

EVOLUTION OF EROSIONAL BADLANDS IN THE EASTERN BLACK SEA REGION DURING THE LATE HOLOCENE

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ABSTRACT. This paper presents the results of geomorphological research conducted in the Mussera Upland (Western Abkhazia) in 2024. Based on morphometric analysis and geomorphological survey within the typical river basin (Ryapsh River basin), the topographical features of the upland were described in detail, and radiocarbon dating of alluvial deposits was performed. We found that the Mussera Upland is a typical humid badland with a dissection density of 3–4 km/km². The formation of a low-order fluvial network begins here within a catchment area of approximately 0.01 km². Within the dendritic catchment of the Ryapsh River, erosional slopes of varying steepness cover 94% of the total area, with only about 6% occupied by alluvial terraces in the valley floor (up to 1.5 m and up to 3.0 m above the riverbed). Both of these terraces were formed during the Holocene within the last thousand years: the low alluvial level formed no earlier than 570–670 cal yr BP, and the upper alluvial level in the Ryapsh River valley was formed about 810–960 cal yr BP. The development of the Mussera badland is occurring with the leading role of erosional and slope processes (primarily landslides) under conditions of ongoing tectonic uplift. The forest cover of the area does not prevent slope denudation, but, instead, it often triggers it. The development of the badland is characterized by two opposing trends: over time, the ridges are lowered due to slope denudation; however the depth of dissection does not decrease due to ongoing tectonic uplift and active stream downcutting. In recent decades climate change has increased the frequency of extreme rainfall events, resulting in a noticeable rise in denudation rates.

KEYWORDS: badlands, tectonic uplift, river downcutting, Caucasus foothills, dissected upland, denudation, Holocene

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INTRODUCTION

The topography of the foothill zone of the Greater Caucasus is characterized by morphological diversity and intense dynamics, driven by a combination of high vertical and horizontal dissection, high seismicity, and climatic factors. The uplands and hills surrounding the northern and the southern slopes of the Greater Caucasus represent a transitional zone (according to Baryshnikov (2012)) and are characterized by active development of geomorphic processes inherent to both mountainous and plain territories. The economic development of these areas is significantly complicated by the existing geomorphological hazards.

The development of the Greater Caucasus and surrounding foothills occurred interconnectedly during the Cenozoic. As a result of continuous denudation, extensive accumulation zones of eroded material formed on the periphery of the mountains. During the Paleogene and Neogene, these areas existed in marine conditions (Geologiya... 1964; Lomov et al. 2025; Milanovsky 1968; Trikhunkov et al. 2024; Adamia et al. 2010). In the Quaternary these shallow sedimentation areas were involved in tectonic uplift and formed extensive foothill plains composed of molasse deposits, which were actively eroded by fluvial, slope, and other subaerial geomorphic processes (Bredikhin et al. 2025). This led to the formation of a highly eroded upland zone at the foot of the southern slope of the Caucasus within Abkhazia and further southeast into Georgia. The Greater Caucasus acts as a barrier protecting the coastal areas from the influence of cold air masses from the north. Therefore, the western part of the southern slope of the Caucasus has a humid subtropical climate with annual precipitation of about 1400–1450 mm/year¹. Due to ongoing tectonic uplift and humid climate, erosion-prone rocks (Paleogene and Neogene molasse deposits) composing the foothills of the southern slope of the Greater Caucasus within Abkhazia have been densely dissected, and uplands have been formed (Mussera, Eshera and others). These deeply and densely dissected uplands have been inhabited by humans for over the last few thousand years; however, land use here is associated with considerable geomorphological risks.

This study aims to characterize the morphology of the dissected terrain in the foothill zone of the Greater Caucasus within Abkhazia using the example of the Mussera Upland, reconstruct the history of its development, and determine current trends in landscape dynamics under the influence of observed climate changes. Recent studies (Bredikhin et al. 2025) have shown that fault tectonics and vertical tectonic movements played a significant role in the formation of the Mussera Upland; the development of the modern river network began at the turn of the Neogene and Quaternary periods. Yet there are just a few studies on the structure and modern dynamics of the denuded areas in the transition zone of the Caucasus within Abkhazia (Eremenko et al. 2025; Sheremetiev et al. 2024) but they do not cover the study area. The question of how the repeated climate changes and Black Sea level fluctuations in the Pleistocene and Holocene affected the evolution of the fluvial landscape in the dissected uplands still remains unresolved. Furthermore, studying modern dynamics and reconstructing landscape development is necessary for forecasting natural hazards under conditions of climate change in the Eastern Black Sea region (Gudko et al. 2024; Keggenhoff et al. 2014; Meredith et al. 2015) and ongoing tectonic uplift (Gurbanov et al. 2023; Tatarinov et al. 2024).

The study area – the Mussera Upland – is located at the foot of the southern slope of the Greater Caucasus, east and north of Cape Pitsunda. The area of the upland is 105 km², it has an elongated shape and extends for 19 km from west to east and no more than 10 km from north to south. Altitude ranges from 0 to 320 m, gradually increasing from south to north (Fig. 1 a). The asymmetry of the upland's slopes is typical: the southern slope is long and relatively gentle, densely dissected by river valleys and streams, while the northern one is significantly steeper (up to 60–70°) and shorter.

Tectonically, the upland is located in the contact zone between the folded orogen of the Greater Caucasus and the Transcaucasian tectonic block (Bolshoy Kavkaz... 2007; Mosar et al. 2022). The ongoing underthrusting of the Transcaucasian block (Transcaucasia) beneath the Scythian Plate caused the formation of the asymmetrical Greater Caucasus mountain structure in the Cenozoic with its inherent fold-and-thrust tectonic structure (Bolshoy Kavkaz... 2007; Adamia et al. 2010). The main part of collisional crustal absorption in the Cenozoic occurred precisely in the area of the southern slope of the Greater Caucasus. The epochs of tectonic deformation coincided with phases of enhanced Red Sea rifting (Kopp 1997). The southern slope of the Greater Caucasus located directly north of the Mussera Upland tectonically corresponds to the axial trough of the Lias-Aalenian basin of the Greater Caucasus and its southern foothills (Bolshoy Kavkaz... 2007). From the Transcaucasian Massive lying to the south, it is separated by a system of major tectonic faults – the Racha-Lechkhumi (Gagra) suture zone, corresponding to the boundary between the orogen and the molasse basin (Bolshoy Kavkaz... 2007; Mosar et al. 2022). The northern boundary of the Mussera Upland is an active third-rank right-lateral strike-slip fault (Bachmanov et al. 2017; Zelenin et al. 2022). This system is also indicated by the westward shift of the Bzyb River valley, clearly noticeable northwest of the Mussera Upland. This right-lateral strike-slip system of the Western Caucasus extends beyond Abkhazia and is connected with the linear-thrust structures of the Racha-Lechkhumi, Adaiyk-Kazbek, and Tyrnyauz suture zones (Rastsvetaev 1989).

According to GPS measurements, the northern component of modern horizontal tectonic movement in the Caucasus is attenuated in the area of its southern slope (Lukk & Shevchenko 2019; McClusky et al. 2000), and the territory located north of the Mussera is rigid (Kopp 1997). Vertical tectonic movements also occur under the influence of thrust structures within the southern slope zone. In particular, at the study area, tectonic uplift occurs at a rate of up to 4–6 mm/year (Tatarinov et al. 2024).

