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Udmurtia: A Combination of Ancient and Current Landforms on the Eastern Part of the Russian Plain

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Abstract—This paper considers ancient and current landforms developed under the influence of specific features of the geological history in the Neogene and the Quaternary and recent exogenic processes. The regional morphostructure is characterized by cuesta-like ridges, stepped landscapes (three surfaces of different ages with different heights), and relict denudation small-hilled terrain called "*puga*." It has been proven that the *puga* deposits are sediments of ancient Late Permian and Triassic rivers, while the *puga* hills are inversion forms. The relict morphosculpture related to periglacial phenomena in the Pleistocene is widespread. It includes the periglacial alluvium of Pleistocene terraces in river valleys and asymmetric cross-sections of small and medium-sized river valleys filled by slopewash–solifluction loams; in the interfluve areas widespread are aeolian landforms such as sand covers and continental dunes (up to 8–12 m high), as well as relic permafrost forms including polygonal–block and depression microterrain, cryogenic–nival niches, and cirques. The recent exogenic processes and related landforms are also analyzed. Channel processes, gully erosion, wave erosion of the banks of water reservoirs, and landslides are predominant. The gully erosion monitoring data on the period from 1978 to 2023 are reported. Karst and suffusion forms are rare. Gully forms of various genesis are widespread.

Keywords: morphostructure, cuestas, pediplains, *puga* deposits, slope asymmetry, relict morphosculpture, periglacial phenomena, fluvial landforms

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1. GEOGRAPHIC LOCATION

The Udmurt Republic (UR) is located in the eastern part of the East European (Russian) Plain, in the Middle Cis-Ural region, between the Kama and Vyatka rivers. The geographical position of the UR is very favorable: on the Kama River, an active shipping route, between the Urals and Siberia, on one side, and the Volga region and Central Russia, on the other (Fig. 1).

The UR is 42 100 km^2 in area. To the north and west, the republic borders on the Kirov region; in the east, on Perm krai; to the southeast, on the Republic of Bashkortostan; and to the south, on the Republic of Tatarstan. It is about 300 km long from north to south and 200 km from west to east. The predominant landscapes include the southern taiga and the mixed coniferous–broad-leaved forest zones [1].

The nature of Udmurtia is rich and picturesque. Its diverse landforms create quite remarkable landscapes: forests and small woods alternate with cultivated fields and meadows with different grasses. This is a land of numerous springs with crystal clear water, large and small rivers and lakes, alternating with peat bogs. The sources of the great and large Kama River with its tributary, the Vyatka, begin in this area.

The moderately continental UR climate is dominated by the incoming sea air from the Atlantic Ocean and the Arctic air from the Arctic Ocean. In summer, the continental tropical air from southern latitudes often comes to this area. The average annual influx of direct solar radiation onto a horizontal surface under clear skies, i.e., the possible influx, varies within the range of 4500–5060 MJ/m^2 across the UR area. In the region described, the average annual temperature varies from +2.3°C in the north to +3.5°C in the south. The average temperatures in January and July vary within the range from –13.3 to –11.9°C and from +18.3 to +19.7°C, respectively, with a pronounced trend of increasing winter air temperatures in the winter months [2, 3]. The stable snow cover lasts for 155–175 days. The average annual precipitation is 500–650 mm [1].

The most widespread soil-forming process over the last 7–8 ka was podzolic. It developed due to predominant coniferous forests in the vegetation cover, washout water conditions, and a lack of carbonate in most soil-forming rocks. In accordance with the *Soil Classification and Diagnostics in Russia* [4], the following soil

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Fig. 1. Physical map of the Udmurt Republic (modified from [1]).

types are predominant in the UR: podzols, podzolic, podzolic–gley, sod–podzolic, agrosod–podzolic, gray, agro-gray, peat–gley, humus–gley, alluvial, and peat. Typical and leached sod–carbonate soils were found in the areas close to carbonate rocks [5].

The UR area is rich in various plant communities; many types of taiga and subtaiga forests and diverse meadow and marsh communities can be found in its area [6–9]. The vegetation is dominated by forests occupying more than 46% of the total area. A distinc-

Fig. 2. Outcrops of the Kazanian Stage rocks (clays, mudstones, and sandstones with limestone and marl interlayers) on the right eroded slope of the Kama River valley downstream from the settlement of Karakulino (photo image by the author).

tive feature of dark coniferous forests is predominant Siberian species in the tree layer, such as Siberian fir and Siberian spruce. In pine forests, Siberian larch is mixed with basic tree species. Siberian species also play an important role in the grass layer. Typical forest species include *Pleurospermum uralense*, *Stellaria bungeana*, *Actaea rubra*, etc.; in addition, near-Ural species are also represented in this area: *Knautia tatarica*, *Cicerbita uralensis*, etc. Along with the basic types, large areas are occupied by mixed forests (spruce–fir–linden, spruce–pine–birch, etc.). Together with zonal spruce–fir forests, large areas are covered by secondary, coniferous–small-leaved and small-leaved forests. The area from north to south is characterized by a gradual enrichment of coniferous forests in broad-leaved species and nemoral herbaceous plants.

2. FEATURES OF THE GEOLOGICAL STRUCTURE

The UR area corresponds in terms of its geological structure to the eastern part of the ancient Russian Platform. The geological section consists of crystalline basement and sedimentary cover rocks. The crystalline basement within the UR is composed of metamorphosed rocks of the Lower Proterozoic Karelian complex: gneisses, crystalline schists, and amphibolites. Igneous gabbro–diabase rocks are widespread [10].

The sedimentary cover is composed of Upper Proterozoic, Devonian, Carboniferous, Permian, Triassic, Neogene, and Quaternary rocks. Only Permian and younger deposits outcrop.

The Permian system is widespread in the UR, and it is represented by all three divisions. The Lower Permian includes five stages with only the Ufimian coming to the surface. It is a layer of marls, clayey limestones, dolomites, sandstones, and siltstones with clay interlayers. The total thickness is up to 230 m [11, 12].

The Middle Permian includes the Kazanian and Urzhumian stages. The Kazanian is widespread throughout the UR and outcrops in the southern and central areas. It is composed of clays, siltstones, and sandstones with conglomerate, limestone, and marl interlayers (Fig. 2). It is up to 225 m thick. The Urzhumian exposed in the central area includes the cognominal horizon composed of conglomerates, sandstones, siltstones, clays, and marls from bottom to top.

The Upper Permian includes two stages outcropping in the northern half of the UR. The Upper Permian base is composed of sandy–siltstone rocks with sandstone and conglomerate interlayers, while the upper part consists of calcareous clays with marls and limestones. Their total thickness reaches up to 150 m.

The Triassic system represented by the Induan stage is distributed in watersheds in the UR northern regions. It consists of alternating sand–gravel and clayey deposits with a total thickness of up to 70 m.

The Neogene system is represented in the UR by its upper division, such as the Pliocene. Its deposits are located in narrow, deeply incised valleys of paleo-Izh, paleo-Kyrykmas, paleo-Vala, and other paleorivers in the southern and southwestern parts of the UR. The base is composed of a sandy–pebble material, yellow clay with spherosiderite, and limonite nodules, while the top is chocolate clay with peat and blue clay interlayers with numerous spherosiderite nodules [13]. The Pliocene is up to 138 m thick.

The Quaternary system is a cover of loose sediments almost everywhere composing the Earth's surface. According to the current ideas, the UR was not covered by glaciers. The Quaternary system includes a complex of alluvial deposits in river valleys (up to four terraces composed of pebbles, gravel, sand, sandy loam, clayey loam, and peat; up to 30 m thick); a complexly built sequence of eluvial–talus and talus–solifluction loams, sandy loams and clays, aeolian sands, and sandy loams on slopes and watersheds; and a cover of landslide, rockslide, and talus coarse-grained and sandy–clay rocks on the slopes (Fig. 3).

Rupture and oscillation movements of the Earth's crust played a key role in the formation of tectonic structures of the platform cover. The former were the most active at the early formation stages of the platform cover in the Early Paleozoic. These processes led to deep depressions known as grabens, and aulacogens lost their activity by the Neogene–Quaternary. Within the Udmurt part of the Russian Platform, the Kilmez and Mamadysh–Kokara troughs can be mentioned as such structures.

