RESEARCH PAPER

KARST LANDFORMS OF THE SINYAYA RIVER VALLEY, PRILENSKOE PLATEAU

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ABSTRACT. Unique karst evolution in Siberia is attributed to climatic factors and the presence of permafrost. Climatic fluctuations in Northern Eurasia had occurred during the Quaternary period and significantly influenced the processes of permafrost aggradation and degradation, as well as the karst activity. Despite their wide popularity and impressive manifestations, the karst landforms on the Prilenskoe Plateau still remain tenuously studied in terms of landform classification and obtaining their morphometric characteristics. The article presents the results of field studies of karst terrain in the Sinyaya River valley in Central Yakutia. Based on field observations and the analysis of the generated digital surface models, we have determined the median relative heights of different types of karst ridges in the Sinyaya River valley: "incipient ridges" - 34 m, "young ridges" - 42 m, "mature ridges" - 79 m and "old ridges" - 58 m. Most ridges that exceed 100 m are "mature and old". The highest ridges are located on the concave parts of river meanders and belong to the type of "mature ridges". In addition, our observations in the Sinyaya River valley have shown "old ridges" are the most common, accounting for over 58% of the overall ridge length. "Mature ridges" make up approximately 25%, "young ridges" 13%, and "incipient" ridges only 4% of the total. This distribution reflects the long history of topographic development in the valley and the significant influence of erosion processes on these features. The most prominent forms of this landscape include karst ridges, which present as rock pillars formed through physical and chemical weathering, with very active frost shattering, gravitational, and erosion processes. Using field surveys conducted with unmanned aerial vehicles (UAVs) and subsequent processing in a geographic information system (GIS), it was determined that the highest ridges are located in the lower reaches of the Sinyaya River, where it cuts through the axial, most elevated part of the Prilenskoe Plateau. The morphometric characteristics of the identified types of karst ridges and their spatial change along the river meanders are associated mainly with the activity of lateral river erosion, which ensures the removal of weathering material and slope deposits.

KEYWORDS: karst landforms, Siberia, Sinsky Pillars, Prilenskoe Plateau, karst ridges, weathering

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INTRODUCTION

Modern karst study is conducted in a wide range of disciplines, including both the study of karst landform entanglement with lithology and tectonics and a set of environmental problems associated with karst development, land and soil degradation, changes in vegetation cover, and connections with water supply (Gillieson et al. 2022; Zhang et al. 2022; Saroli et al. 2022). Researchers use new methods to study karst topography, such as unmanned aerial vehicle (UAV) surveys for constructing digital elevation models and obtaining detailed karst landform characteristics (Silva et al. 2017; Doumit and Ghanem 2021; Kim and Hong 2024). The studies are mainly devoted to the tropical and subtropical karst or karst landforms in temperate climate. There is a lack of modern publications on karst in permafrost.

Sinsky Pillars within the Prilenskoe Plateau were inscribed on the List of UNESCO World Heritage[1] in 2016 as a part of National Park Lena Pillars. In the middle and lower reaches of the Sinyaya River, various karst forms are present, including high pillars (Fig. 1a). Karst ridges are confined to both sides of the meandering river (Fig. 1b, c). Sinsk Pillars are not directly related to the SDGs (Sustainable

[1]UNESCO World Heritage Convention (2012), https://whc.unesco.org/en/list/1299/documents/

Development Goals)[2] themselves. However, their significance as a UNESCO World Heritage Site, particularly for their geological and paleontological value, indirectly contributes to several SDGs, especially those related to environmental sustainability and knowledge, Sinsk Pillars connect to the SDGs. SDG 15 Life on Land serves as a prime example of geological formations and ecosystems that deserve protection and preservation. They showcase the planet's history and contribute to biodiversity conservation. SDG 13 Climate Action. The study of the Sinsk Pillars can offer new perspectives on past climate changes and the long-term impacts of environmental processes, aiding in understanding and mitigating current climate challenges. SDG 4 Quality Education - National Park Lena Pillars offers opportunities for educational and research initiatives, raising awareness about the importance of natural heritage and promoting scientific understanding. SDG 11 Sustainable Cities and Communities - National Park Lena Pillars supports ecotourism and sustainable development in local communities, providing economic opportunities while preserving the environment. SDG 17 Partnerships for the Goals - National Park Lena Pillars' inclusion on the UNESCO World Heritage List demonstrates the international collaboration needed to safeguard natural sites and promote sustainable practices (UN SDGs).

STUDY AREA

The distinctive characteristics of the Prilenskoe Plateau karst are attributable to its formation under permafrost conditions, with a thickness reaching up to 500 m (The Foundation… 2011). According to S.S. Korzhuev (1961), permafrost does not stop karst but only slows it down, and water moves freely in strongly fractured limestones and dolomites. In the middle reaches of the Lena River between the mouth of the Vitim River and the town of Pokrovsk, S.S. Korzhuev (1961) identified underground and surface forms of karst: 1) sinkholes, saucers, and baths; 2) caves, niches, canopies, and corridors; 3) disappearing streams and karst springs; 4) karst lakes; 5) ditches of slope subsidence; 6) spots of limestone scaling; 7) clay karst.

In Prilenskoe Plateau, the karst is developed in the Lower Cambrian limestones and dolomites 400-500 m thick (State geologic… 2022), covered by Quaternary deposits in the valleys and on the interfluve area of the Lena, Buotama, and Sinyaya Rivers (Fig. 2a, b). During the Middle Pleistocene ~400 ka Prilenskoe Plateau has been uplifted 150–300 m above the regional base level of erosion (Tolstikhin and Spektor 2004; Lena Pillars… 2012).