The geological structure of the Mussera Upland comprises rocks of the Neogene system – Miocene and Pliocene terrigenous and carbonate formations (molasse), represented by layered strata consisting of clay, siltstone, sandstone, and conglomerate. Molasse is characterized by the folded structure with dips up to 25–30° which increase from south to north (Fig. 1b, c) (Bukiya & Abamelik 1971). The lower molasse strata belong to the Miocene and are exposed only on the northern periphery of the Mussera Upland. They are up to 400 m, and the strata are represented by clay, clayey sandstone, sandstone, and conglomerate (Bukiya et al. 1971). Overlying deposits attributed to the Sarmatian stage are composed of coarse pebbles and have a massive structure and carbonate cement, forming the northern slope of the upland facing the Greater Caucasus. Pliocene rocks composing most of the upland are

¹Climate data for cities around the world (2025). Gagra [online]. Available at: <https://ru.climate-data.org> [Accessed 01 Nov. 2025]

characterized by relatively weak cementation, low density, and high lithological diversity. The older ones, attributed to the Meotian stage, compose the central and northern parts of the upland. In the lower part they are represented by massive conglomerate, and in the upper part – by an alternation of layers of sandy clay, sand, and sandstone with layers of shells and conglomerate. The total thickness of Meotian deposits reaches 200–250 m (Bukiya et al. 1971). These deposits are the most widespread in the detailed study area (Ryapsh River catchment). In the western and eastern parts of the upland, Meotian rocks are overlain by a thick (up to 200–300 m) stratum of predominantly terrigenous rocks of the Pontian stage (in the lower part – sandstone and conglomerate, in the upper part – sand with layers of gravel and clay with layers of marl). Fragmentarily, on the periphery of the upland, terrigenous complexes of

the Kimmerian stage of the Pliocene are preserved, mainly composed by conglomerate with layers of clay (Bukiya & Abamelik 1971).

The arrangement features of Neogene rocks demonstrate substantial lateral differentiation of vertical tectonic movements within the study area during the Neogene-Quaternary. It can be concluded that the amplitude of tectonic uplift was higher in the central part of the upland (in the area of the Ryapsh River catchment) compared to its periphery. Rocks younger than Meotian are absent here, which is apparently related to more intense and possibly prolonged denudation. More intensive tectonic uplift of the central part of the upland west of the Ryapsh River is also indicated by the consistently observed eastward dip of layers in the cliffs east of the Ryapsh River mouth (Fig. 2).

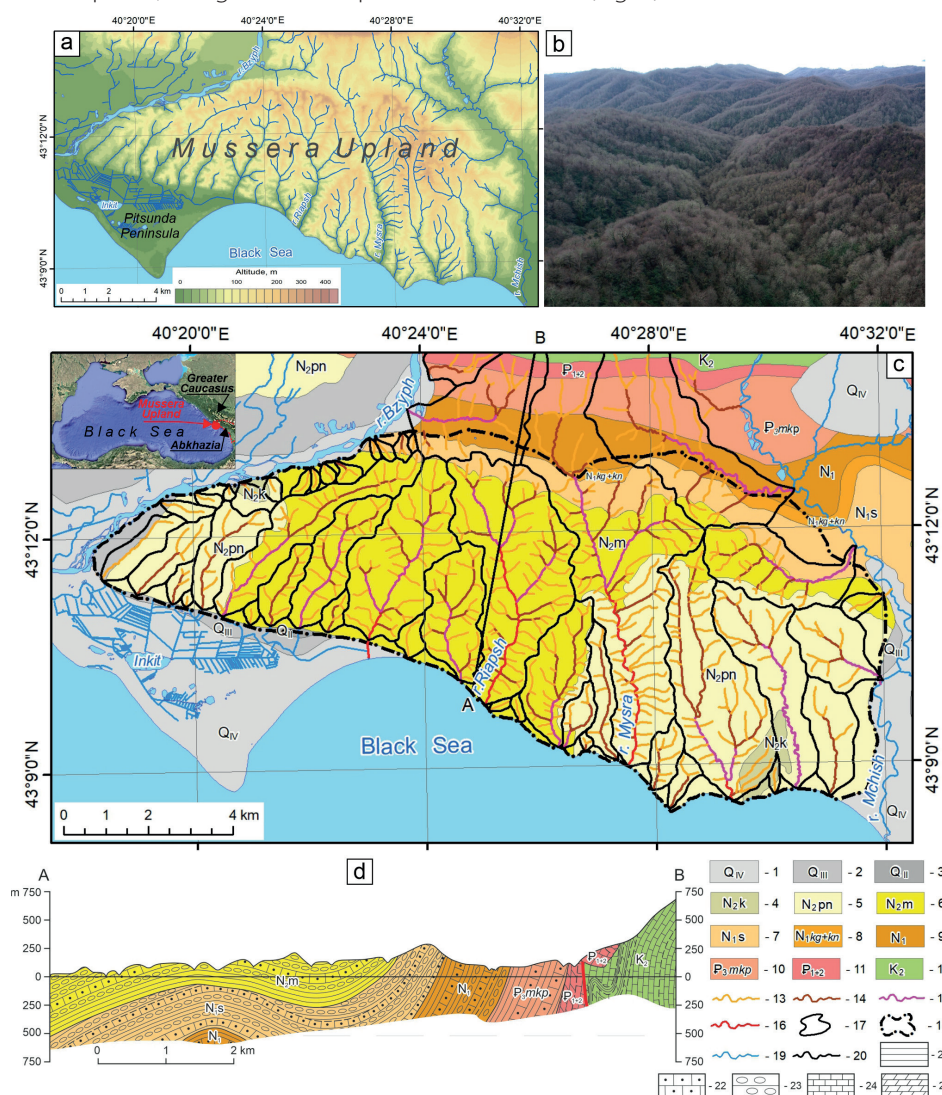


Fig. 1. Topography and geological structure of the Mussera Upland: a – digital elevation model based on FABDEM data (Neal & Hawker 2023); b – general view of the upland from north to south; c – geological structure of the area according to Bukiya & Abamelik (1971) (the inset shows the location of the study area within the Eastern Black Sea region); d – geological cross-section along line A–B. Legend. Quaternary rocks: 1 – Holocene marine and alluvial deposits (sand with pebbles, containing lenses of loam and clay), 2 – Upper Quaternary marine and alluvial deposits (pebbles and sand with interlayers of sandy clay), 3 – Middle Quaternary marine and alluvial deposits (weakly cemented pebbles, sand with interlayers of loam and clay). Upper Neogene (Pliocene) rocks: 4 – Cimmerician (coarse-pebble conglomerate, sand, and clays), 5 – Pontian (clay, sandstone, conglomerate), 6 – Meotian (sandstone, conglomerate, clay). Lower Neogene (Miocene) rocks: 7 – Sarmatian (conglomerate, sandstone, clay), 8 – Konikian and Karangatian (sandstone, clay and marl), 9 – Chokrakian, Tarkhanian, and Sakaraulian (clay, sandstone and conglomerate), 10 – Oligocene (Maykopian Formation) rocks (gypsum-bearing laminated bituminous clay and sandstone), 11 – Paleocene-Eocene marl and limestone, 12 – Upper Cretaceous limestone and marl. Stream orders: 13 – second order, 14 – third order, 15 – fourth order, 16 – fifth (highest) order. 17 – catchment boundaries, 18 – boundary of the Mussera Upland, 19 – streams outside the study area, 20 – geological cross-section A–B. Lithology (on the cross-section): 21 – clay, 22 – sandstone, 23 – conglomerate, 24 – limestone, 25 – marl

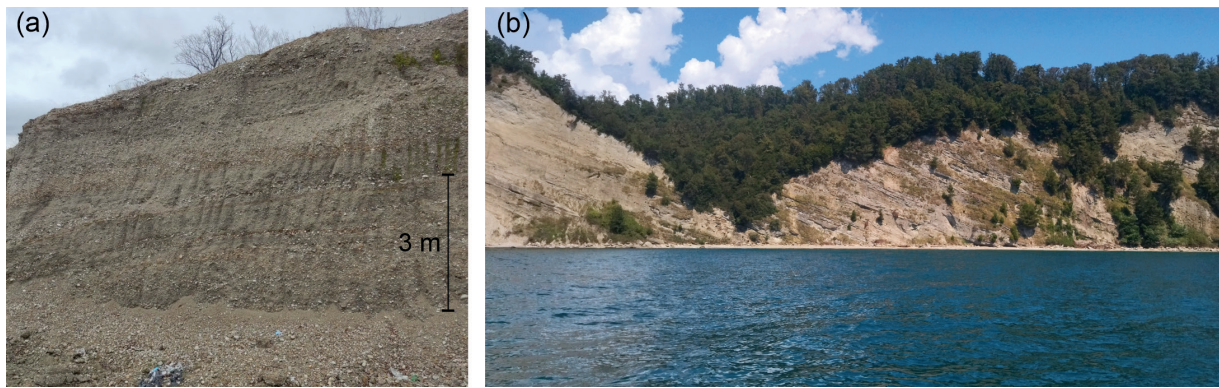


Fig. 2. Neogene (Meotian) conglomerate with sandstone interlayers: a – in the slope of a road cut in the upper reaches of the Ryapsh River; b – in cliffs 0.8 km east of the mouth of the Ryapsh River

MATERIALS AND METHODS

The investigation of the Mussera Upland's topography and river valleys employed a multi-faceted approach, which included morphometric and field geomorphological surveys. This was complemented by a detailed examination of alluvial terrace sequences in exposed sections within the Ryapsh River catchment area and radiocarbon dating of the associated deposits.