3. MORPHOSTRUCTURE

The current landforms are occasionally observed as platform folds that resulted from ancient mountain-building processes. When such folds are exposed to the Earth's surface, their gentle wings, especially those directed to warm bearings (to the south and west), are subject to the active influence of exogenic processes such as sloping and erosion of upper links of the fluvial systems. A slope formed at the fold wing site loses its structural predetermination. Slopes similar to *cuestas* begin to be formed on the gentle, extensive arch of the fold and, occasionally, in the contours of the "darkened" wing, under the influence of exogenic processes. Cuestas are ridges with an asymmetric cross section that resulted from erosion and denudation in a monoclinal formation of layers with different resistance to denudation processes. There are two latitudinal cuesta-like ridges in the Udmurtia area: Kuliga–Pudem in the north and Sharkan–Multan in the central part (Fig. 4). The relative height of the cuesta-like slopes from their base to edge varies between 40 and 60 m, occasionally reaching 80 m or more (Fig. 5a).

The recent landforms of Udmurtia began to be formed at the turn of the Oligocene and Miocene (about 25–30 Ma BP), at the activation stage of intra-earth processes, at the last stages of the Alpine tectogenesis cycle. The study of neotectonics made it possible to reveal very interesting relations between the Earth's crust and terrain structures. It turned out that some orographic elements (highlands and lowlands) spatially corresponded to structural elements of the basement or platform cover. Such aggregated, spatially and genetically related structures of the Earth's crust and surface were called *morphostructures* [14]. A classic example of the morphostructure in Udmurtia is the Upper Kama Upland. In terms of space, it borrows a well-known tectonic structure of the Russian Platform, such as the Upper Kama Depression. This morphostructure is reversed (or inverted): the upland was formed at the depression site as a result of vertical movements of the Earth's crust that ended in the Miocene. The direct morphostructure is the Kilmez Lowland the spatial position of which corresponds, in general, to the northeastern strike of the Kilmez trough. Surfaces of the Mozhga and Sarapul uplands are "neutral" to the platform cover structures. Their denudation surfaces "cut off" different structures of the platform cover and are astructural.

One of the characteristic structural features of the Earth's surface of Udmurtia is its *stepped nature*. The upper step is located at absolute marks of 250 m or more. Relatively large areas with such marks are preserved within the Upper Kama Upland. Its most elevated areas are located at absolute marks of 320–330 m. The highest point of Udmurtia (332.6 m) is confined to its surface at the headwaters of the Pyzep River, 10 km north of the settlement of Karsovai. The high step known as the *"upper plateau"* occupies a large area of the Russian Plain [15]. On other elevations of Udmurtia, its surface is observed only in spots. In the Mozhga Upland, it is preserved in the nodal parts of the interfluves as separate relict hills. Their height does not exceed 265 m. In the Sarapul Upland, only the "roots" of relict hills are preserved. Their peaks vary at a level of 240 m, but do not exceed 250 m. A predominant part of the surface of the Mozhga and Sarapul uplands corresponds to the step known in the Russian plain as the *"lower plateau."* Absolute marks of the lower plateau's surface vary within the range of 180–220 m (Fig. 4).

The stepped terrain records the latest rhythmic tectonic movements. A deep dismembering of the ancient post-Permian land surface by river valleys was related to the tectonic movement revival phases. The stabilization of tectonic movements gave impetus to the formation of regional erosion surfaces. They were formed due to smoothing and leveling of the dismembered terrain to bottoms of the river valleys at that time [16, 17].

Four activation phases of tectonic movements were noted with the beginning of the neotectonic stage: pre-Miocene (at the turn of the Oligocene and Miocene), pre-Kinelian (at the beginning of the Pliocene), pre-Venedian (at the boundary of the Eo- and Neopleistocene), and pre-Würmian (at the beginning of the Late

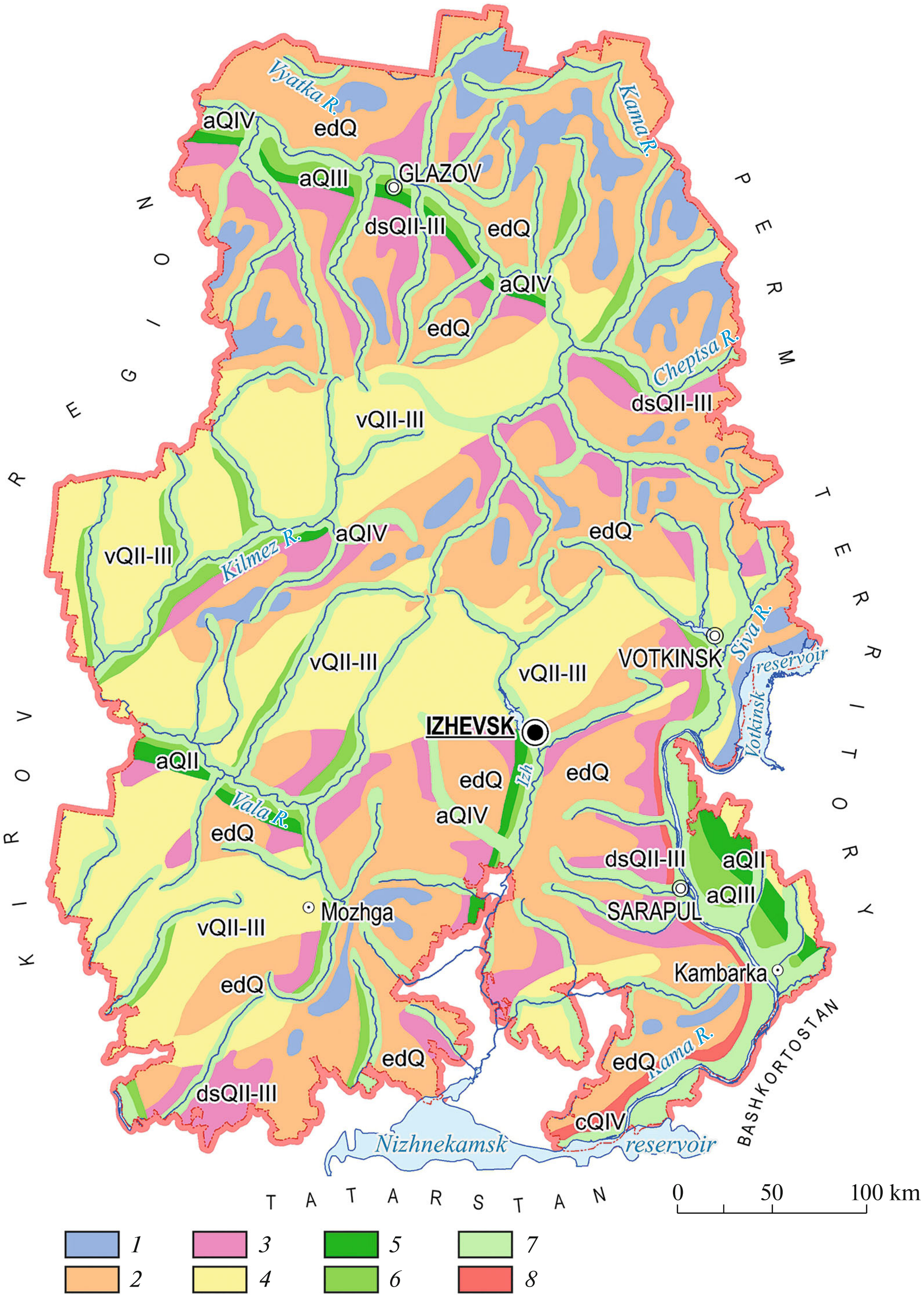

Fig. 3. Generalized map of Quaternary deposits in Udmurtia (modified from [1]). (*1*) Outcrops of pre-Quaternary rocks, (*2*) undivided Quaternary eluvial–slopewash deposits (edQ), (*3*) Middle–Upper Quaternary slopewash–solifluction deposits (dsQII-III), (*4*) Middle–Upper Quaternary aeolian deposits (vQII-III), (*5*) Middle Quaternary alluvial deposits (aQII), (*6*) Upper Quaternary alluvial deposits (aQIII), (*7*) current alluvial deposits (aQIV), and (*8*) current landslide deposits (cQIV).

