J. Mt. Sci. (2024) 21(9): 3047-3067 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-024-8617-9

Original Article

Evaluation of periglacial landforms and formation of soil properties on the Mount Honaz, SW Türkiye

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Citation: Serin S, Uncu L, Dede V, et al. (2024) Evaluation of periglacial landforms and formation of soil properties on the Mount Honaz, SW Türkiye. Journal of Mountain Science 21(9). https://doi.org/10.1007/s11629-024-8617-9

Abstract: The main aim of this study is to explain periglacial processes on the summits of Mount Honaz (2571 m a.s.l.), define periglacial landforms, and determine the relationships between morphometric features and topographic factors. Mud circles, stony earth circles, non sorted steps, and non sorted stripes were identified on the summits of Mount Honaz. Pearson's correlation coefficient (r) and linear regression analyses were performed by taking metric measurements from 125 periglacial landforms to describe their morphometric features (length, width, height) of periglacial landforms and explain the relationships between them and topographic factors (elevation, slope). To explain the relationships between periglacial landforms and soil properties, soil samples from 11 periglacial landforms were taken and analysed. Periglacial landforms, which continue to develop on the summits of Mount Honaz today, have been evaluated with present climate data. Analysis of soil samples indicates a notable impact of parent material on the genesis of periglacial landforms. The high ratio of organic matter in mud circle and non sorted step landforms and the high lime ratio in stony earth circle landforms prove a strong relationship between the formation mechanisms of landforms and the soil properties. Furthermore, it is consistent with the findings obtained from the analysis that severe periglacial processes and washing and scavenging events are experienced more on the northern slopes.

Keywords: Periglacial processes and geomorphology; Soil analysis; Morphometric analysis; Mount Honaz; Türkiye

Received: 11-Jan-2024
1st Revision: 22-Apr-2024
2nd Revision: 24-Jul-2024
Accepted: 26-Jul-2024

1 Introduction

Periglacial regions are known as areas affected by cold climate processes. In these regions, landforms occur because of freeze-thaw activities. The term periglacial is generally used to describe climatic conditions, processes, landforms, sediment layers, and soil structures associated with environments without glaciers (Lozinski 1909; Brunsden and Thornes 1979; French 2007; Murton 2021). The periglacial belt is in the highest parts of temperate mountains. The balance between mean air and ground temperatures and the presence of water determines the effectiveness of periglacial processes related to permafrost, the active layer or seasonally frozen ground (Serrano et al. 2019). Periglacial environments can occur in two opposing but overlapping regions in terms of formation mechanisms, namely polar areas and alpine periglacial areas at lower latitudes (Harris 1988). Regarding this, while periglacial regions occur in the high parts of mountains in the middle belt, they are shaped in lower areas at high latitudes (e.g., Fukui et al. 2007; López-Martínez et al. 2012; Vandenberghe et al. 2014; D'Amico et al. 2019; Serrano et al. 2020a; Ponti et al. 2021; Melón-Nava et al. 2022; Dobinski et al. 2023; Uxa et al. 2024). Beyond coexisting in specific regions under current climatic conditions, periglacial processes demonstrated effectiveness during cold past conditions as well (e.g., Huissteden et al. 2003; Hubberten et al. 2004; Lehmkuhl 2016; Ruszkiczay-Rüdiger and Kern 2016; Opel et al. 2018; Merritts and Rahnis 2022; Zhang et al. 2023; Magnin et al. 2024).

Scientific studies have been carried out for many years to determine periglacial environments, cold past conditions, and their distribution on the Earth, explain their evolution under current climatic conditions, and create future models (e.g., Washburn 1980; Velichko and Nechaev 1992; Stendel and Christensen 2002; Levavasseur et al. 2011; Vandenberghe et al. 2012; Saito et al. 2013; Oliva et al. 2016; Rivkina et al. 2018; Serrano et al. 2020b; Khani et al. 2023; Carraha et al. 2024). In addition to these studies, geostatistical analyses have been conducted, and the morphometry of periglacial landforms has been tried to be explained using statistical methods in recent years. Thus, inferences about temporal changes have been obtained (e.g., Ballantyne 1996; Hjort and Luoto 2006; Ridefelt et al. 2010; Treml et al. 2010; Feuillet 2011; Křížek and Uxa 2013; Uxa et al. 2017; Serrano et al. 2018; Hughson et al. 2022; Nakai et al. 2023; Fame et al. 2024). Moreover, soil development is very important in periglacial regions and areas with permafrost. During the formation and development of landforms, physical, chemical, and biological processes, their effects and results, and the freeze-thaw activity in the soil have been studied (e.g., Ugolini et al. 2006; Becher et al. 2013; Chaves et al. 2017; Jelinski et al. 2017; Watanabe et al. 2017; Droppo et al. 2022; Liu et al. 2023; Kushnov et al. 2024).