Morphometric analysis was based on digital elevation models (DEMs), including both open-access and non-public models (based on laser scanning point clouds). The survey used two elevation models: 1) FABDEM v1.2 (Neal & Hawker 2023), resampled at a resolution of 22.5 m (corresponding to 1" along the parallel at the study area's latitude of 43°N), presented in the UTM 37N coordinate system; 2) a proprietary DEM with a resolution of 2.5 m, constructed from the results of a 2014 LiDAR survey with a point density about 1–6 pts/m² and presented in the same projection. The latter DEM was created using a simple filter that takes the minimum elevation value within a raster cell to filter out trees. Processing of the initial data and calculation of morphometric characteristics were carried out according to the method described in detail in (Bredikhin et al. 2025). Local topography characteristics were calculated in SAGA GIS using the Zevenbergene-Thorne (1987) method. Hydro-geomorphological analysis was carried out on a detailed DEM (2.5 m) corrected using the Wang and Liu method (2006). The Multiple Flow Direction (MFD) method developed by Freeman (1991) and Quinn et al. (1991) was used for flow path tracing and calculating per-pixel catchment area values. Threshold catchment area values for tracing perennial streams were determined by calibration, taking into account field observations during the low-flow winter season (January–February 2024); for tracing thalwegs of erosional incisions, thresholds were calibrated by visual inspection of incision heads on the detailed DEM (hillshade). The depth of erosion dissection was calculated as the average value of the vertical distance between modern surface and base surface passing through the thalweg lines ("vertical distance to channel network" by Tucker et al. (2001) and others). For constructing watershed schemes (and subsequent aggregation of morphometrical characteristics by them), the Horton-Strahler-Filosofov methodology (Strahler 1957; Filosofov 1960) was used. The basin orders were assigned according to the main channel order within the catchment area. Transverse and longitudinal valley profiles have also been constructed from the DEM using GIS tools.

Field geomorphological survey and mapping. Field geomorphological research was carried out in winter 2024. Along several transects in the Ryapsh River basin (from its headwaters to the mouth) descriptions of the valley

topography (morphology of the slopes, length, height and width of the alluvial terraces, main channel structure), as well as the thickness and composition of deposits overlying valley slopes and the alluvial terraces, were carried out; samples for radiocarbon dating were collected, and photo documentation was also conducted.

Geological cross-sections were placed along five cross-profiles in the Ryapsh River valley in sites with different morphology. The thickness and composition of the slope deposits on the valley slopes and the composition of the underlying bedrock were characterized. In the alluvial sections, layers differing in lithological composition and inclusion characteristics were identified, and the composition of the underlying rocks was described. Within the river channel, sections with different gradients, rapids, and waterfalls, as well as the character of the topography (point-bars, pools, chutes, etc.) were also identified. Manifestations of modern geomorphic processes were documented separately: down-cutting and bank erosion in the main river channel and its tributaries, gully erosion, landslides and rockfalls, subsurface erosion, and karst processes. The results from geomorphological field research were used to compile geomorphological maps.

The geomorphological maps were created using the traditional morphogenetic approach: the origin of the landforms is shown by color, while the morphology of them is indicated by color shades. The delineation of geomorphological boundaries was based on field survey data and a digital elevation model. On the map of geomorphological processes, the dominant process within each topographic element is shown by color, and its intensity is indicated by color shades. The maps were created using the cartographic tools of the QGIS software package.

Radiocarbon Dating. Five samples were dated by the radiocarbon method using a 0.2 MV Mini Radiocarbon Dating System (MICADAS). They were pretreated, combusted, and graphitized, and the ¹⁴C/¹²C ratios in the graphite samples were measured at the Xi'an Accelerator Mass Spectrometry Center, the State Key Laboratory of Loess Science, in the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS). The samples were pretreated using a conventional acid-base-acid (ABA) protocol with multiple base extractions (Brock et al. 2010). The sample was treated sequentially: leaching with 1 M HCl at 80 °C overnight, washing with distilled water until neutral, leaching with 0.5 M NaOH at 80 °C until the supernatant is clear, washing until neutral, leaching with 1 M HCl at 80 °C for 1 h, and washing until neutral. The pretreated sample was then dried at 80 °C. After each step, the supernatant was removed by pipetting. The carbon remaining in the pretreated samples was converted to CO₂ by combustion in sealed pre-baked quartz tubes containing copper oxide wire. The collected

CO₂ was converted to graphite by reduction using zinc and a catalyst (Marzaioli et al. 2008). The graphite was then loaded into an aluminum target holder and measured at the 3MV AMS system at the Xi'an AMS Center. Uncalibrated dates are given in radiocarbon years before the present (BP, 0 BP = 1950 CE) for calibration with the half-life of 5568 years. The ¹⁴C dates were calibrated using the OxCal 4.4.4 software² with the calibration dataset Intcal 20 (Reimer et al. 2020).

RESULTS

Morphology of the Mussera Upland. The topography of the study area is characterized by dense and deep erosional dissection with no leveled summit surfaces. The altitude difference reaches 300 m. However, the median elevation is only slightly above 100 m; 93% of the area lies below 200 m. The territory is classified as an upland due to high density and depth of dissection, as well as high slope steepness despite the relatively low altitude. Surface steepness ranges from 0° to 90° on individual segments of vertical cliffs along the shore or on the slopes of the river valleys. The slope steepness reaches 66° with an average value of 16° (according to FABDEM with surface generalization to pixels of 22.5 m size).

The upland has an asymmetrical structure. Its southern slope occupies 80–90% of the north-south extent, while the northern one occupies the remaining 10–20%. The valley bottoms are narrow, not more than 100 m in width (Fig. 3b), except for the larger rivers in their lower reaches (the Mussera, Ryapsh (Fig. 3d), Tsanigvarta). Interfluvial spaces are practically absent; slopes of adjacent valleys converge to form narrow (several meters wide) watershed ridges (Fig. 3c).

Based on field observations and morphometry analysis, it can be concluded that a perennial hydrographic network

is formed here within a catchment area of 0.4–0.5 km². However, morphologically distinct erosional dissection (rills) occurs already in a catchment area of 0.01 km² (1 hectare), and often (though not always) these incisions appear as small funnel-shaped depressions (Fig. 4). On average, gully heads do not reach the watershed divide by 100–200 m. The average density of erosional networks is about 3600–3700 ± 1540 m/km² (mean ± standard deviation).

Most river catchments in the Mussera Upland belong to the low orders (1–4) (Table 1). Only three catchments belong to the highest, fifth order – the basins of the Mussera, Ryapsh, and Tsanigvarta rivers. The Ryapsh River basin is characterized by a medium size, a slightly higher average elevation, and, consequently, more deep erosional dissection and lower drainage density. There are no significant differences in altitude and slope steepness among the largest catchments. For a detailed study of the geological structure and topography, we selected the Ryapsh River catchment, which is located in the center of the upland and has an average area among the basins of the highest fifth order.

Topography of the Ryapsh River basin and main valley

The Ryapsh River basin oriented north-south spans 10 km in length and 2.5 km in width. The river system has a dendritic structure. The length of the Ryapsh River is 7 km. Valleys in the river system are separated by narrow rounded-crest ridges that are 6–8 m wide. In some parts they have been graded for the unpaved road construction. These ridges serve as natural boundaries between primary and secondary valleys constituting the structure of the basin (Fig. 5).