Neopleistocene). The landforms were leveled, and the upper plateau surface was formed mostly in the Miocene, while the lower plateau surface developed in the Eopleistocene. Both surfaces are *pediplains* in terms of origin. They resulted from the retreat of slopes in parallel to themselves. This process is called pediplanization (pediplanation), and the denudation plain formed in this way is called "a pediplain" [18].

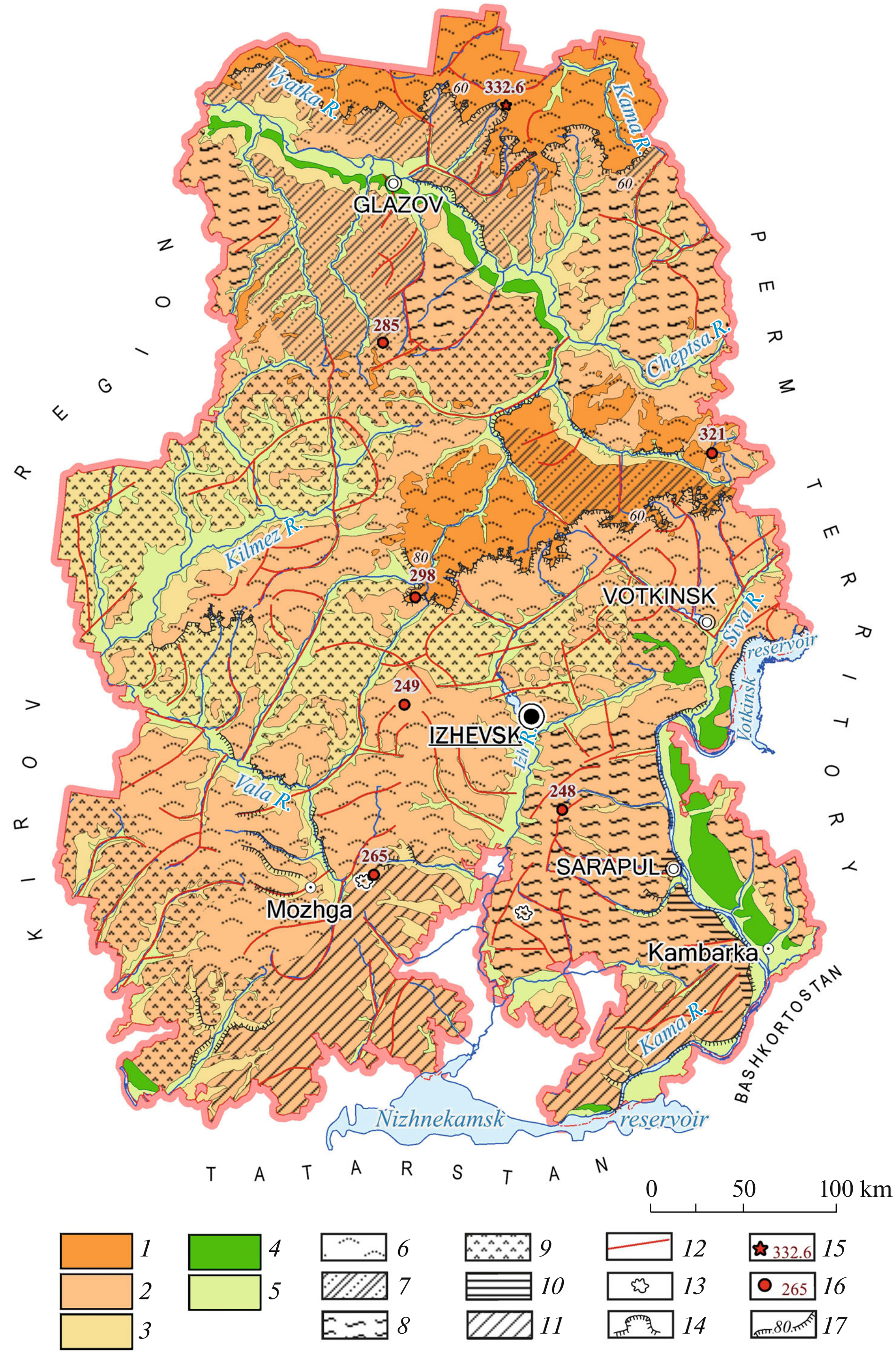

Fig. 4. Geomorphological map of Udmurtia (compiled by A.G. Illarionov and I.I. Rysin). (*1*) Miocene pediplain ("upper plateau"), (*2*) Eopleistocene pediplain ("lower plateau"), (*3*) Pleistocene planation surface, (*4*) high (III–IV) river terraces, (*5*) low (I–II) river terraces and floodplains; types of interfluves: (*6*) hills, (*7*) low-elevation ridges (landscape with elongated hills oriented in the same direction), (*8*) combination of hills and low-elevation ridges, (*9*) hillocky ridges, (*10*) flat-topped landscape formed on horizontally bedded bedrock, (*11*) landscape on monoclinal sequences, (*12*) linearly elongated terrain forms (lineaments), (*13*) karst sinkholes, (*14*) nival forms, (*15*) the highest point of Udmurtia, (*16*) the highest points of highlands (*pugas*), (*17*) high cuesta-like steep slopes.

The morphological consequences of the last two revival phases of tectonic movements are outlined mainly within the present-day river valleys. The lowest step—the "Pleistocene planation" level—was related to the pre-Venedian phase. This step with absolute marks of 140–160 m, including levels of the high

Fig. 5. Examples of the morphostructure and relic morphosculpture form in Udmurtia. (a) Cuesta-like terrain (in the background) near the settlement of Kykva, Sharkan district (photo image by A.V. Fertikov); (b) Kargurez *puga* in the Sharkan district (photo image by Yu.F. Frolov).

(third and fourth) floodplain terraces, was apparently formed in the first half of the Neopleistocene. It should be noted that this step goes beyond the Kama and Vyatka valleys within Udmurtia. Along the Kilmez–Uva–Lyukshudya–Kvarsa line of settlements, it forms a narrow latitudinal Central Udmurt Lowland. This lowland is only 25–30 km wide. Its height varies from 140 to 160–170 m. It has preserved separate small relics of the lower plateau with absolute marks of up to 220–230 m. The Central Udmurt Lowland separates the UR northern uplands from the southern ones. In contrast to other lowlands in the region, it is not directly genetically related to the river activity. It is possible that the Central Udmurt Lowland is a young morphostructure superimposed on the surface of the upper and lower plateaus after they were formed [19].

The pre-Würmian (at the beginning of the Late Neopleistocene) revival phase of tectonic movements was a forerunner of the erosion–accumulation activity of rivers related to the formation of the Late Pleistocene (second and first) terraces.