The climate of the region is strongly continental; as reported by the Pokrovsk meteorological station, there has

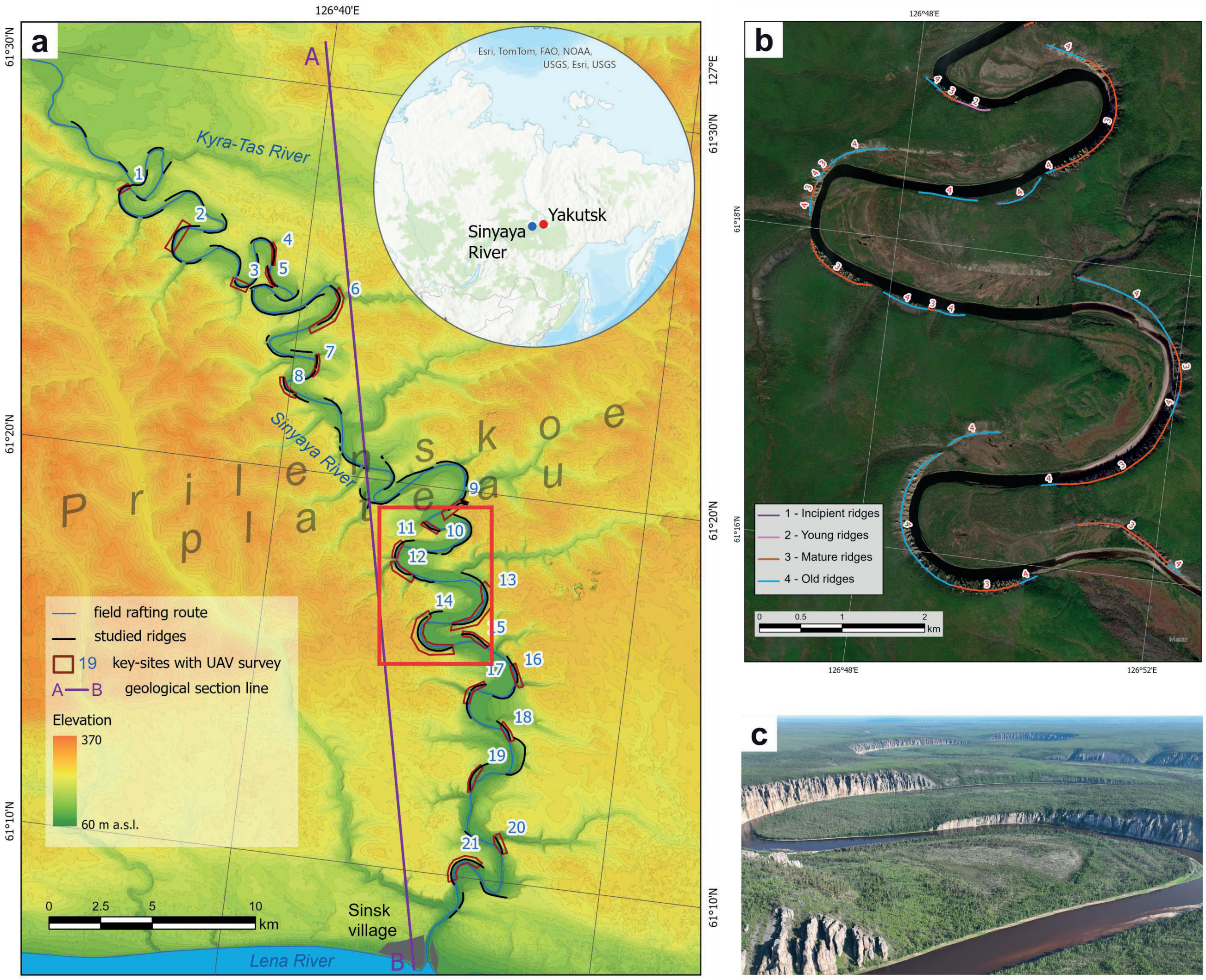

Fig. 1. Study area. a - the area of karst landform field studies in the Sinyaya River valley in 2023 and key sites with UAV surveys. ArcticDEM Mosaic (Porter, Claire et al., 2023) is used as elevation data, b - spatial distribution of ridges of various types along the Sinyaya River valley (a red rectangle on a). The map is based on ESRI Basemap World Imagery; c - areas of surface karst with ridge formation are confined to the areas of undercutting of the valley sides of the actively meandering Sinyaya River valley