The valley slopes predominantly have a convex profile. In their upper parts, the slope steepness ranges from 20°

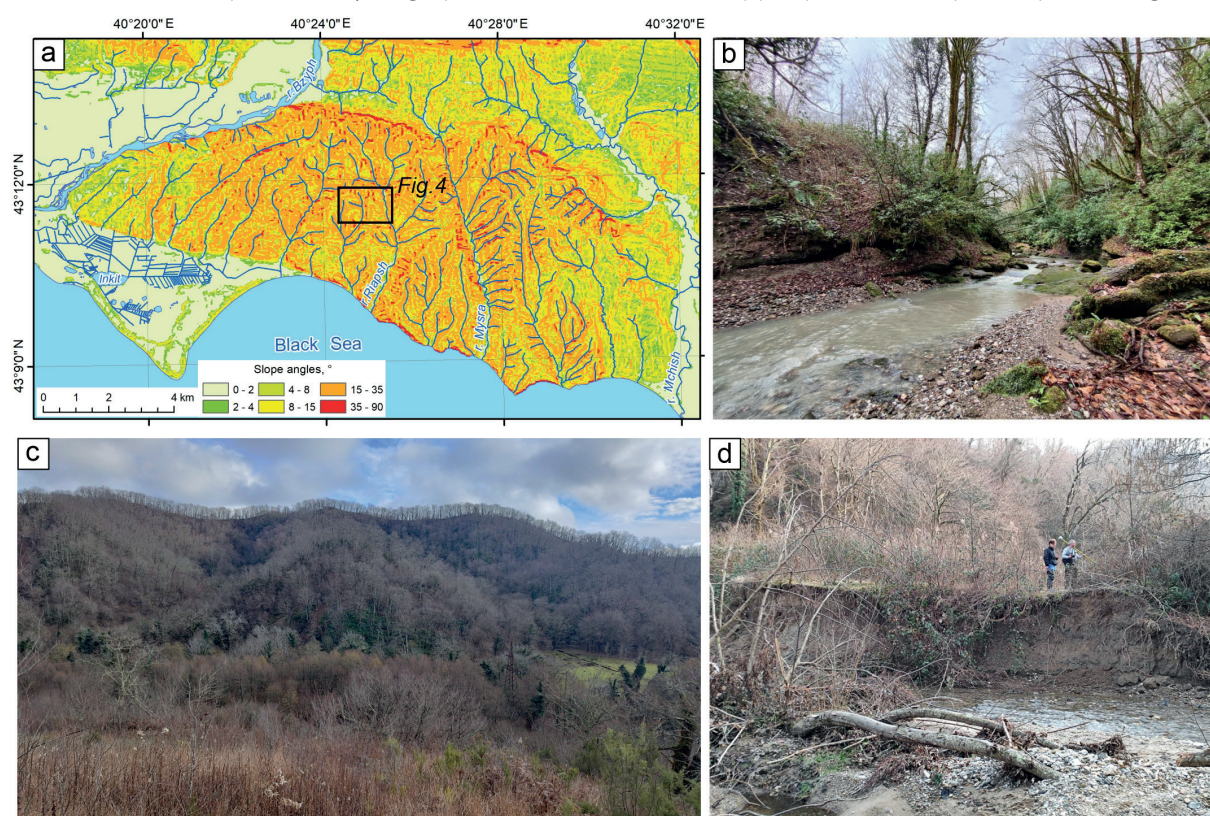


Fig. 3. The morphology of the Mussera upland topography: a – slope steepness (the black frame indicates the area shown in Fig. 4); b – channel of the Ryapsh River in its middle reaches; c – watershed ridge on the left bank of the Ryapsh River in its lower reaches; d – channel of the Ryapsh River and a high alluvial terrace in the lower reaches of the valley

²Ramsey C. (2021). OxCal 4.4.4 [software]. <http://c14.arch.ox.ac.uk/oxcal.html>.

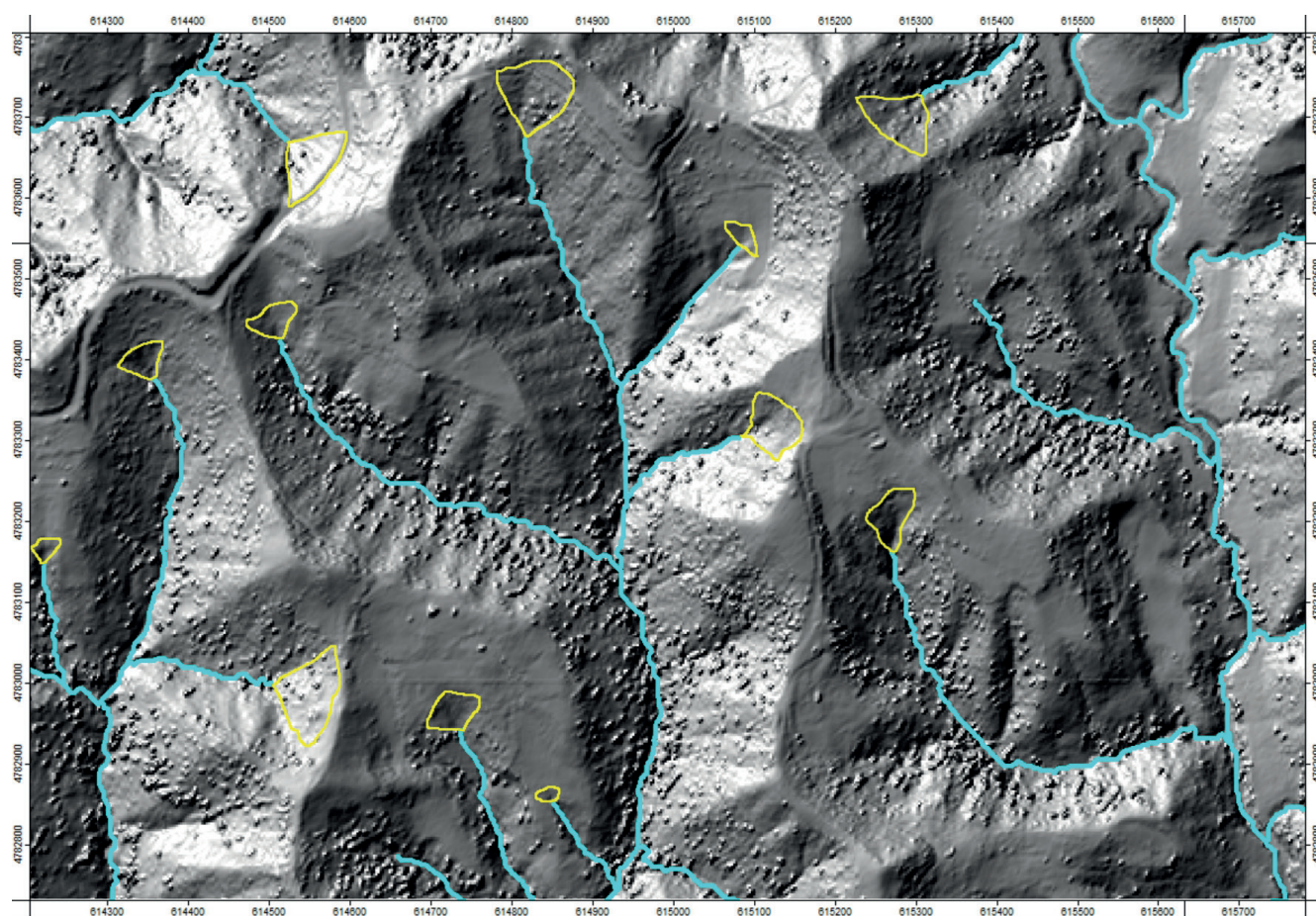


Fig. 4. Morphology of the upper reaches (erosional landforms with the catchment areas from 1 ha) of the erosional network of the Mussera Upland. The frame shows coordinates in the UTM 37N projection. Blue lines indicate thalwegs of erosional forms; yellow lines outline funnel-shaped depressions

Table 1. Statistical distribution of areas by catchment order (Strahler system), ha

Stream Order	Min	1 st Q	Median	Mean	3 rd Q	Max
1	1	1.3	1.9	2.4	2.9	20.5
2	1	4.5	7.4	9.8	12.3	148
3	9.9	23.3	41.1	54.5	63.5	561
4	15.1	75.5	131	189	245	922

Table 2. Morphometric parameters of the fifth-order basins of the Mussera Upland

Basin	Area, km ²	Mean elevation, m	Max elevation, m	Mean slope, °	Mean DD*, m/km ²	Mean VDCN**, m
Mussera	16	186	324	12.7	3820	63
Ryapsh	11	194	324	12.7	3220	82
Tsanigvarta	6.8	163	268	12.3	3240	71

* — mean density of erosional dissection within the catchment area, m/km²

** — mean vertical distance to channel network, m

to 35° and in the lower parts, it locally reaches 80°–90°. The river and its tributaries, in their upper and middle reaches, flow in deep gorges (up to 10–12 m). Their channels, with widths of up to 3–4 m occupy the entire valley floor (Fig. 3b). Riffles and waterfalls with a height up to 1.5 m are typical for the channel morphology. Such gorges often have asymmetrical cross-profiles: one riverbank is vertical to overhanging, with heights up to 12 m, while the opposite bank is less steep (about 45°), with an average height of 5–7 m.