The lowest level of the Earth's surface characteristic for the bottoms of river valleys is a complex of floodplain–channel forms. In the lower reaches of the Kama and Vyatka, this level is located at an absolute mark of about 60 m (with waterline marks of 52–53 m). Therefore, it is necessary to note the high total dismembering amplitude of the regional uplands (about 280 m). Within individual uplands, the average depth of erosion dismembering usually does not exceed 100 m and is 89 m for the Upper Kama Upland and 92 m for the Mozhga Upland. Only in the Kama

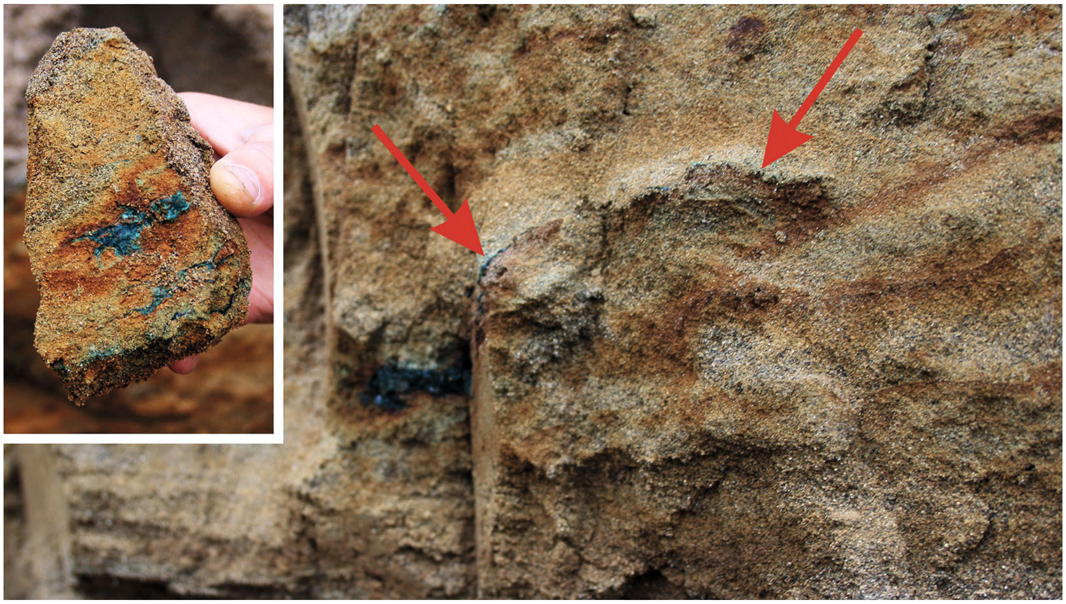

Fig. 6. Volkonskoite interbed in sandy–gravel sediments composing the *puga*. Photo image by the author.

region, within the Sarapul Upland, does it increase to 105 m.

4. RELICT MORPHOSCULPTURE

A morphological form of the Udmurtia plains is highly dependent on the composition of outcropping rocks. When compact, horizontally lying rocks (sandstones and limestones) come out onto the daytime surface, the plains acquire flat outlines. An apron composed of a detrital material (sands and pebbles) can also be of secondary origin. The secondary apron composed of detrital material accumulates during the weathering of (Permian and Triassic) bedrock. In the course of the long-term denudation, clay particles are washed out of the latter and the detrital material is gradually projected onto the daytime surface and forms a coarse-grained eluvium apron. The same process leads to the formation of a very specific relict small-hill terrain within the region.

Small hills composed of a gravel and pebble material have been known as *"pugas"* since the end of the nineteenth century, since the time of the study carried out by Professor P.I. Krotov of Kazan University [20]. The origin of *pugas* was a matter of debates for a century. Krotov [20] considered *pugas* to be moraines of the Pleistocene ice sheets. On this basis, he believed that the northern part of the Vyatka–Kama interfluve, right up to the Cheptsa valley, was covered by an ice sheet during the era of maximum glaciation of the Russian Plain. Only a century later did scientists from Kazan and Udmurt Universities, under the leadership of Professor A.P. Dedkov [21], prove that the *puga* deposits were sediments of ancient Late Permian and Triassic rivers and that the *pugas* proper were inversion forms. The deposits that made up the *pugas* were transformed as a result of the calcite cement leaching and the enrichment of upper layers in a coarse-grained material under the fine-grained earth washing-out. All these data are indicative of the fact that the *pugas* are denudation relics developed in sand–conglomerate rocks of different ages (Fig. 5b).

Currently, sand and gravel are mined for local needs at most *pugas*. In the *pugas*, among the sand and gravel layers, we can find segregations of a rare mineral such as *volkonskoite* (chemical formula $CaO_3(Cr, Mg)_2(Si,Al)_4O_{10}(OH)_2 \cdot 4H_2O$). Volkonskoite is a rare green mineral, similar in outward appearance to malachite (Fig. 6), which can be used to produce a high-quality paint. Its color density depends on the iron content in the mineral with the corresponding decrease in chromium oxide. However, this mineral does not accumulate on a commercial scale.

One more important condition for the formation and development of the Earth's surface landforms is the exogenic factor. The force that controls it is the radiant energy of the Sun. This energy is transformed in various geographic envelope areas such as the upper part of the lithosphere and in the atmosphere, the hydrosphere, and the biosphere, and serves as the cause of exogenic terrain-forming processes. Their combined complex or "spectrum" includes different processes: weathering; slope processes; fluvial processes related to the activity of temporary and permanent watercourses; karst process accompanied by the dissolving activity of surface and ground water; permafrost impact; wind activity; and waves on the shores of lakes, seas, and artificial water reservoirs. Since the amount of the incoming solar energy depends on the geographic latitude, the exogenic terrain-forming processes are, first of all, zoned in nature. The Earth's surface landforms created by the exogenic processes are terrain *morphosculptures* [22] zonally superimposed on morphostructures.

Hence, the climate–landscape environment controls the range of exogenic terrain-forming processes. However, this environment has changed periodically over the last 1.5 Ma, in the Quaternary period. The periodicity of climate–landscape changes was related to alternating climate cooling and warming periods. Ice sheets were formed during the cooling periods. In some eras, at their development peak, glaciers occupied the entire northern and central parts of the Russian Plain. Under climate warming, in the interglacial periods, the climate and landscape conditions became similar to the current ones.

In the Pleistocene glaciation period, Udmurtia was located beyond the ice sheets, in the so-called *periglacial* zone. The climate and landscape conditions of this zone were formed under the indirect influence of the ice sheets. The upper part of the Earth's crust was bound by "permafrost" and turned into a cryolithic zone; the forest, as a plant formation, was greatly reduced in area and survived only in unique "shelters" such as refugia; the cool climate contributed to the preservation of snowfields during most of the summer months and their terrain-forming activity, for example, nivation, etc.

The periodic changes in the interglacial and glacial epochs, similar to the renewal and stabilization phases of tectonic movements, were accompanied by either terrain dismembering or leveling. Interglacials corresponded to terrain dismembering, while glaciations corresponded to the terrain smoothing and leveling. In the interglacial periods, a continuous vegetation cover (forest and grass) significantly relieved watercourses from sediment runoff. The river energy was spent mainly for erosion and riverbed deepening. In the glaciation period, under periglacial conditions, the degradation of the vegetation cover resulted in active slope processes such as solifluction (highly moistened soil flow through permafrost) and talus washout. The rivers loaded by abundant sediments were not able to transport them. Therefore, sediments were actively transported and accumulated in the channels and at the bottoms of river valleys. As a result, interglacial alluvial deposits, differentiated into various facies, were covered by sediments of stagnant, poorly flowing water bodies in the glaciation periods. These sediments were called thte *"periglacial"* alluvium. Hence, the Pleistocene terraces of the periglacial zone consist of two sequences.

The UR plain area is dismembered by a dense network of rivers with a total length of almost 30000 km, while the average density of the river network is 0.71 km/km^2. It is observed as a zonal increase in the density of the river network from south to north (0.45–0.95 km/km^2 and more) and in the river runoff modulus (from 4.5–5.0 to 8–9 l/s km^2). Wide floodplain rivers with active meandering processes are predominant in this area [1, 23, 24].

River valleys are subdivided into three types: large rivers of ancient origin, medium-sized rivers with a full complex of Quaternary (Pleistocene) terraces, and small rivers.

The first type includes the Kama and Vyatka valleys. In the cross section of these river valleys, according to the drilling data, there are deep erosion cuts composed of Pliocene and Early–Middle Quaternary deposits [13]. The current morphological form of the Kama and Vyatka valleys resulted from the erosion and accumulation activity of the rivers started at the later Pleistocene stages and in the Holocene. The traces of activity are preserved in the current landforms as terraces. The largest ancient terrace is the fourth floodplain terrace the height of which above the rivers is 60–90 m. River (alluvium) deposits making up the terrace consist of two parts: the bottom (25–30 m) is composed of sediments corresponding in terms of the accumulation time to the Likhvin Interglacial and overlain by a periglacial alluvium of up to 40 m thick; the Middle Quaternary, the Dnieper age. The third floodplain terrace (height above the rivers is 35–50 m) also belongs to the complex of high terraces. Alluvial deposits accumulated during the Odintsovo Interglacial and Moscow Glaciation make up its structure in the same sequence.