Studies have been conducted to explain periglacial processes, the existence of periglacial landforms, and the geomorphological developments of these landforms in Anatolia (e.g., Turoğlu 2009; Bayrakdar and Özdemir 2010; Türkeş and Öztürk 2008, 2011; Sarıkaya and Tekeli 2014; Dede et al. 2015, 2017; Çiner et al. 2017; Oliva et al. 2018; Çiner and Sarıkaya 2023; Öztürk and Taşoğlu 2024). Additionally, periglacial geomorphology studies have been carried in mountainous areas of this region that are not subject to glaciation but cold climate processes are effective (e.g., Erinç 1955; Bilgin 1960; Erinç et al. 1961; Planhol and Bilgin 1961; Çakır and Kopar 2017; Kızılkaya et al. 2019; Dede et al. 2020, 2021, 2022a, 2022b, 2023, 2024; Turoğlu 2022; Zorlu and Dede 2023; Dede and Zorlu 2023; Dede 2023; Demirağ Turan et al. 2023; Türkeş et al. 2023). The only study examining the periglacial features and landforms of Mount Honaz was conducted by Erinç (1955).

The most important scientific question is how the geomorphological evoluation of periglacial landforms occurred on Mount Honaz. In addition, in terms of understanding the role of periglacial processes, it is important to reveal influences of both cold environmental conditions and cold morphoclimatic processes in creating periglacial landforms on the high mountainous areas in Western Anatolia. Consequently, this study aims to 1) determine the active periglacial processes occurring on the Mount Honaz and explain the development of periglacial landforms, 2) to define and classify the landforms formed under periglacial morphoclimatic conditions, unveiling their current morphometric properties and their development mechanism, and 3) to determine the soil properties where periglacial landforms are formed and developed.

2 Study Area

Mount Honaz (2571 m a.s.l.) is located in the Aegean Region, within the borders of the Honaz district of Denizli province in Türkiye. Mount Honaz (37°75'-37°65' N, 29°22'-29°32' E) is approximately 20 km away from Denizli city center, 200 km from the Aegean Sea, and 160 km from the Mediterranean Sea (Fig. 1). The study area, which exhibits the feature of a single mountain in the western extension of the Taurus Mountains with its location and geographical features, has a spreading area of 15 km in the north-south direction and 10 km in the east-west direction. Mount Honaz rises as a single mountain separated from the mountain ranges in the south of the Çürüksu Basin, a