In the lower reaches, the floor of the Ryapsh River valley widens to a width of 100–150 m. The river meanders, and

several alluvial terraces are being formed on the convex banks. The valley slopes have predominantly a concave profile (Fig. 5, profile 6). Nevertheless, they are also as densely dissected by gullies as the slopes in the upper and middle parts of the valley.

Within the basin area, erosion slopes with angles of 15–35° are absolutely predominant, covering 6.59 km² (59.9% of the total area of the Ryapsh River basin) (Fig. 6a). Steep slopes (>35°) and gentle slopes (<15°) also occupy significant areas: 1.13 km² (10.3%) and 1.50 km² (13.6%), respectively. Slopes with angles of 15–35° are uniformly distributed throughout the area, while steep slopes (>35°)

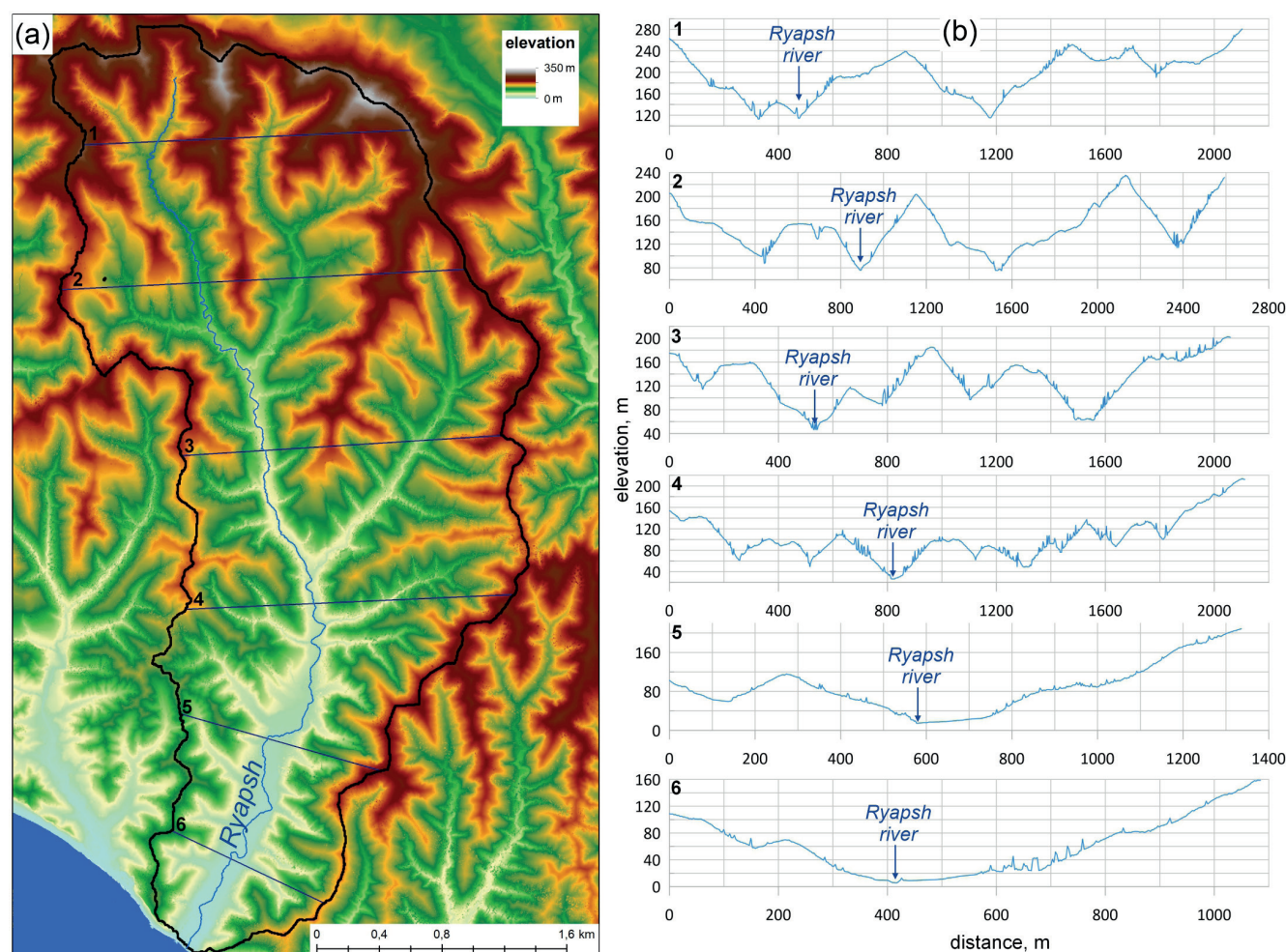


Fig. 5. The topography of the Ryapsh River basin: a – hypsometric map of the basin; b – cross-sections (from west to east) of the basin based on the results of the lidar survey in 2014. Blue line on the map – the main high-order channel

are concentrated mainly in the southeastern and northern parts of the basin and generally correspond to the midsections of valley slopes. Slopes with an angle of less than 15° are bordered by narrow, rounded-crest ridges and are also typical for the lower parts of the valley slopes in the lower reaches of the river. Here they represent aprons overlying the upper alluvial terrace. The lower parts of gully slopes in their upstream areas and partly in their bottoms are also characterized by relatively low angles ($8\text{--}15^\circ$) due to the dominance of creep over gully down-cutting in the upper reaches of the fluvial network.

In total, the slope aprons cover 1.14 km^2 (10.4%) of the area within the Ryapsh River basin, while only 5.8% of the basin area is occupied by flat surfaces formed by alluvium accumulation on the floor of the Ryapsh River valley and its main tributaries.

The Ryapsh River has a mixed hydrological regime (dominated by rainfall and groundwater). Flashy flood-driven hydrological pattern are ordinary phenomena. The most significant water level rise occurs during periods of heavy rainfalls, primarily in summer and less frequently in autumn. The longitudinal profile of the Ryapsh River along its thalweg is slightly concave. In the upper reaches its gradient reaches 14% decreasing to 1.9% in the middle part and to 0.8% in the lower reaches (Fig. 7, left). There are numerous small steps in the profile which are caused by variations in the erosion of the Neogene conglomerates of different density, as well as the presence of sandstone and siltstone within this layer. Within a narrow channel (up to 3–4 m wide) bedrock is widely exposed. Large blocks of conglomerate up to 3–4 m long and 1–2 m wide are observed at the foot of the gorge slopes. This colluvium

forms riffles and small waterfalls in the main riverbed. Point bars and mid-channel bars composed of pebbles and small boulders are also present (Fig. 7, profiles 1a–1b and 3a–3b). The average river depth is 0.3–0.4 m increasing up to 0.6 m in the potholes. In the lower reaches the channel width increases to 6–8 m (Fig. 7, profiles 4a–4b, 5a–5b). The riverbed, point bars, and mid-channel bars are composed of sand and pebble material with pebbles predominating. The average depth of the river is 0.5–0.6 m and decreases to 0.2–0.3 m at the rapids.