The lower part of the terrace section, corresponding in terms of the accumulation time to the interglacial periods, consists of the following facies: channel alluvium (coarse-grained sand–gravel–pebble sediments with a characteristic oblique and diagonal stratification); overbank alluvium composed of horizontal layers of fine sand, silt and loam; and oxbow facies usually observed as clay lenses highly enriched in organic residues and, sometimes, as pure peat lenses [25].

The interglacial alluvial sequences are covered by periglacial alluvium which has a relatively uniform structure everywhere. It is dominated by a finely detrital material (sands, siltstones, and clays) which has a thin horizontal, occasionally, very specific, intertwined layering (Fig. 7a). The periglacial alluvium is 2–3 times thicker than the interglacial alluvium, which is evidence of increased rates of alluvial sedimentation in periglacial environments.

Intensive accumulation of the periglacial alluvium at the bottom of the Pleistocene river valleys contributed to a slow vertical rise of the floodplain–channel complex. The consequence of this process was of a great terrain-forming importance. Precisely this process resulted in outcropping of the floodplain–channel complex that emerged from the river valleys onto the surface of the low interfluves.

In the valleys of small rivers, the slope processes considerably suppressed the channel processes. The

Fig. 7. Examples of sediments composing river valleys. (a) Periglacial alluvium in the landslide exposure on the left slope of the Pleistocene terrace of the Vyatka River near Krymskaya Sludka. (b) Slopewash–solifluction deposits on the slope of the gully near the settlement of Fertiki, Votkinsk district. Photo images by the author.

slopes of river valleys were covered by an apron of talus–solifluction deposits; they were widespread and consisted of relatively thick (from 3–5 to 30–38 m) loams with a yellowish brown, brown with a pale yellow tint, or dark brown color (Fig. 7b) [26]. The box-shaped bottoms of interglacial river valleys acquired the form of gentle troughs in the glaciation periods.

Vast interfluve areas and slopes of river valleys, where they were not undercut by the rivers, remained "preserved" from the time of the previous glacial epochs. Currently, they are observed as relict forms. In terms of the Udmurtia topography, they occupy the largest area. They are also predominant in terms of genetic diversity. This fact is clearly indicative of a wider range of exogenic terrain-forming processes in the glaciation periods.

The example of relict are asymmetrical cross-sections of the valleys of small and medium-sized rivers. The valley slopes faced to warm directions (to the south and west) are steeper than the opposite ones (Fig. 8a). The morphology and morphometry of the slopes acquired such differences in the glaciation periods. They were caused by different intensity and spectrum of exogenic processes on differently faced slopes. "Warm" south and west-faced slopes underwent a greater nivation impact. However, they were cleared of snow earlier and dried out earlier, in contrast to the opposite "shaded" slopes. The latter had snow on them longer. The apron of moistened soil and ground sediments formed by glacial solifluction and talus processes led to a very gentle profile of "cold slopes." This is the way of formation of the "climatic" asymmetry type of river valley slopes, being very widespread in the region [27].

The formation and development of steep slopes in the valleys of large rivers with a runoff volume of at least 1000 m^3/s are considered, in particular, as a consequence of the general planetary cause. The "Baer–Babinet law" was developed in the middle of the nineteenth century as a result of studying such banks in geomorphology. Steep cliffs, similar to those on the Volga, were found in the valleys of large rivers and always, regardless of their flow direction, on the right bank. This pattern was related to a unidirectional, right-lateral shift of river channels. This shift was caused by the Coriolis force resulting from the Earth's rotation around its axis. This is a way of forming the planetary asymmetry of the slopes of large river valleys.

The low terrace complex includes the first and second and floodplain terraces. The ledge dividing the terraces of different complexes (35–50 m high) controls in many respects the morphological form of the current river valleys (Fig. 8b). The height above the rivers of the first terrace is 8–12 m; the second terrace, 17–20 m. Low terraces were formed in the Late Quaternary. In the postglacial period, floodplain terraces were formed in the valleys of all rivers. Low terraces and floodplains are abundant with large palaeochannels of Late Glacial age that indicate high values of river runoff 13–18 ka BP [28, 29]. In floodplain deposits one may found the Holocene buried soils indicating periods of runoff decrease [30]. In the valleys of medium-sized rivers (Cheptsa, Vala, Kilmez, Siva, Izh, and Kyrykmas), Pliocene and Early–Middle Quaternary erosion incisions are poorly defined. In small river valleys, only low terraces may be found.

The most characteristic forms include cryogenic (permafrost), cryogenic–nival, of relics of periglacial morphosculpture preserved since the Pleistocene cold epochs eolian, and solifluction–talus.

Permafrost forms are represented by the polygonal–block and depression microterrain. The polygonal–block terrain consists of 4- to 6-angle blocks ranging from 20–40 to 80–120 m in diameter. A modification of the polygonal–block landforms is the depression terrain formed at the junctions of microdepressions separating the blocks. Cryogenic–nival niches and cirques developed on steep high slopes of river valleys and cuesta benches (Fig. 8c). The bottom

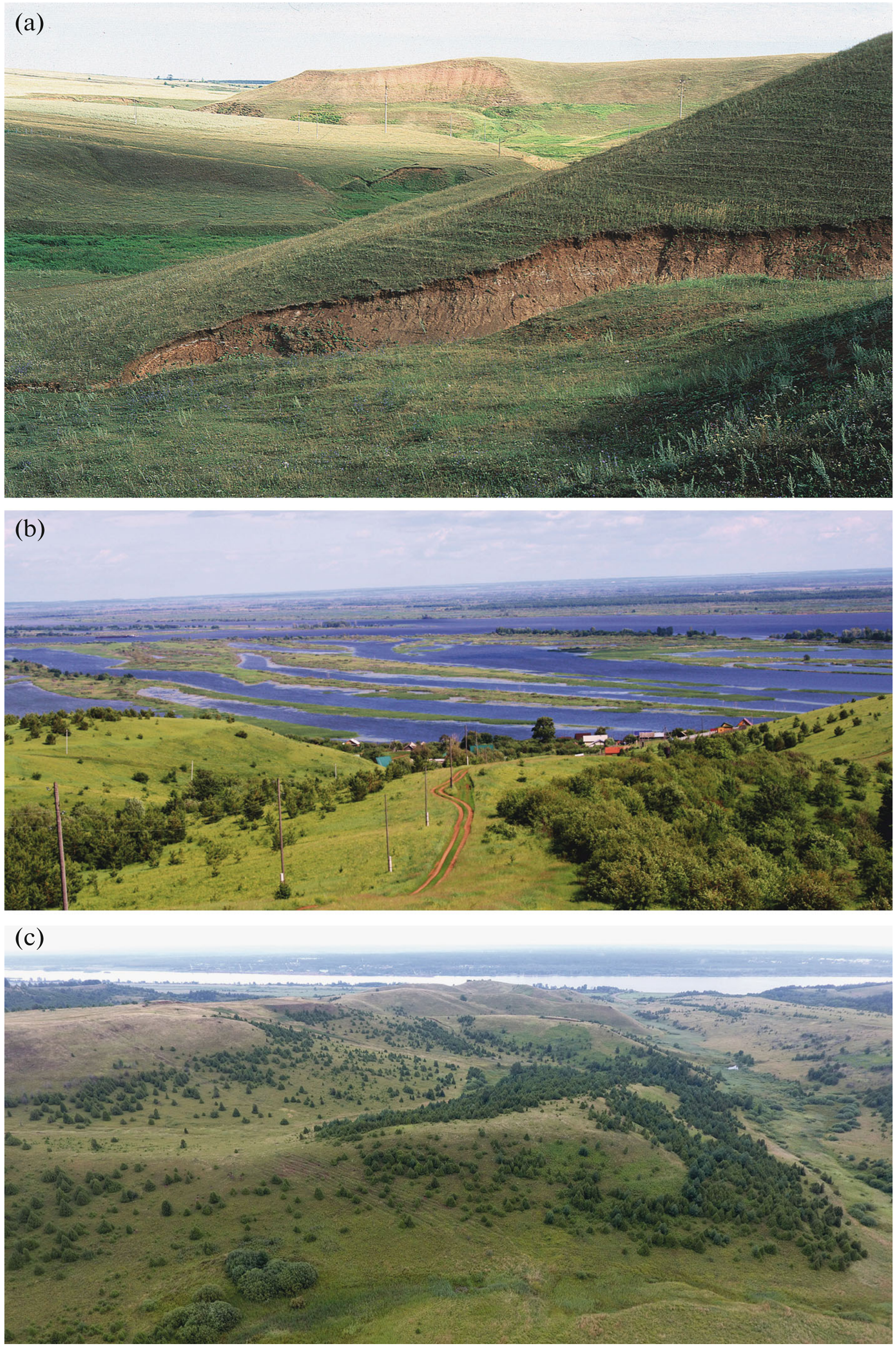

Fig. 8. Examples of fluvial landforms. (a) Symmetric slope of the river valley on the right bank of the Kama River in the Karakulinskii District (photo image by A.V. Fertikov). (b) Kama River floodplain with steep terrace steps near the Zuevyi Klyuchi Settlement (photo image by the author). (c) Cryogenic–nival (erosion–nival) cirques on the right slope of the Kama River valley near the settlement of Sokolovka (photo image by I.I. Grigor'ev by means of a quadrocopter).

