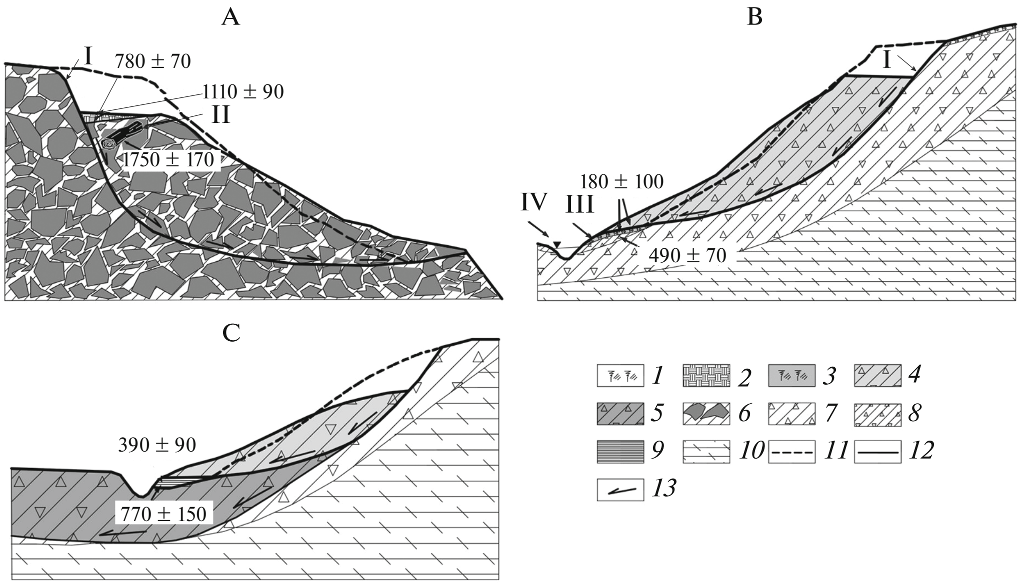

Fig. 2. Schematic cross-sections of landslides indicating the locations of sampling of organic matter for ^{14}C dating: A, on the southern slope of the Aibga Ridge (16-C4); B, on the northern slope of the Psekhako Ridge (16-C3); C, on the northern slope of the Psekhako Ridge (16-C5 and 16-C6): (*1*) soil; (*2*) brown mountain-forest soils; (*3*) humus horizon (in situ); (*4*, *5*) landslide deposits; (*6*) landslide-collapse deposits; (*7*) deluvial deposits; (*8*) fragments of mud cones; (*9*) bog sediments; (*10*) bedrocks (argillites); (*11*) initial morphology of slope; (*12*) modern morphology of slope; (*13*) direction of displacement. (I) the main scar; (II) overload of organic matter; (III) burning organic matter; (IV) water level of stream.

surface in the frontal part of landslide 16-C6 (Fig. 2C). Parallel to this, the landslide body blocked the stream bed and formed a dam. Mud flows occurred many times there after this. Upon the activation of mudflow processes approximately 750 and 400 years BP, the leveled landslide surface was covered by suspended mud with organic material. Some time later, the suspended material was accumulated and formed clay deposits with organic matter. Less than 400 years BP, the ground mass shifted again on the local landslide slope. Landslide 16-C5, which was 250000 m^3 in volume, moved down the slope and buried the more ancient landslide (16-C6) and bog sediments.

CONCLUSIONS

(1) The study of landslides in the mountains of Western Caucasus using radiocarbon dating has shown that the youngest landslides occurred on the southern slope of the Psekhako Ridge. Their ages are less than 200 and 400 years BP and more than 800 years BP. The oldest block landslide on the northern slope of the Aibga Ridge is 1110 years BP.

(2) The generalized data of instrumental seismological observations in the area of Western Caucasus, paleoseismic studies, and the data of radiocarbon dating revealed a correlation between landslide processes and paleoearthquakes.

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