A low alluvial terrace is characterized by a height up to 1–1.5 m above the river water level and is clearly distinguished on the floor of the Ryapsh River valley and its largest tributaries. Its width in the upper and middle reaches of the valley varies from several meters up to 7–8 m (Fig. 7b, profiles 1a–1b, 2a–2b, and 3a–3b). Alluvial deposits forming the low terrace were studied in section s02 (Fig. 7b, profile 4a–4b, (c)). The alluvium has a total thickness of about 1.6 m and it is mainly composed of pebbles in a sandy matrix. The surface of the terrace is covered by sandy deposits up to 0.4–0.5 m thick accumulated during the flash flood in the summer of 2023, when the water levels in all rivers in the western part of the Mussera Upland rose to their maximum levels in the last 70 years. In the bottom part of the alluvium, at a height of about 0.1–0.2 m above the river water level, there is a layer of dark-colored dense sandy clay with rare pebbles that contains numerous pyrogenic charcoal fragments (up to 3–5 mm) sampled for radiocarbon dating. Two of these samples showed similar ages (606 ± 27 and 633 ± 39 yr BP, Table 3), which imply that the low alluvial terrace formed no earlier than 570–670 cal yr BP.

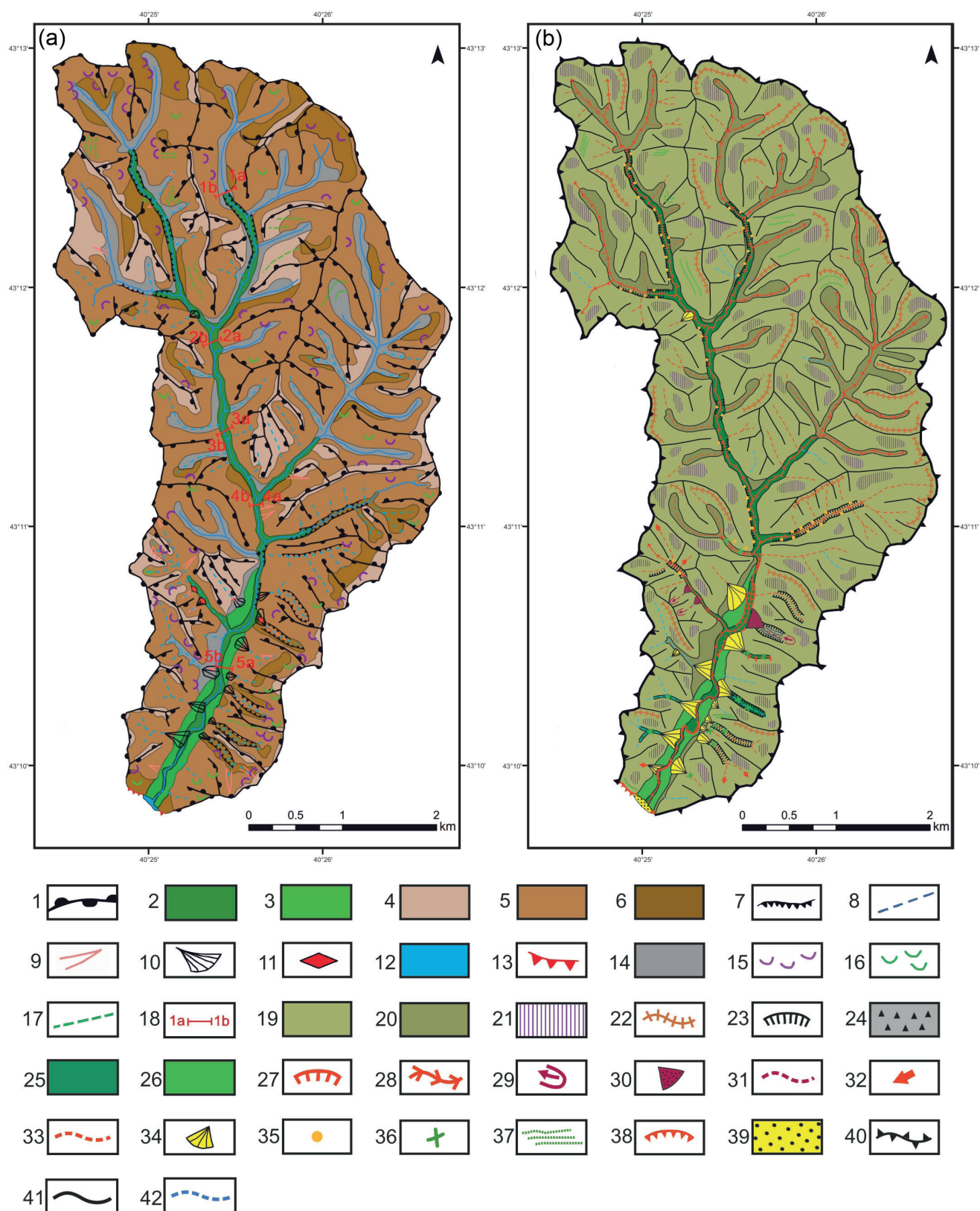


Fig. 6. Geomorphological maps of the Ryapsh River basin: a – morphology and origin of the landforms; b – geomorphic processes. Legend. For map (a): 1 – rounded-crest ridges, 2 – low alluvial terrace, 3 – high alluvial terrace, 4–7 – erosional slopes (4 – up to 15°, 5 – 15–35°, 6 – more than 35°, 7 – scarps), 8 – thalwegs, 9 – rills, 10 – gully fans, 11 – debris flow ridges, 12 – beach along the coastline, 13 – sea cliff, 14 – aprons, 15 – landslides, 16 – large tree throw pits, 17 – cattle tracks, 18 – cross-sections (see Fig. 7, b). For map (b): 19 – soil creep (predominant denudation), 20 – soil creep (predominant accumulation), 21 – landsliding, 22 – slope detachment (tension cracks), 23 – rockfalls, 24 – alluvial accumulation (high frequency), 25 – alluvial accumulation (low frequency), 26 – bank erosion, 27 – river downcutting, 28 – debris flow formation areas, 29 – debris flow accumulation (fans), 30 – debris flow erosion (channels), 31 – heads of bottom rills within gullies, 32 – gully downcutting, 33 – proluvial accumulation, 34 – karst flowstone formations, 35 – accumulation of woody debris, 36 – tearing along cattle tracks, 37 – coastal erosion, 38 – coastal accumulation (beach formation), 39 – Ryapsh River basin boundary, 40 – local catchment boundaries, 41 – gully thalwegs with no signs of downcutting