of cirques is composed of talus–solifluction deposits indicating that the catchment sinkholes on the slopes served as a place for the formation of snowfields contributed to the activation of frost weathering and solifluction. These processes led to expansion and leveling of the bottoms of the catchment sinkholes and their transformation into nival niches and cirques.

Aeolian landforms occur as sand sheets and dunes. Among aeolian forms, *dunes*—parabolic, longitudinal, and transverse—are distinguished by a morphological "freshness" [26]. Relatively rare *parabolic dunes* are most often observed on the surface of Pleistocene terraces, because their development requires a high sand thickness. The dunes vary from 4 to 8–12 m high (Fig. 9).

Fig. 9. Dune landforms in the upper reaches of the Kilmez River. (a) Longitudinal dune near the settlement of Malyagurt; (b) longitudinal dune eroded by the Kilmez River channel. Photo image by the author.

Their length along the axis in the Vyatka River valley is 100–250 m. The width at the base in the middle part is 15–25 m. The steepness of the inner slope varies from 4°–5° to 20°, and that of the outer one, from 12° to 25°. *Longitudinal dunes* are common and due to the separation of highly elongated "horns" of parabolic dunes. Their characteristic feature that makes it possible to distinguished them from similar transverse dunes is the slope symmetry. The genetic relationship of longitudinal and parabolic dunes is confirmed by the frequently observed various transitional forms. Longitudinal dunes are observed on the surface of Pleistocene sand terraces of most rivers in the region and in watershed sand massifs. Well-defined longitudinal dunes of 8–10 m high are observed in the Kilmez massif, in the upper reaches of the Izh River, where they are oriented northeastward. *Transverse dunes* are extremely rare in this region. They are observed in the Vyatka River valley. They are 200–250 m long, 70 m wide at the base, and 5 m high. The slopes are asymmetrical: the southwestern slope is 7°, and the northeastern slope is 11°. The transverse dunes are more noticeably emphasized by the layering inclined northeastward at an angle of 11°–15°.

The study of dune landforms is of great paleogeographic importance, because it makes it possible to determine the wind direction at the time of their formation. Based on the study data on the region described, southerly and southwesterly winds prevailed.

The aprons of thin eolian sands in Udmurtia are located as two large massifs, the Vyatka and the Kilmez. The first one extends eastward from the Lower Vyatka, reaches the Vala River, and doubles. The southern band extends to the middle reaches of the Izh River; the northern one reaches the Siva River. The Kilmez massif occupies not only the cognominal lowland, it crosses the entire republic and reaches the headwaters of the Cheptsa River (Fig. 3). These sand covers are of aeolian origin: they were formed under the action of winds blowing out loose river sands from the terrace surface at the end of the Late Quaternary glaciation. Within the continental dunes, not only landforms are relict, but so is the vegetation cover.

Hence, the morphological form of the Earth's surface in Udmurtia is largely due to the Pleistocene relict landforms.

5. PRESENT-DAY MORPHOSCULPTURE

The current terrain formation includes a wide range of fluvial processes related to the activity of permanent and temporary water flows, as well as various gravity (on slopes) and wave erosion processes on the banks of water reservoirs. Local karst and suffusion processes are also known.

Steep erosion benches (known as ravines or mountains) are formed in the areas where rivers undercut terraces or valley sides. Mount Baigurez, a steep bedrock slope of the Cheptsa River valley near the settlement of Debesy, is of this nature (Fig. 10a). After the erosion process stops, the erosion benches turn into talus slopes, which, in the cases of widespread clay rocks, are also characterized by landslide processes (along the right bank of the Kama River, as well as along the banks of the Vyatka and Cheptsa rivers and their tributaries).

Such a landslide was formed in 2001 on the left slope of the Vyatka River valley, composed of Pleistocene (periglacial) loess-like loams. It is located in the northern margin of the settlement of Krymskaya Sludka (Fig. 10b). Tacheometric survey of the landslide has been carried out annually since 2003, when its volume was about 100000 m^3, and the area, respectively, was 12000 m^2. In 2022, its volume increased to 112000 m^3, and its area increased to 14 600 m^2. The relative height of the slope edge above the water's edge is 37 m, on average. According to the study results, the length of the landslide body is gradually increasing: it was only 220 m in 2003, and it was already 290 m in 2023. The maximum retreat values of the landslide

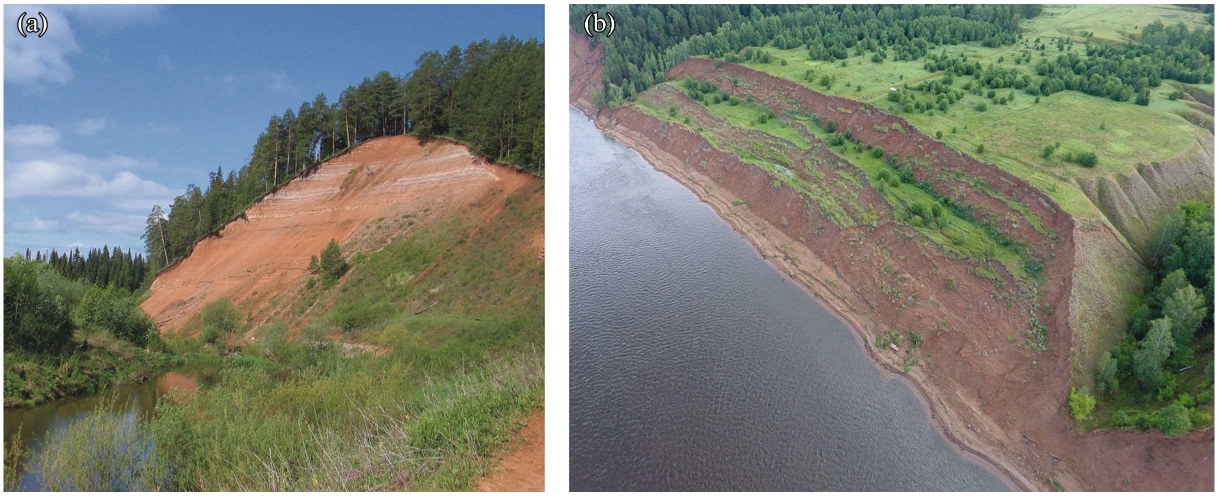

Fig. 10. Landforms created by recent processes. (a) Mount Baigurez known in the literature as the right slope of the Cheptsa River valley near the settlement of Debesy (photo image by the author); (b) landslide on the left slope of the Vyatka River near Krymskaya Sludka (photo image by I.I. Grigor'ev by means of a quadrocopter).

shear wall were recorded in 2012 (17.1 m) and 2005 (16.9 m). They were also high in 2011 (7.8 m), 2009 (5.8 m), and 2023 (5.5 m). The total average retreat of the shear wall over the past 21 years was 42.2 m [31].