[2]UN THE 17 GOALS, Sustainable Development, https://sdgs.un.org/goals

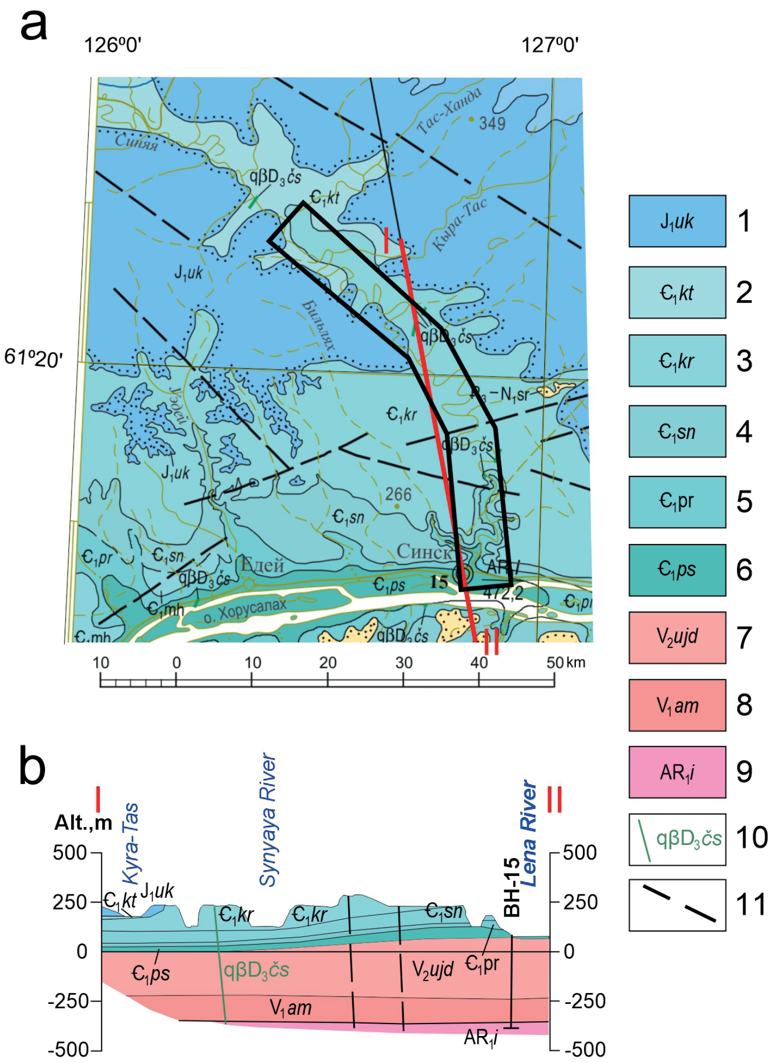

Fig. 2. Pre-Quaternary geology of the key site: a - fragment of the geological map scale 1:1 000 000; b - deposit cross-section. 1 Early Jurassic *Ukugut formation*; 2-6 Early Cambrian formations: *Keteme, Kutorgin, Sinsk, Perekhod, Pestrocvet*; 7-9 Precambrian formations: *Udoma, Amga, Iengra*; 10 Late Devonian diabase dykes; 11 Fault lines

been an increase in the average annual air temperature from -9.4 to -7.5°C between 2006 and 2023. The long-term average temperature of the coldest month, January, is -38.1°C, while the warmest month, July, has an average temperature of +19.2°C. The annual precipitation on average is 268 mm, with more than half of this amount falling during the warm season. The northern part of the Prilenskoe Plateau is distinguished by the presence of continuous permafrost, with a thickness of up to 400 m. In this region, the mean annual ground temperature is recorded to be -5°C. In contrast, the central part of the Prilenskoe Plateau exhibits a discontinuous permafrost, with a thickness ranging from 50 to 300 m. The mean annual ground temperature in this area varies from -1 to -4°C (Spektor et al. 2009).

For the Lena Pillars (and they are similar for Sinsky Pillars) M. Veress obtained 4 phases of development (Veress et al. 2014). Phase 1 – process of karstification occurred during a period of warmer climate conditions than are observed today, a time before the development of permafrost. Consequently, it was possible to form a karst water zone within the rock formation. The karst water level was situated close to the surface, with the karst surface exhibiting a height that was only marginally higher than the base level of erosion. The surface's altitude was therefore low, and the Lena had not yet undergone downcutting processes. Consequently, the development of caverns occurred in close proximity to the surface, with the formation of these caverns being driven by the presence of fractures. The process of karstification gave rise to a fracture-controlled phreatic network, which in turn gave rise to the formation of narrow, vertically developed corridor networks. These networks were characterized by the development of grikes on the surface, which were aligned perpendicular to the fracture systems. This resulted in the rock being dissected into clints, bordered by a grikes system. Phase 2 – the karst water table sank due to the uplift of the area. The deepening of the grikes resulted in the floors of some grikes reaching the caverns. The coalescence of the caverns and grikes occurred due to the caverns exceeding the water surface during this period. Consequently, the formation of giant grikes was initiated. The development of pinnacles from one part of the clints occurred during the dissolution of grike walls. Phase 3 – grikes were filled and buried. Phase 4 – the Lena River underwent a period of development, resulting in the destruction of some grikes and clints due to its downcutting activity. This process exposed the feature assemblage, leading to the partial destruction of the filling sediment in the remaining grikes. The walls of the exposed grikes exhibited potential for widening through frost weathering. The development of newer pinnacles was observed, indicating a transformation in the rock features of the pillars and the remaining karstic features. These features underwent destruction or transformation due to frost weathering, mass movements, sheet wash, and gully erosion. This ongoing process is a contemporary phenomenon.

The karst landforms in the Sinyaya River valley are concentrated in the part where it crosses the Prilenskoe Plateau. Various surface and underground karst features are prevalent along the Sinyaya River valley, including funnels, ponors, karst lakes, karren, karst niches, canopies, caves, sinkholes, and karst remnants (Trofimova 2012). Morphological classification of karst landforms of Lena Pillars was performed by E.V. Trofimova (2012, 2013, 2017, and 2018). She identified 4 types of karst ridges, using a description of their morphological features without numerical characteristics, which could be collected only on the basis of processing a significant number of sites. E.V. Trofimova noted that a comprehensive geomorphological survey and mapping of morphometric characteristics of karst features is still lacking (Trofimova 2012). In our research, we decided to rely on the classification proposed by E.V. Trofimova, since this is currently the most relevant classification developed specifically for the study area. It should be noted that Veress et al. (2014) conducted a morphological classification but for individual karst landforms - rock pillars.

The objective of this research is to provide a comprehensive description of the karst features found in the Sinaya River Valley, which exhibit various stages of development. The specific tasks include: 1) acquiring quantitative morphometric data regarding karst ridges; 2) validating the distinctions among the types identified by E.V. Trofimova based on this data; 3) identifying patterns in the spatial distribution of the different ridge types; and 4) characterizing the array of processes that influence the topography in karst regions.

MATERIALS AND METHODS

In June 2023, field route observations were conducted on the lower section of the Sinyaya River that passes through the Prilenskoe Plateau. (Fig. 1a). During the rafting expedition on the river, field descriptions and mapping of karst formations were conducted, along with photo documentation with GPS tracking and the capture of key sites using a UAV. The total length of the route was 126 km. The field studies utilize the approaches related to the stages of relief formation (Davis, 1899) and morphometric analysis of the relief (Simonov 1998; Simonov 1999). A UAV survey was undertaken at 21 key sites without ground control points. We captured high-resolution images of karst features using the DJI Mavic 3 drone with a 20 mpx Hasselblad 4/3 CMOS camera. Vertical and perspective shooting modes were used. UAV survey data were processed using Agisoft PhotoScan software based on Structure-from-Motion (SfM) photogrammetry. This way, point-cloud models, 3D and digital surface models (DSMs) were created with a spatial resolution of 0.1–0.2 m for each key site. The relative accuracy of the adjustment of the created point clouds, as reported by Agisoft for all key sites, is as follows: the root mean square (RMS) for reprojection errors ranges from 0.1 to 0.13 m, while the maximum errors range from 0.3 to 0.4 m. These DSMs were used to analyzed morphometric characteristics, such as the relative heights of ridges and rock pillars. Measurements of relative heights of karst ridges and rock pillars in our study were carried out with an accuracy of 1 m, ensured by the accuracy of the created point clouds and DSMs. To extract the heights from DSMs, the standard ArcGIS Pro Profile tool was used.