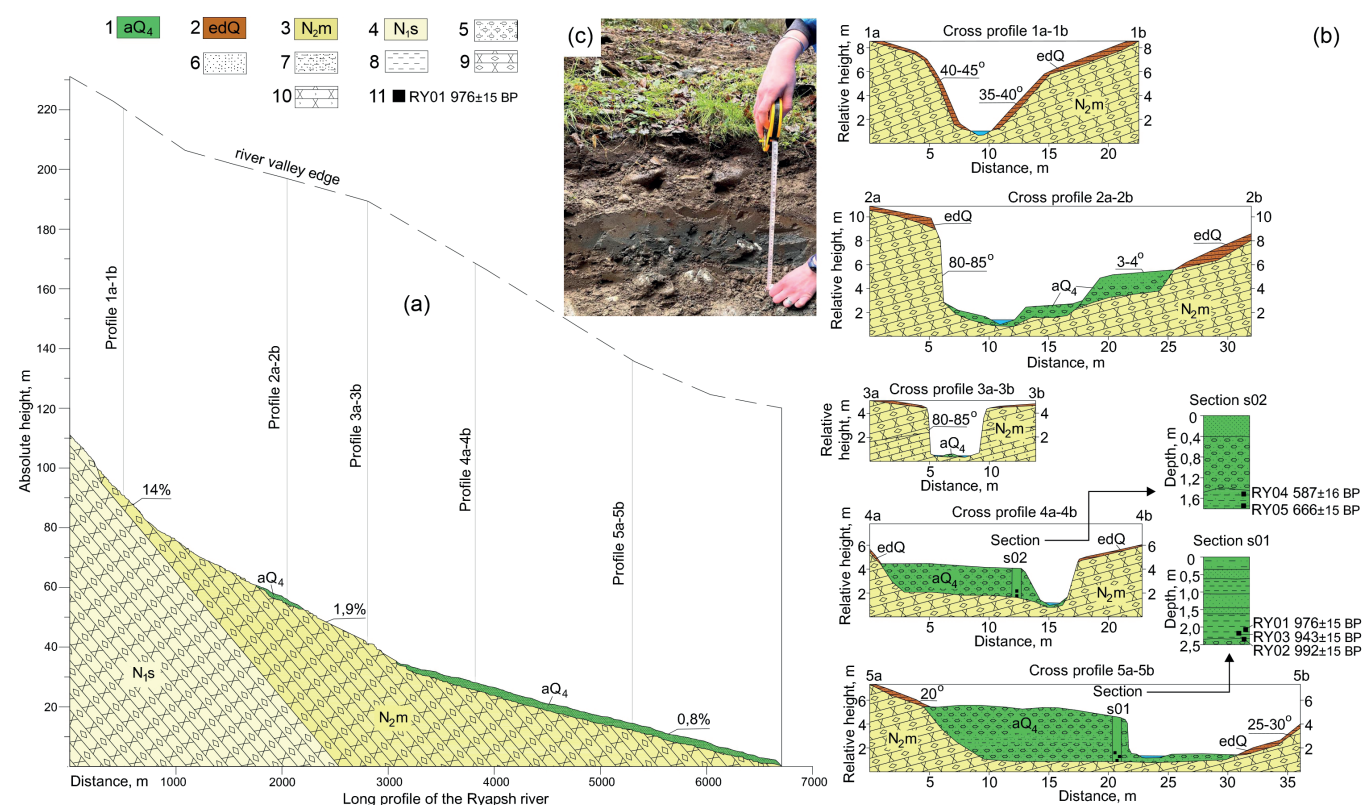


Fig. 7. Geological profiles of the Ryapsh River valley floor: longitudinal (a) and cross-profiles (b), c – lower part of section s02
Legend: 1 – Holocene alluvial deposits, 2 – Pleistocene and Holocene slope deposits, 3 – Pliocene (Meotian) marine deposits, 4 – Miocene (Sarmatian) marine deposits, 5 – pebbles with small boulders and sandy matrix, 6 – sand, 7 – sandy clay, 8 – clay, 9 – conglomerate with sandstone interbeds, 10 – sandstone with conglomerate interbeds, 11 – sampling points for radiocarbon dating and the obtained radiocarbon age (in years BP)

In its lower reaches the Ryapsh River channel is meandering, and another alluvial level appears within the valley floor (up to 2.5–3 m above the river water level) (Fig. 3d). Its width on the convex banks reaches 100–120 m. Alluvial deposits composing the high terrace have been studied in section s01 (Fig. 7b, profile 5a–5b). The total thickness of these deposits is 2.55 m. In the section s01 from the surface of the terrace to a depth of 2.35 m interbedded sands and loams with inclusions of gravel and pebbles are exposed. Scattered fine pyrogenic charcoal fragments up to 2 mm in size were found in the lower 30 cm (2.05–2.35 m) of the alluvial layer. The gravel-pebble layer, with a sandy matrix approximately 0.3–0.4 m thick, is exposed at a depth of about 1.5 m. The gravel-pebble mixture with a sandy matrix is exposed at the base of the section at a depth of 2.35–2.55 m. This layer is rich of organic including fine pyrogenic charcoal fragments up to 3–4 mm. Pyrogenic charcoal was sampled for radiocarbon dating. The ages of all three samples from depths of 2.10, 2.20 and 2.38 m are very close: 857±40, 847±35, and 917±40 yr BP, respectively (Table 3). Thus, the upper alluvial level in the Ryapsh River valley was formed about 810–960 cal yr BP.

Gullies and rills are widely distributed on slopes within the Ryapsh River basin. There are distinct rills up to 1.5–2 m deep with a V-shaped cross-profile incised into funnel-shaped depressions in the upper reaches of many gullies. The longitudinal profile of the gullies typically has a stepped shape, which is related to the heterogeneity of the conglomerate they dissect. Gully bottoms often have armor layers, and in the lower reaches they are covered with proluvium. In the middle reaches of the Ryapsh River, gullies and small valleys of tributaries often form canyons from 3–4 m to 7–8 m deep. In the lower reaches their bottoms widen, and signs of proluvium accumulation are present. Many gullies have well-defined fans covering the Ryapsh River

alluvial terraces. The fans are composed of sand and pebbles with boulders, cobbles, and woody debris. The fan's length is 50–60 m and their width is up to 70–80 m. The presence of debrisflow landforms indicates the debris-flow hazard in the lower reaches of some gullies–tributaries. Debrisflow landforms are represented by elongated ridges up to 1 m high aligned parallel to the channels and composed of unsorted clastic material and woody debris. Debrisflow accumulation levels (pseudoterraces) up to 2–3 m high above the thalweg are also located in the lower reaches.

Geomorphic processes in the Ryapsh River Basin

The topography of the basin and the Ryapsh River valley floor clearly demonstrates that denudation processes are dominant within the badlands of the Mussera Upland. These include active downcutting in the valleys and gullies, as well as soil creep and landsliding. Accumulative landforms such as alluvial terraces, fans, and aprons occupy less than 20% of the total basin area.

The most extensive geomorphological process in the Ryapsh River basin is soil creep, which is widespread on slopes exceeding 8°, including forested ones (forests cover about 96% of the basin, while meadows account for 4%) (Fig. 6b). In the upper reaches where channel flows are less capable, soil creep results in the formation of convex-concave slope profiles and the accumulation of slope deposits at their foot. Further downstream the discharge in the channel network increases, allowing the material supplied from the slopes to be carried away by rivers and streams. In these sections the rates of stream downcutting apparently exceed the rates of bottom infilling by slope deposits leading to the formation of convex longitudinal profiles in gullies and valleys.

Landslide processes significantly affect slope

Table 3. Radiocarbon dates of alluvial deposits from the Ryapsh River

No	Lab. code	Sample name	Sample depth	F ¹⁴ C		¹⁴ C Age (yr BP)		Calibrated age (cal yr BP)		$\delta^{13}\text{C}$
				F14C	Error (1 σ)	¹⁴ C Age	Error (1 σ)	median age	(2 σ)	
1	XA61242	RY01	2.10 m	0.8855	0.0017	976	15	857	40	-26.3
2	XA61243	RY02	2.38 m	0.8838	0.0017	992	15	917	40	-27.0
3	XA61244	RY03	2.20 m	0.8893	0.0017	943	15	847	35	-29.3
4	XA61245	RY04	0.2 m above the river water level	0.9295	0.0019	587	16	606	27	-29.2
5	XA61246	RY05	0.1 m above the river water level	0.9205	0.0017	666	15	633	39	-27.4

morphology. Small landslides (about 1–1.5 m thick) are common on slopes due to the low thickness of slope deposits (on average less than 2 m), humid climate, and forest cover. Landslides are typical on slopes steeper than 15° and are especially active during long and heavy rains. Forests are dominated by broadleaf species – such as oak, beech, hornbeam, and moisture retained by tree crowns increases the pressure on the unconsolidated cover of slope deposits. The Neogene bedrock's low permeability makes its upper surface prone to slipping, leading to landslides that entrain slope cover and the trees growing on it. Deeper landslides (up to 5–7 m) are also observed on valley slopes, mainly associated with convex slopes and near the edges of deep gorges. Terrace-like steps created by landslides can extend up to 30 m in width and 40–50 m in length. Field research has revealed both recent and older landslides (3–5 years or older) characterized by smoother outlines. The surfaces of the landslide terraces slope gently towards the river channels or sometimes tilt slightly backwards. On the densely vegetated valley slopes landslide scarps are not always clearly visible and are distinct only for recent landslides.