Based on the analysis of topographic maps, this area is a relatively straight section of a gentle segmental bend with a maximum steepness downstream. It corresponds to the location of Krymskaya Sludka, where, according to local long-lived residents, seven streets along with houses and a church have been washed away over the past 70–75 years. According to the archive maps, the distance between adjacent streets is about 40–50 m. Hence, the average annual erosion rate is approximately no less than 5 m/yr confirmed by our observations. The lateral erosion rate of floodplains and terraces by river channels reaches 10–15 m/yr in large rivers, 3–5 m/yr in medium-sized rivers, and less than 1 m/yr in small rivers [32].

The most common river channel form within the studied region is meanders. Their proportion in the territory of Udmurtia is 77%, on average [23]. They are very diverse in terms of genesis and outward appearance. According to the classification [33], the rivers of Udmurtia are dominated by wide floodplain channels characterized by free meandering and an absence of restrictions from the valley's bedrock slopes. The upper and lower areas of the rivers are characterized by relatively straight unbranched channels reaching from 16% (Siva River basin) to 28% (Izh River basin).

The proportion of segmental bends with longitudinal displacement averages 62%. Their high number is indicative of various developmental stages of the bends and is indirect evidence of active transformation processes of the meandering channel as a whole. Some rivers are distinguished by all three development stages of the segmental bends: from gentle to steep.

The construction of water reservoirs in the valleys of large rivers led to replacement of channel processes by destruction related to wave activity. The banks, composed of loose Quaternary deposits with various genesis, mainly clayey and sandy loam, were transformed more actively. They retreated in parallel toward the watershed at an average rate of 1–2 m/yr and had an almost vertical cliff the base of which corresponded to the water level in the water reservoir [19].

Since the mass development of the study area began only in the seventeenth century, its surface underwent a considerable impact of economic activity. For this short period of time, forests decreased by more than two times, and 60–70% of the areas cleared of forests were converted into arable land. This activity dramatically increased the soil erosion from plowed slopes. The formation process of gullies and ravines on plowed slopes was intensified.

Gully erosion is one of the most dangerous natural and man-induced terrain-forming processes causing great damage to agriculture and the surrounding landscape. Gullies result in erosion, transit, and accumulation of sediments from their catchments, and they contribute to the flow of runoff products into the channels of temporary and permanent watercourses. There are more than 4000 gullies within the UR with the total length of more than 900 km, total area of more than 1200 ha and the area of gully-affected lands 4.2 times this value [34]. Agrogenic gullies are most typical for the southern regions of the republic, where their density reaches 500–1000 m/km^2 or more. In the northern regions of the republic, man-made gullies are more widespread [35].

Since 1978, we have continuously monitored different types of Udmurtia gullies developing in various landscape and geomorphological conditions. As of

2023, the monitoring system on agricultural lands includes 169 gully tops located in 28 key areas. At most sites (127 gully tops), the observations are carried out once a year (in summer), and at nine key sites (42 gullies), the measurements are carried out twice: in May, after the snow melts, and in October, after the end of the summer–autumn rainfall season [36–38]. The linear, area, and volume indicators of erosion in gullies were calculated on the basis of geodetic surveys using electronic tacheometers and unmanned aerial devices.

All gullies included in the monitoring network were divided into two groups: slope and bottom gullies. The slope gullies were divided into three types: watershed gullies including all gullies developing on the slopes of interfluvial spaces (Fig. 11a), balkas (small dry valleys) wall gullies (Fig. 11b), and river valley wall gullies (Fig. 11c). Bottom gullies include apex gullies in the upper reaches of balkas and hollows (Fig. 11d), gullies at the bottoms of balkas (Fig. 11e), and gullies on the river floodplains (Fig. 11f).

Over the entire 46-year observation period, against the background of a general downward trend, four well-defined peaks with maximum values refer to the first observation stage from 1978 to 1997 (Fig. 12). An increased retreat rate of the gully tops in these years was due to a high flood runoff rate and a considerable proportion of arable land in the gully catchments [33].

The maximum annual growth rate of agrogenic gullies is over 80 m/yr, and that of manmade gullies is over 200 m/yr. The secondary gullies develop more actively than the primary ones (Fig. 12). This fact can be explained by their larger drainage areas and easily eroded loams of the balka alluvium. Among the primary varieties, watershed gullies are the most active, and among the secondary varieties, the bottom gullies.

The more than fourfold reduction in the linear growth rate of the tops of agrogenic gullies in 1998–2023 compared to the previous monitoring period (1978–1997) is due to a considerable decrease in surface runoff from their catchments during the spring snowmelt in turn related to a decreased soil freezing depth in the winter months. Meanwhile, the linear growth of gullies in the period of rainfall runoff slowed down just slightly. This process ultimately led to a more than twofold increase in the proportion of rainfall runoff from 20% in the period of 1978–1997 to 47% in the period of 1998–2017 [39].

The distribution of balkas in the Vyatka–Kama interfluve is drastically different. The density of gullies rapidly decreases northward to almost complete disappearance, whereas that of balkas, on the contrary, increases. With the average density of gullies (0.98 km/km^2 throughout the entire region), in the Kama region of Tatarstan and Southern Udmurtia, their density does not exceed 0.5 km/km^2. In the north of Udmurtia, it is close to 1.0, and in the Perm Kama region, it is more than 1.0 and even reaches 2.25 km/km^2. Similarly, the maximum density values vary across the region, exceeding 2.0 and even 4.0 km/km^2 [40]. Depending on their morphology and age, these balkas are divided into ancient (Pleistocene) and recent (Holocene). When overgrown, current gullies gradually turn into ravines [41]. Balkas are stable erosion forms with grassed slopes and bottoms, usually used as hayfields and pastures.

Karst and suffusion sinkholes are local in the described area. The former are confined to outcrops or areas where carbonate rock (limestones and marls) layers are close to the daytime surface. They are described in the limestone mining area near the Gornyak Settlement in the Mozhga district and near the Kiyasovo Settlement. They are usually within 2–3 m deep and about 10–12 m in diameter. Suffusion sinkholes and funnels are much more common. Scientists describe suffusion as a complex physical and chemical process that combines dissolution, washout, and erosion processes. Its extreme process is simply the mechanical removal of small particles and aggregates. In general, mechanical suffusion removal is primarily related to sand deposits, where its action consists in removal of individual particles from pores and in sand loosening and subsequent removal. They develop especially actively in man-made soils under asphalt pavement, where their consequences and development rates are increased by static and dynamic loads, and, less often, in alluvial deposits [42].

6. CONCLUSIONS

The Udmurtia landscapes are characterized by a wide variety of landforms both inherited from ancient events of geological history and produced by recent exogenic processes. Tectonic structures are observed in the terrain as both direct and inverted morphostructures. Cuesta-like ridges are characteristic landforms. An important feature of the terrain is its stepped nature as a reflection of the latest rhythmic tectonic movements. The high step known as the "upper plateau" more than 250 m above sea level is well-defined. The predominant step termed as the "lower plateau" is elevated at of 180–220 m a.s.l. The lowest step—the "Pleistocene planation" level 140–160 m m a.s.l., including the high (third and fourth) river terraces—is related to the pre-Venedian revival phase of tectonic movements in the first half of the Neopleistocene.

A very specific relict small-hill terrain was formed within the region described. Small hills composed of a gravel and pebble material have been called "*pugas*" since the end of the nineteenth century. The *puga* deposits are proved to be sediments of ancient Late Permian and Triassic rivers, while the *pugas* proper are inversion forms.