Through analysis of field data, including information from UAV surveys, photographs, and field descriptions, as well as very-high-resolution satellite imagery from the ESRI basemap (World Imagery), areas of rock ridges along the Sinyaya River Valley have been identified. Additionally, the segmentation of karst features by age, morphometric, and morphological characteristics has been carried out (Fig. 1). To characterize the topography of the area along the Sinyaya River valley, we used ArcticDEM Mosaic data with a spatial resolution of 2 m (Porter, Claire, et al., 2023). Ridge heights for the non-drone surveyed areas were measured using the Profile tool module in QGIS software. Elevation differences from the top of the ridge to the bottom of the slope were extracted from the profiles. Statistical analyses were performed in R (Samsonov 2024). The *tidyverse* package was used to determine the spatial distribution of ridges along the river. The *ggplot2* package was used to construct the graphs.

RESULTS

Following the classification introduced by E.V. Trofimova (2013), two distinct groups of karst features have been identified: surface and underground features. Surface features encompass positive forms like ridges, individual rock remnants, and pinnacles, along with negative forms such as cracks, corridors, and sinkholes. On the other hand, underground features include canopies, niches, caves, and tunnels. According to E.V. Trofimova (2013, 2017), positive landforms such as ridges can be classified based on their age, morphometric, and morphological characteristics. These categories include “incipient”, “young”, “mature”, and “old” ridges (Fig. 3). Table 1 (Appendix) provides photographs that depict the distinct features and differences between these identified ridge types.

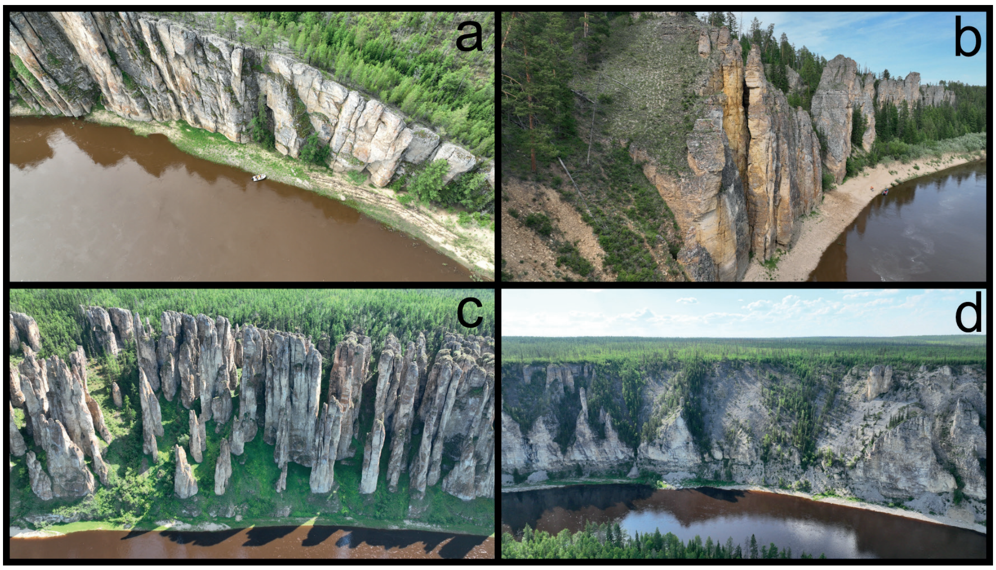

Fig. 3. Categories of ridges on the Sinyaya River Valley: a – incipient; b – young; c - mature; d – old

The "incipient ridges" are linear morphostructural elements that delineate the limestone cliffs. They are minimally cut by denudation and present nearly continuous cliffs with rare cracks. The altitude difference of "incipient ridges" between the summit and their base can reach 52 m with the rock's blocks from 15 to 28 m height. Primarily situated along the Sinyaya River banks, these ridges are located in places where the riverbed has arrived recently. "Incipient ridges" are directly cut by the river erosion, often resulting in the absence of a stable accumulative beach.

The "young ridges" are the next stage of the landform's transformation process due to denudation. These ridges mainly look like subvertical cliffs that are divided into blocks by cracks and erosion cuts. The height of" young ridges" can reach 113 m above the water, and the height of rock pillars can be up to 60 m. As well as "incipient", the "young ridges" are also located along the river bank.

"Mature ridges" mark the stage of significant separation of the limestone massif by karst and other denudation processes, which leads to the formation of a series of rock remnants. "Mature ridges" represent the most impressive positive karst landforms, including pronounced groups of banshee-shaped pinnacle pillars of various morphologies as needle-shaped, cylindrical, cone-shaped. They can be either standing alone or merged in the base, forming peculiar brushes or short ridges. Even within the same area, pinnacles differ in both morphology and height. In the studied areas, the relative heights of the pillars vary widely, from 20 to 124 m (the maximum heights of the "mature ridges" pillars are discovered within the key-site № 11).

For "old ridges", a characteristic feature is the presence of remnants or single pillars on the slopes, surrounded by a debris cover. "Old ridges" can be found either at a distance from the current position of the riverbed, such as on the periphery of meanders, or in areas where lateral erosion is not active now. Initially, "incipient ridges" are aligned along the meandering riverbed. Due to karst, slope, and erosion processes, these ridges divide into blocks that form short transverse micro-ridges perpendicular to the riverbed. Such a series of linear, elongated, halted ridges without mutual orientation can often be found within "old ridges" with an uphill gradient of up to 30-35°. Remnants can be represented by low cones and pillars. The relative height of pillars above the surface of the slopes, varies mainly depending on the age of the ridges, ranging from a few up to 92 m (the highest pillars of "old ridges" are discovered within the key-site № 14). It should be noted that local "rejuvenation" of ridges can occur in areas where the riverbed, as a result of meandering, begins to erode the base of an "old ridge" intensively, leading to the removal of the debris cover and the formation of a subvertical cliff of limestone at the base of the slope directly near the river.