Fluvial processes are represented by stream downcutting in the river channels, gullies and rills, and bank erosion in the lower reaches of the Ryapsh River (Fig. 6b). The most intensive accumulation of alluvium occurs on the surface of the low alluvial terrace in the Ryapsh River valley floor. The high alluvial level is rarely flooded, only during extreme flood events (e.g., in July 2023 (Sheremetiev et al. 2024)). The high alluvial level flooding is largely affected by water input from tributaries (gullies, small valleys), because their mouths often lie at the foot of valley slopes that rest on the high alluvial terrace. It can be concluded that sediment input from the tributaries currently plays an important role in forming the alluvium of the high terrace as well as the normal accumulation of material transported by the river from the upstream.

The greatest threat to land use in the Ryapsh River basin is debris flow, which occurs both in tributaries and in the main channel of the Ryapsh River, particularly in its upper and middle reaches. When heavy rainfall occurs, the steep slopes, high density of the erosional network, low permeability of the Neogene bedrock, and thin slope cover contribute to an extremely rapid rise of water levels in the main channels, resulting in the influx of enormous amounts of sediment, primarily due to landslides. A geomorphological survey conducted in winter 2024 revealed that during the intense rainfall event in July 2023, which lasted about 14 hours, dozens of landslides were formed on the slopes of gullies and valleys. On average, 2–3 landslides occurred for every 100 m of the erosional

landform's length. The eroded material moved downstream in suspension and by rolling. Woody debris, such as floating tree trunks and branches, significantly contributed to this transport process, carrying large particles, including boulders, through flotation. At the concave break in the longitudinal profile of the Ryapsh River (near profile 3a–3b, Fig. 7a), the flow velocity decreases, and the accumulation of coarse clastic material begins. The accumulation of woody debris results in specific channel morphology as described by Abbe and Montgomery (1996), including arc-shaped bars, crescentic pools, and back channels in the valley bottom. Therefore, these debris flows do not extend to the lower reaches of the Ryapsh River.

DISCUSSION

The results of the geomorphological study of the Ryapsh River basin and Mussera Upland allow us to conclude that this area is a classic example of a humid badland, as defined by Gallart et al. (2002). In this badland denudation dominates over accumulation, with the latter occurring in narrowly localized areas. The unique feature of the Mussera humid badland manifested in the density and depth of dissection is its two-fold evolution driven by both tectonic forces (a “bottom-up” control, according to Faulkner (2008)) and climate (“top-down” control). Published studies on such badlands emphasize that they can continue to persist indefinitely in the absence of accumulation areas, and denudation rates can remain extremely high (Faulkner 2008; Fryirs et al. 2007). Badlands like this, classified as Mediterranean humid by Avcioglu et al. (2022), are found in transitional zones of uplifting mountains in a humid climate, in particular, in Turkey (Avcioglu et al. 2022), the French Alps (Descroix & Claude 2002; Ariagno et al. 2022), and the Pyrenees (Gallart et al. 2002; Nadal-Romero & Regüés 2010). The evolution of the Mussera badland during the Holocene mostly proceeds under the interaction of two leading exogenous processes: river down-cutting and landsliding. Landslides supply large amounts of loose material to stream channels. Due to the steep channel gradients, the vast majority of this material is exported beyond the drainage basins.

The tectonic uplift of the Greater Caucasus, which intensified notably in the Middle Pleistocene (Trikhunkov et al. 2024), and the associated uplifting of the southern foothills of the Caucasus, occurring at a rate of a few mm/yr over the last 100 years according to Tatarinov et al. (2024) stimulate the development of stream downcutting. In spite of repeated changes in the Black Sea level, which is the base level for the Ryapsh River, during the Pleistocene and Holocene, there are no traces of such changes in

the structure of the valley. This can be explained by the dominance of downcutting in the valleys throughout the entire Quaternary time. Meanwhile, narrow alluvial terraces may have existed in the lower reaches of fluvial systems in the past; however, with increasing incision depths, they were likely destroyed by bank erosion or slope denudation, which are extremely active in the humid climate. Currently, Holocene alluvial terraces are the only alluvial features present on the valley floor, and they are relatively young, with the age less than 1000 years. Our results confirm and extend previously obtained conclusions that denudation processes prevailed over accumulation during the Pleistocene on the Mussera Upland (Bredikhin et al. 2025).

The humid subtropical climate also contributes to the prevalence of denudation over accumulation in the entire Mussera badland. As the orographic barrier of the Caucasus has grown during the Quaternary, the role of extreme precipitation in the formation of badlands has increased. Heavy rainfalls are the main triggers for the mass movement on valley slopes, while steep gradients in the channels contribute to the removal of the denuded material from the basins. A similar mechanism of the humid badland formation with a leading role for extreme rainfalls was described by Gallart et al. (2002), using the example from key sites in the southern foothills of the Alps and the Pyrenees. The variability in water flow parameters of the Mussera badland rivers throughout the year is associated with the episodes of floods. This statement is confirmed by the extreme lithological diversity of the Holocene alluvial deposits described in the Ryapsh River valley (alternating pebbles, sands, and sandy clays).

The morphology of the valleys in the Mussera Upland demonstrates the absence of evidence of episodes of prolonged cessation of tectonic uplift on the southern periphery of the Greater Caucasus during the Quaternary. A slowdown or cessation of uplift would inevitably lead to a decrease of downcutting, slopes flattening, and changes in their profiles from convex to concave. Subsequent resumption in uplift could lead to the development of deeper incisions at the valley bottoms. However, there is no evidence of this scenario even in the large valleys of the Mussera badland. Valley slopes are often convex or straight, and the alluvial deposits do not exceed normal thickness. At the same time, under the humid conditions, the traces of alternate periods of valley incision and aggradation could have been completely destroyed by active slope denudation (especially landslides).

In recent decades, increasing rates of exogenous processes in the Eastern Black Sea region have been noted in connection with observed climate changes, which have manifested, in particular, through the increase in extreme rainfall events (Gudko et al. 2024; Meredith et al. 2015). This leads to increased erosional dissection and denudation

rates, as shown by the example of the badlands in the Pyrenees (Llena et al. 2020). These trends represent a threat to existing land use patterns, which are already constrained by extremely dense and deep erosional dissection. In particular, heavy rainfalls cause flooding of the high alluvial terraces in the valleys (Sheremetiev et al. 2024) that remain the main zones of residential development.

CONCLUSION

The results of the research lead to the following main conclusions:

1. The Mussera Upland, located at the foot of the southern slopes of the Greater Caucasus, can be described as a typical humid badland (according to Gallart et al. 2002). The density of the fluvial network reaches 3–4 km/km² and an average depth of 60–80 m for river valleys. River valleys are divided by narrow ridges here; flat interfluvial surfaces are absent, and the average slope angles reach 16°. The development of a dense network of low-order channels begins within a catchment area of only 0.01 km² (1 hectare).

2. The slopes of varying steepness account for 94% of the total area of the Ryapsh River basin (one of the three largest rivers in the Mussera Upland, fifth order Strahler), while only 6% of it is occupied by flat surfaces – alluvial terraces on the valley floor in its lower reaches. Most of the slopes have a convex longitudinal profile, and a high scarp often occurs at their feet. Only in the lower reaches of the main channel (the Ryapsh River) two alluvial terraces present (up to 1.5 m and up to 3.0 m above the river water level). Both are of Holocene age and were formed within the last thousand years.

3. The development of the Mussera badland is ongoing with the leading role of denudation (erosional and slope processes, primarily landslides) under conditions of ongoing tectonic uplift. Forest cover does not prevent mass movement on the slopes; instead, it often triggers it. As the result of active landsliding and continuous creep, a large amount of sediments (including woody debris) enter stream channels and are further transported downstream. Thus, the badland development is characterized by two opposing trends: over time, ridges become lower due to slope denudation, but the depth of dissection does not decrease because of active stream downcutting under conditions of ongoing tectonic uplift.

4. The increase of cyclonic activity in the eastern sector of the Black Sea due to climate change has led to an increase in the frequency of extreme rainfalls, resulting in the noticeable growth of denudation rates. This creates a threat of flooding and destruction for residential buildings located on the high alluvial terrace within the river valleys. In July 2023, flooding of this terrace was recorded for the first time since at least 70 years ago in the major valleys of the Mussera Upland (the Ryapsh, Mussera, and Tsanigvarta rivers). ■

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