The relict morphosculpture was formed in periglacial conditions under the indirect influence of ice sheets. The Pleistocene terraces of the periglacial zone consist of two sequences. The lower part of a terrace

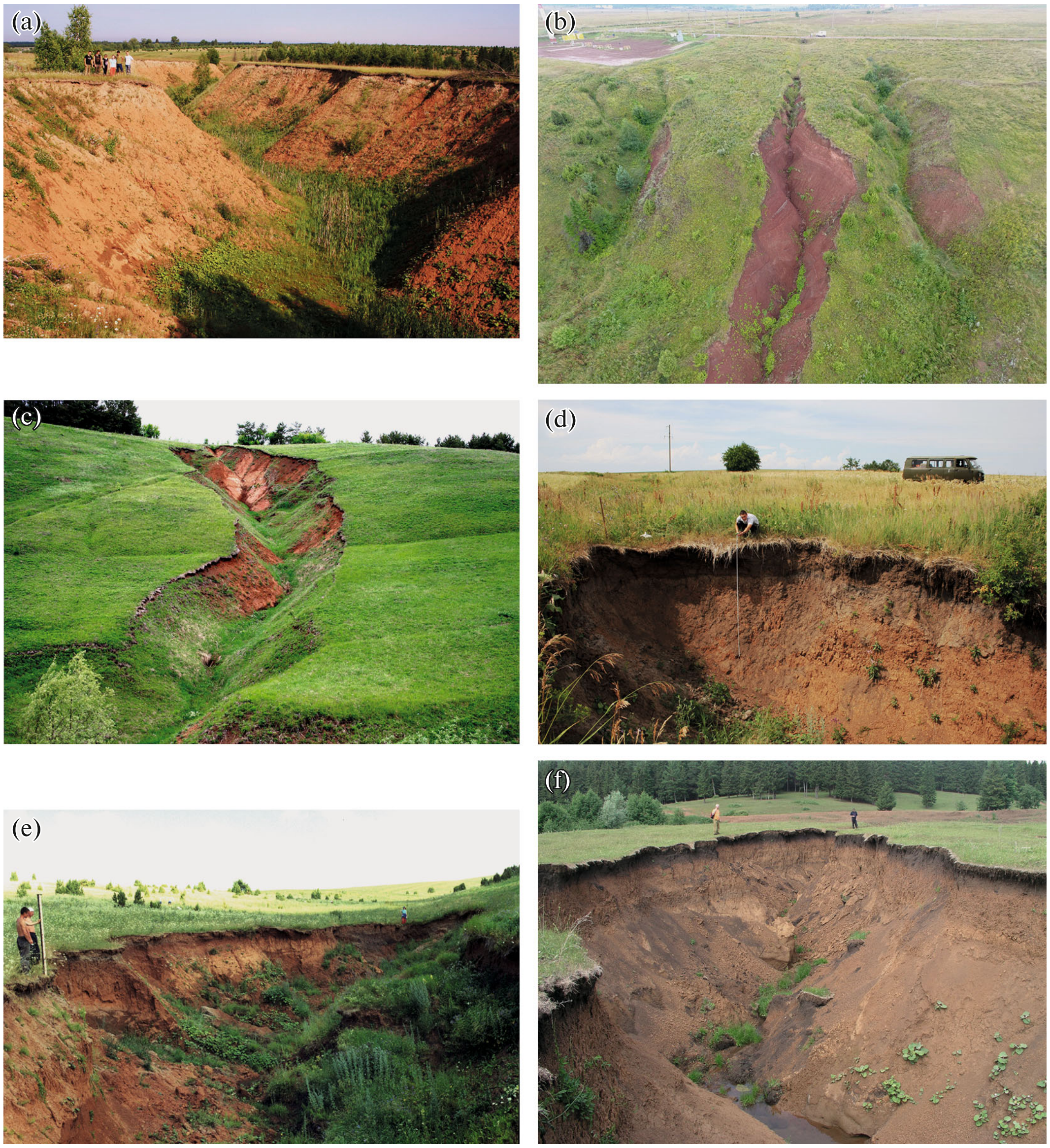

Fig. 11. Types of gullies in the eastern part of the Russian Plain. Slope gullies: (a) watershed, (b) valley-wall, (c) balka (small dry valley) side. Bottom gullies: (d) balka/hollow source, (e) balka bottom, (f) river floodplain.

section is composed of facially variable interglacial alluvium that is overlapped by a periglacial alluvium, which is dominated by fine-grained material (sands, siltst, and loams) having a thin horizontal, occasionally very specific, interlaced lamination. The periglacial alluvium is 2–3 times thicker than the interglacial alluvium.

A classic example of relict features in the region is asymmetric form of cross-sections of the valleys of small and medium-sized rivers. The slopes of valleys faced to warm directions (to the south and west) are steeper than the opposite ones. River valleys in Udmurtia are divided into three types: valleys of large rivers of ancient origin, valleys of medium-sized rivers with a full complex of Quaternary terraces, and valleys of small rivers. Each river valley type is characterized by the morphology and composition features of the sediments that make up floodplain and river terraces, depending on their age. Permafrost forms of the relict morphosculpture are observed as a polygonal–block and depression microtopography. Cryogenic–nival niches and cirques developed on steep high slopes of river valleys and cuesta benches. The slopes of river valleys are covered by an apron of slopewash–solifluction deposits; they are widespread and are composed of relatively thick (from 3–5 to 30–38 m) loams. Eolian landforms are observed as sand covers and dunes 8–12 m high.

The current morphogenesis processes are dominated by river channel deformations and gully erosion.

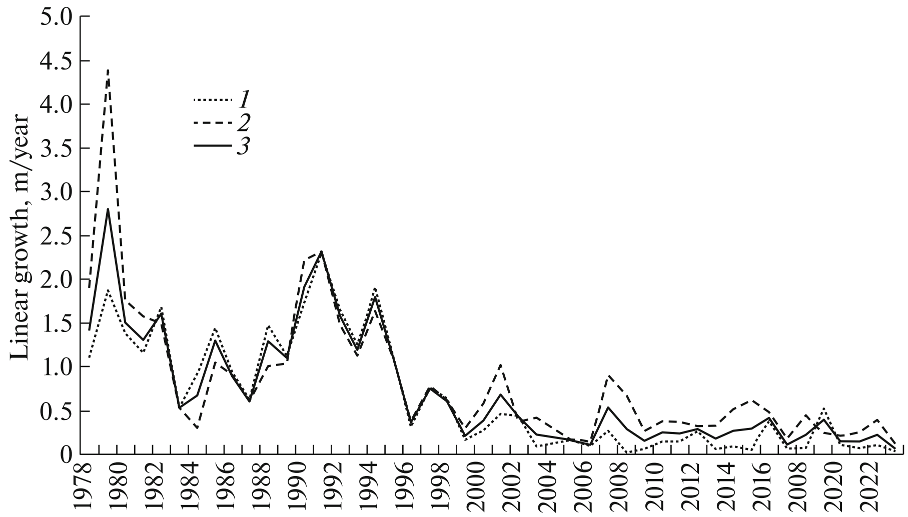

Fig. 12. Average annual growth velocity of gullies in Udmurtia in the period 1978–2023. (*1*) Slope gullies, (*2*) bottom gullies, (*3*) all gullies.

The bank erosion rates of floodplains and terraces in large rivers reaches 10–15 m/yr; in medium-sized rivers, 3–5 m/yr; and in small rivers, less than 1 m/yr. Present-day (active) and overgrown landslides are common on steep slopes of large rivers. The retreat rate of shear walls of active landslides exceeds 12–15 m/yr. There are more than 4000 gullies within Udmurtia with a total length of more than 900 km and occupied area of more than 1200 ha, and the area of gully-affected lands 4.2 times this value. Agrogenic gullies are the most typical for the southern regions of Udmurtia, where their density is 500–1000 m/km^2 or more. In the northern regions of the republic, technogenic gullies are more widespread. A more than fourfold reduction in the linear growth rate of the agrogenic gully tops in the period 1998–2017 compared to the previous monitoring period (1978–1997) is due to a significant decrease in surface runoff from their catchments during the spring snowmelt in turn related to a decrease in the soil freezing depth in the winter months. Meanwhile, the linear growth of gullies in the period of rainfall runoff decreased just slightly, which ultimately led to a more than twofold increase in the contribution of rainfall runoff from 20% in 1978–1997 to 47% in 1998–2017.

The distribution of balkas (small dry valleys) in the area described is drastically different. The density of gullies decreases rapidly northward to almost complete disappearance, whereas that of balkas, on the contrary, increases to 2 km/km^2 or more. The banks of reservoirs composed of unconsolidated Quaternary deposits are destroyed actively as a result of erosion and retreat with an average rate of 1–2 m/yr. Karst and suffusion forms are local in this area due to the unfavourable geological conditions.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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