In addition to the selected types of ridges, there are also intermediate states. Often, within the same extensive ridge, transitions between these selected types are observed, as well as alternating fragments. Several intermediate stages between "mature" and "old" ridges cover areas with varying degrees of erosion of limestone massif, their relative elevation above the surface of the slopes, and the proportion of areas of rock remnants compared to the debris covered slopes around them.

The median height for "mature ridges" is 79 m (the maximum is 134 m), and for "old ridges" - 58 m and 125 m, respectively. If for "mature ridges" these values characterize, among other things, the height of steep cliffs and pillars (which sometimes approach the full height of the ridge), then for "old ridges" this is the difference in height from the foot of the slopes (often covered with clastic material) to bedrock outcrops in the upper parts of the valley slopes. The heights of rock pillars within the "old ridges" are much lower and range from a few meters to a few tens of meters (Appendix).

"Incipient" and "young ridges" are lower than the other two types, which is reflected both in the maximum values (86 m and 104 m) and in fairly similar median heights (34 m and 42 m for "incipient" and "young ridges", respectively).

The "incipient ridges" are mainly localized in the middle part and the beginning of the second half of the observed part of the Sinaya River valley (Appendix), which corresponds to the most elevated part of the Prilenskoe Plateau. In this part, the river is intensively meandering, and along the bends, a long section of karst ridges is formed, which, according to morphological and morphometric characteristics, are segmented into several types. "Incipient ridges" with steep, weakly dissected cliffs mark the areas where the river channel has shifted relatively recently.

"Young ridges" are distributed along almost the entire length of the study part of the valley, mainly in the beginning and middle, the median value of appearance is located in the first half. Karst ridges of this type are beginning to appear in the upper part of the river. Closer to the mouth of the Sinyaya River, this type of ridges disappears; "mature" and "old ridges" prevail there. We assume that such a change in the occurrence of ridges of different types along the river is associated with a change in the intensity of lateral erosion and the restructuring of meanders due to the flattening of the longitudinal profile of the river as it approaches the mouth.

DISCUSSION

The methods we applied to obtain data on the morphometric characteristics of the landforms, using UAVs and GIS analysis, enabled us to gather information about both the height of karst ridges and rock pillars, as well as the spatial distribution of landforms and the relationship with a complex of relief-forming processes in the study area. The use of optical and LIDAR survey data from UAVs is widely used to study the topography, also in areas with karst landforms (Silva et al 2017; Kim and Hong 2024). Our study also fits into this context. Methods of morphometric data extraction and landform classification based on DSM are actively developing (Cao et al. 2023). A similar approach and automation of algorithms for remote sensing data processing and DSM analysis is a promising direction for further research.

The study area topography is the result of the joint development of relief-forming processes: 1) karst related to dissolution of carbonate rocks, 2) physical weathering, 3) fluvial processes, and 4) gravitational (slope) processes.

Karst activity is facilitated by fracturing limestones in the area of supra-permafrost groundwater. Deeper penetration of cracks contributes to the formation of vertical karst features because water dissolves minerals along the cracks and warms the permafrost. The cryogenic factor of physical weathering is most clearly manifested during cycles of systematic freezing and thawing. There are two main mechanisms of cryogenic weathering (Konishchev 1981) here: 1) frost weathering, when ice freezing in cracks splits frozen rocks into coarse fragments - blocks, rubble, debris; 2) cryohydration weathering, when the disjoining pressure of capillary water in microcracks when changing the phase state of water crushes and grinds the clastic material into small fractions of silty and fine sand grain sizes. Rock fragments disintegrated by physical weathering are thus prepared for further movement by other relief-forming processes.

Clastic rocks are moved on slopes under the influence of gravity in various forms and are transported by the action of flowing water in streams and rivers. Within the fragments of "old ridges", the slopes surrounding isolated rocky outcrops are covered with a stone coarse clastic cover. Various types of mass movements are observed. These debris fields creep like kurum stones due to the accumulation and melting of ice under the active layer. In sites where coarse clastic material is presented with finely dispersed loamy filler, in the case of local excessive water saturation, some types of landslides occur in the forms of translational landslides or debris avalanches (Fig. 4).

Among the fluvial processes determining morphological features of the karst landforms of the Sinyaya River valley, it is necessary to highlight the lateral erosion leading to the undercutting of carbonate rock outcrops on the concave parts of modern river meanders (Fig. 1c).

In some sites there is no beach, and a vertical rock cliff goes below the river's water level. In these cases, dissolution of limestone complements the activity of lateral erosion (Fig. 5). On the apex of the river meanders, significant karst landforms with rock pillars are located (Appendix, Table 1).

On the periphery of modern river meanders, along the sides of the valley with adjoining floodplain terraces, the absence of lateral erosion activity in the river leads to a decrease in the dissection of the terrain. More "mature" ridges are located here, the modern development of which is dominated by the role of karst proper, physical weathering of rock, gravitational processes which determine the movement of clastic material on slopes.

In spatial terms, ridges alternate on the left and right sides of the valley without a clearly expressed prevalence. The extent of ridge fragments is determined by the dimensions, primarily the radius, of the river meanders along which they are located. In the transverse profile of the Prilenskoe Plateau, the absolute elevations increase in the middle part, slightly closer to the Lena River valley. This pattern is also manifested in the relative heights of karst ridges. Within the study area, the highest karst ridge height, exceeding 100 m, are located in the second half of the Sinyaya River valley, closest to the mouth (Fig. 6a). Such significant heights are most typical for "mature" and some "old ridges" (Fig. 6b, c).

Within the studied area of the Sinyaya River valley, "old" ridges predominate, their length is 52.2 km, which is more than 58% of the total length of the studied ridges. The length of "mature" ridges is 21.9 km, which is about 25% of the length of all ridges; "young" ridges is 11.6 km (13%),

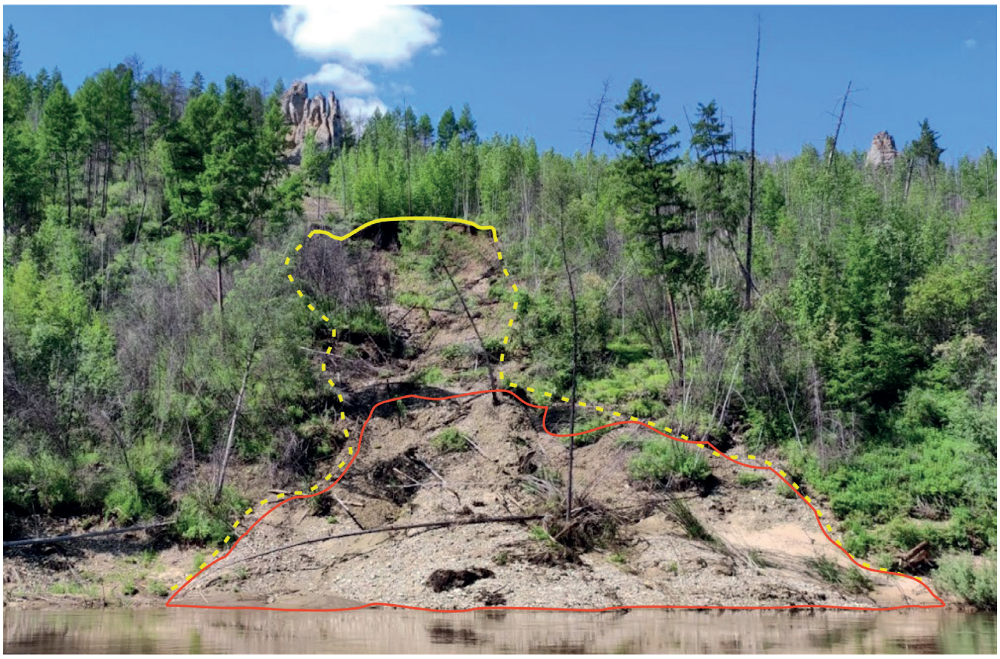

Fig. 4. Landslide (debris avalanche) of coarse clastic material in the section of the «old» ridge. The yellow line indicates the headscarp, the dashed yellow line - the transit zone, the red line - the accumulative landslide body borders

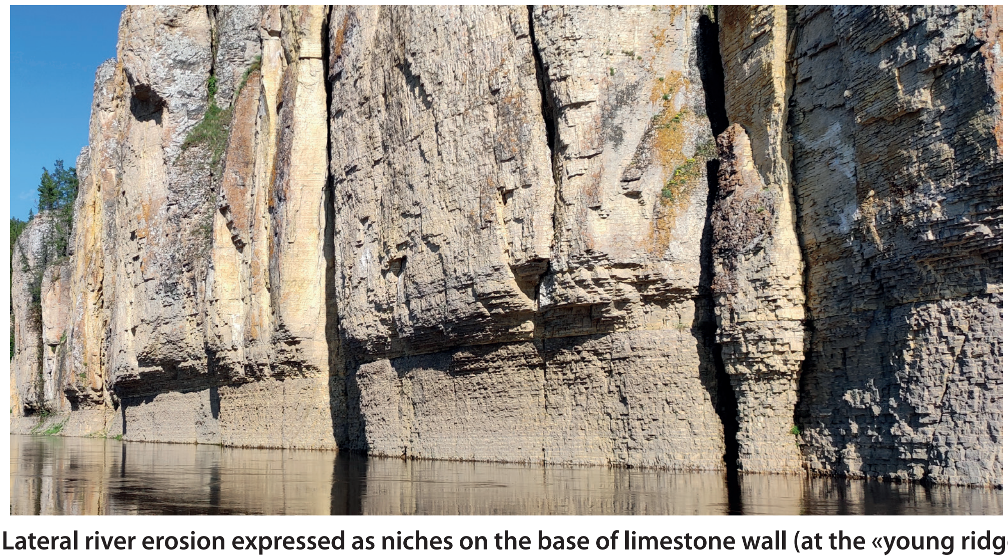

Fig. 5. Lateral river erosion expressed as niches on the base of limestone wall (at the «young ridge" site)

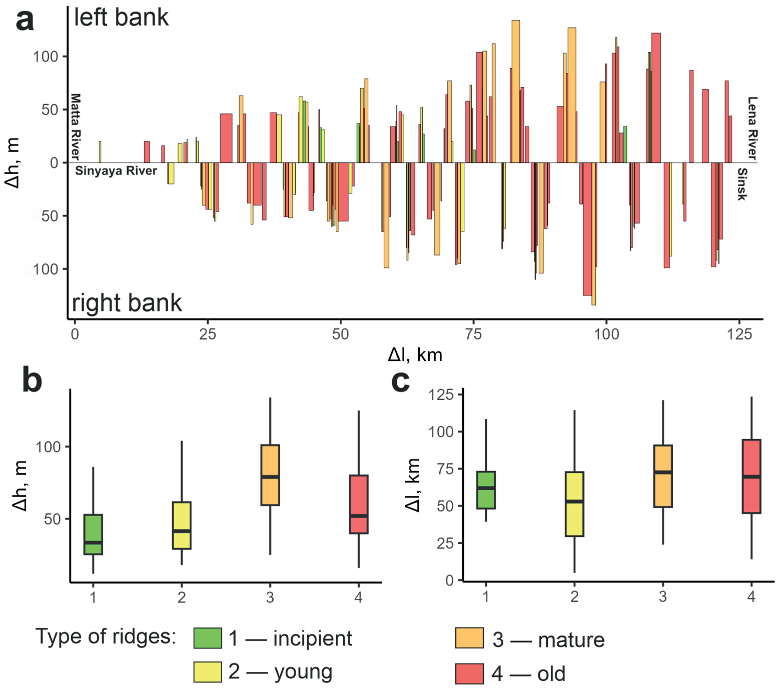

Fig. 6. Spatial analysis of ridge types according to E.V. Trofimova (2013) and their morphometric characteristics in the studied area from the mouth of the Matta River to the mouth of the Sinyaya River: a - location, length, and relative height of all ridge's types; b - height difference from the top level of the ridge to the foot of the slope; c - remoteness of the ridge in the downstream direction from the mouth of the Matta River to the Lena River. Check the Fig. 1 for the ridges' location

"incipient" ridges is 3.7 km (4%). Such distribution indicates a long history of the valley topography formation and a significant impact of denudation processes on the ridges.

There is a unity in the morphology of karst landforms and ridge types with the nearby Lena Pillars, which are included in one generalized region of karst development within permafrost (Spektor and Spektor 2009; Veress et al. 2014). The Lena Pillars region is also characterized by a significant diversity of karst landforms, and E.V. Trofimova (2013) identified ridge types similar to the Sinsky ones. The height of ridges, including rock remnants with vertical walls, reaches 200 m (Trofimova 2013), within which pinnacles up to 100 m high are located (Veress et al. 2014). Such karst landforms are quite rare for temperate latitudes. Alone-standing limestone towers (pillars or pinnacles) are most typical of tropical karst. In Guangxi Province, China, the Guilin karst is characterized by standing alone steep pillar towers up to 100 m high (Tang and Day 2000; Waltham 2008). These rock pillars are rising from an alluvial plain between Yangshuo and Fuli. On the Siberian platform, ancient buried karst is widespread; however, it lacks the striking positive landforms found in the Lena and Sinsky Pillars. On the Patom Plateau, the Proterozoic limestones are dominated by sinkholes, partly transformed into lakes. In the Aldan-Timpton interfluve and in the neighboring regions of southern Yakutia, where karst is developed in the carbonate rocks of the Cambrian, landforms of modern karst are widespread as sinkholes, depressions, funnels, and other negative landforms (Korzhuev 1961; Tolstikhin and Spektor 2004; Spektor and Spektor 2009; Veress et al. 2014; Trofimova 2018; Vaks et al. 2020).

CONCLUSIONS

The karst landforms in the Sinyaya River valley are the result of karst, river erosion, and slope processes paragenesis. These processes interact in a complex way to create a diverse range of landforms and to set their spatial distribution. Each process has varying degrees of influence on the formation of the terrain characteristics, leading to a unique landscape.

As a result of field observations and analysis of the created DSMs, morphometric characteristics of the previously identified types of karst ridges of the Sinyaya River valley were obtained: 1) "incipient ridges" with a median height of 34 m; 2) "young ridges" with a median height of 34 m, 3) "mature ridges" with a median height of 79 m; and 4) "old ridges" with a median height of 58 m. Most of the ridges with a height exceeding 100 m are of "mature" type. In spatial terms, the greatest heights of the ridges are observed where the valley cuts through the most elevated part of the Prilenskoe Plateau. Here, the highest single standing pinnacle pillars reaching 124 m are observed, located within the "mature ridges" (Appendix).

In the Sinyaya River valley "old" ridges are the most prevalent over 58% of the overall length of the examined ridges. "Mature" ridges represented approximately 25% of the total ridge length; "young" ridges 13%; while "incipient" ridges were 4%. This distribution reflects the extensive history of topographic development in the valley and highlights the significant influence of denudation processes on the ridges.

Within the river meander, a consistent change in the types of ridges is observed. "Incipient ridges" are located where the river channel came relatively recently. "Young" and "mature ridges" are located at the concave eroded river banks. "Old ridges" are usually located on the periphery of meanders where the river channel has gone or lateral erosion is not active.

The obtained data could be used in further studies on the stages of karst landform development in permafrost, as well as in regional studies on the terrain dynamics within the Prilenskoe Plateau, providing detailed morphometric characteristics of karst landforms.

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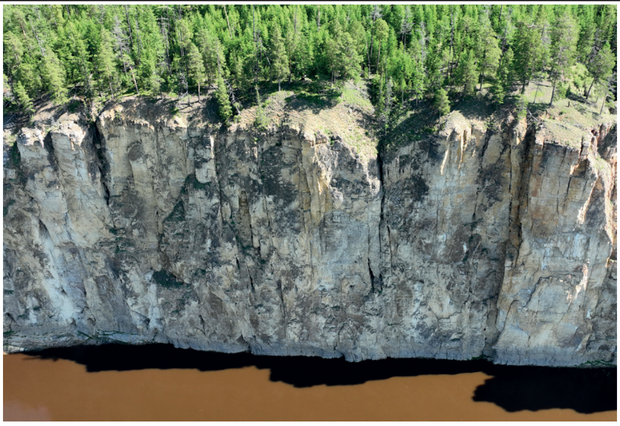
APPENDIX

Table 1. Morphometric terrain characteristics of key-sites with UAV survey

Key area №	Presented ridge types	Elevation difference from the top of the ridge to the bottom of the slope	Relative heights of single standing rock pillars
1	"Old" / and "mature." Behind the first row of the "mature" ridge there is a debris covered slope with forest - the "old ridge". Transitional state between "old" and "mature". Several caves (holes) in the upper part of the remnants	43-49 m	up to 46 m
2	In the upper part of the river meander, a "mature ridge» is located. The wall approaches the river channel, the blocks are cut by slits separating the pillars. In the lower (downstream) part of the river meander there is an "old ridge" represented by several eroded remnants surrounded with a slope with coarse clastic cover, partially forested	- on "the mature ridge" section - 40-74 m (height increases towards the middle part of the meander) - on the old ridge section - 37-50 m	- on the "mature ridge" section - 44-74 m, - on the "old ridge" section - up to 50 m (50 m high single standing pinnacle)
3	In the upper part of the meander there is a rising "incipient ridge". Further located "mature ridge" and after that "old" (remnants surrounded by slopes)	- "incipient ridge" - 25-52 m (height increases towards the middle part of the river meander), - "mature ridge" - up to 62 m, - "old ridge" - up to 68 m	- "incipient ridge" - 15-28 m, - "mature ridge" - up to 29 m, - "old ridge" - up to 44 m
4	"Incipient ridge", "mature" / "old". The "mature" part of the ridge is undercut by the river lateral erosion	- "incipient ridge" - up to 64 m, - "mature ridge" - up to 66 m, - "old ridge" - up to 54 m	- "incipient ridge" - up to 20 m, - "mature ridge" - up to 60 m, - "old ridge" - 14-40 m
5	"Old ridge" / one short fragment of a "young" one	- "young ridge" - up to 40 m, - "old ridge" - up to 44 m	- "young ridge" - up to 22 m, - "old ridge" up to 35 m
6	"Incipient ridge" / "young" / "mature" / "old"	- "incipient ridge" - up to 43 m, - "young ridges" - up to 56 m, - "mature ridges" - up to 73 m, - "old ridges" - up to 68 m	- "incipient ridge" - up to 20 m, - "young ridges" - up to 28 m, - "mature ridges" - up to 33 m, - "old ridges" - up to 25 m
7	"Incipient ridge" / "young" / "old"	- "incipient ridge" - up to 44 m, - "young ridge" - up to 43 m, - "old ridges" - up to 62 m	- "incipient ridge" - up to 19 m, - "young ridge" - up to 30 m, - "old ridges" - up to 15 m (subvertical cliff near the river channel is 15 m high, above there is a slope with debris cover and outcrops of bedrock)
8	"Incipient ridge" / "mature" / "old"	- "incipient ridge" - from 38 to 95 m, - "mature ridge" - up to 100 m, - "old ridges" - up to 100 m	- "incipient ridge" - up to 10 m, - "mature ridge" - up to 64 m, - "old ridges" - up to 45 m
9	Transitional state from "mature" to "old ridge". Highlighted as «mature» in the diagram (Fig.6)	up to 91 m	up to 80 m
10	"Young ridge" / "mature" / "old" The "young ridge" is offset 20-30 m from the river bank; between the bank and the foot of the ridge there is a slope covered with coarse clastic stone material	- "young ridges" - up to 46 m, - "mature ridges" - up to 87 m, - "old ridges" - up to 82 m	- "young ridges" - up to 27 meters, - "mature ridges" - up to 67 m, - "old ridges" - up to 39 m (cliff near the river channel is 39 m high, above there is a slope with debris cover and outcrops of bedrock)
11	"Mature ridges" / "old"	- "mature ridges" - up to 128 m, - "old ridges" - up to 120 m	- "mature ridges" - up to 124 m, - "old ridges" - up to 52 m
12	"Mature ridge". Initial stage of transition from "mature" to "old ridge"	up to 119 m	up to 112 m
13	"Mature ridge". Transitional stage from "mature" to "old ridge". Some fragments of "old ridges"	- "mature ridges" - up to 131 m, - "old ridges" - up to 102 m	- "mature ridges" - up to 117 m, - "old ridges" - up to 52 m

14	Fragments of "mature", and "old ridge". This is also a transitional state. The part of the "mature ridge" is located in the downstream part of the river meander	- "mature ridges" - up to 147 m, - "old ridges" - up to 142 m	- "mature ridges" - up to 90 m, - "old ridges" - up to 92 m
15	"Mature" / "old ridges"	- "mature ridges" - up to 108 m, - "old ridges" - up to 100 m	- "mature ridges" - up to 91 m, - "old ridges"- up to 66 m (cliff near the river from 37 to 66 m high, above there is a slope with debris cover and outcrops of bedrock)
16	"Old ridge" with a fragment of "mature ridge" (transitional state from "mature" to "old") . There are preconditions for more intensive disintegration of the massif	- "mature ridge" - up to 136 m, - "old ridge" up to 125 m	- "mature ridge" - up to 75 m, - "old ridge" - up to 66 m. The river channel undercuts the foot of the slope with the formation of a subvertical cliff from 10 to 27 m high.
17	Fragments of "young ridges", short fragments of "mature ridges" and predominantly "old ridges". There are preconditions for more intensive disintegration of the bedrock massif	- "young ridge" - up to 100 m, - "mature ridge" up to 102 m, - "old ridge" up to 95 m	- "young ridge" - up to 60 m, - "mature ridge" - up to 55 m, - "old ridge" - up to 20 m. The river channel undercuts the foot of the slope of the "old ridges", that form a subvertical cliff 15 to 28 m high. The foot of the "young" and "mature ridges" goes below the water level
18	Fragments of «young", "mature" and "old ridges". "Old ridges" are located along the river bend periphery. In the downstream part of the river meander, the foot of the slope of the "old ridge" is undercut by the river erosion	- "young ridge" - up to 113 m, - "mature ridge" - up to 113 m, - "old ridges" - up to 112 m	- "young ridge" - up to 40 m, - "mature ridge" - up to 54 m, - "old ridges" - up to 42 m. At the foot of the old ridge, a subvertical cliff 14-16 m high has been formed. The foot of the "young" and "mature ridges" goes below the water level
19	The "old ridge" with varying degrees of bedrock remnants in topography (some short parts can be classified as transitional from the "mature ridge"). In the downstream part of the river meander, the foot of the slope is undercut by the river erosion	up to 105 m	up to 50 m A 14-16 m high subvertical cliff was formed at the foot of the ridge in the downstream part of the river meander
20	The "old ridge" with a short fragment in the center, which can be attributed to a transitional type from a "mature ridge". In the downstream part of the river meander, the foot of the slope of the ridge is undercut by the river erosion	up to 96 m	up to 45 m. A 20-31 m high subvertical cliff formed at the foot of the ridge in the downstream part of the river meander
21	The "old ridge" with small fragments in the center, which can be attributed to a transitional type from a "mature ridge". In the upstream part of the river meander, where a low terrace is attached to the foot of the ridge, the lower half of the ridge slope has a subvertical cliff that looks like a "young ridge"	"old ridge" and "mature" fragments - up to 113 m	- "mature" - up to 40 m, - "old" - up to 34 m high. Subvertical cliff 20-31 m high is located at the lower part of the ridge

Table 2. Appearance of selected types of karst ridges

Photo from the ground (water)	Perspective photo from a UAV
1. Incipient ridges	
 	  
2. Young ridges	
	

3. Mature ridges

4. Old ridges