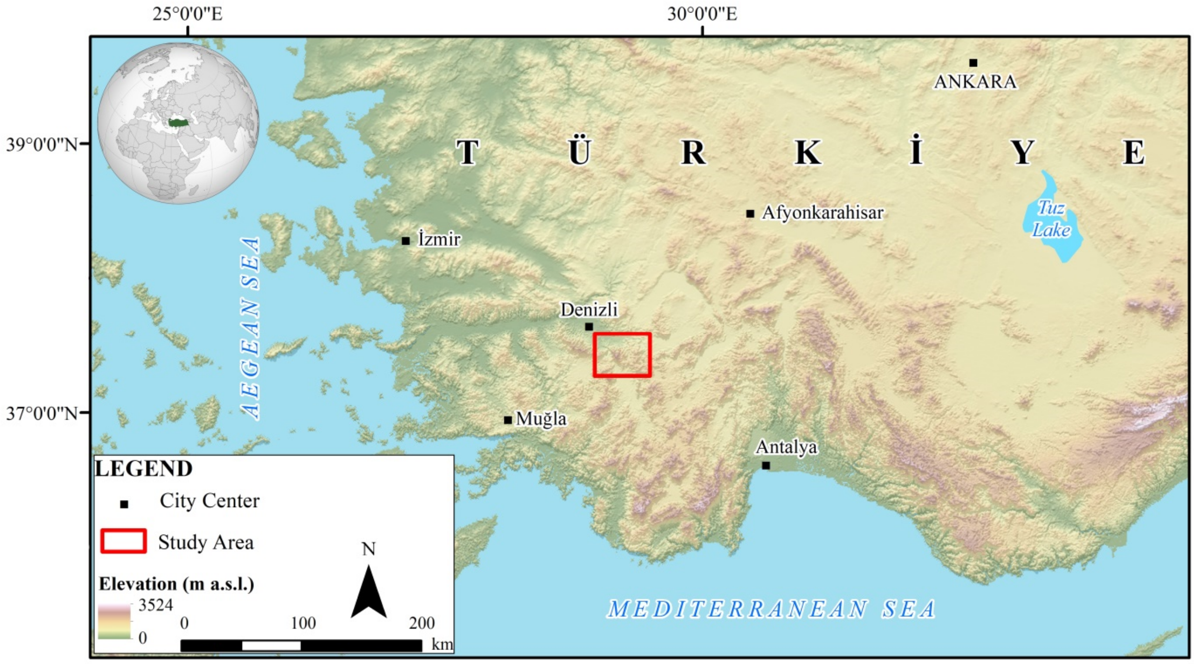

Fig. 1 Location of the study area of Mount Honaz.

branch of the Büyük Menderes River in Western Anatolia. In this section, the Mount Honaz, which starts with steep fault surfaces due to the Honaz fault, limiting the mountain from the north, contains many peaks that exceed 2000 m a.s.l. The lowest hill in the study area is Gündoğmuş Hill (1160 m a.s.l.). According to the elevation values, the important peaks of the mountain are Dokuzçam Hill (1409 m a.s.l.), Bozkaya Hill (1600 m a.s.l.), Göbecik Hill (1659 m a.s.l.), Kara Hill (1920 m a.s.l.), Kozaklı Hill (2024 m a.s.l.), Honaz Hill (2080 m a.s.l.), Yüksekeğrek Hill (2100 m a.s.l.), Deliktaş Hill (2113 m a.s.l.), Kılıç Hill (2571 m a.s.l.), respectively.

The study area, which is currently affected by tectonic activities, is also diverse in terms of geology. The elevation of Mount Honaz is mostly composed of the Mesozoic-aged carbonate succession, which is paraautochthonous and allochthonous. The carbonate rock mass forming the mountain covers the underlying allochthonous ophiolite nappes and Eocene-aged sediments with a thrust contact (Pekuz 2007). The basement rocks in the study area are represented by metamorphic rocks (phyllites and calcschists), Mesozoic marine carbonate sequences of the Lycian nappes, ophiolitic mélange, and Oligocene continental sedimentary rocks. The fluvial sediments of the Honaz and Aksu Streams in the modern graben are interbedded with large-scale neighboring alluvial fans deposited on the valley floor (Özkaymak 2015). The Honaz shale, which consists of green phyllites, is located under the Menderes Massif and forms the core of Mount Honaz. The core of Mount Honaz consists of massive dark bluish, green, heavily fractured and folded, slightly metamorphosed shale and siltstone. The cream-colored, medium-thick bedded, locally chert lensed micritic limestones with abundant microfossils are called Bozkaya Hill limestone (Okay 1989). Crystallized limestones and metamorphic schists occupy the largest part of the structure of Mount Honaz. The semi-marbled and blue-colored limestones are domed in a large anticline. Under the limestones that cover the entire summit, there is a metamorphic complex with phyllites and occasional schist limestones between them. These metamorphics emerged in the parts where the limestone cover was broken down by erosion in the north slopes (Erinç 1955). While there are geological units of different lithologies and ages in the area, Jurassic limestones are widespread in the summit parts, which are the main research subject (Fig. 2).

Alpine plants constitute the vegetation of the areas where periglacial landforms spread on Mount Honaz. This alpine vegetation spreads from 2000 m a.s.l. on the northern slopes and from 1700 m a.s.l. on the southern slopes to the summits. The main plant species that are spread on Mount Honaz were identified as *Acantholimon, Daphne oleides, Rhamnus thymifolius, Astragalus, Asperula nitida,*

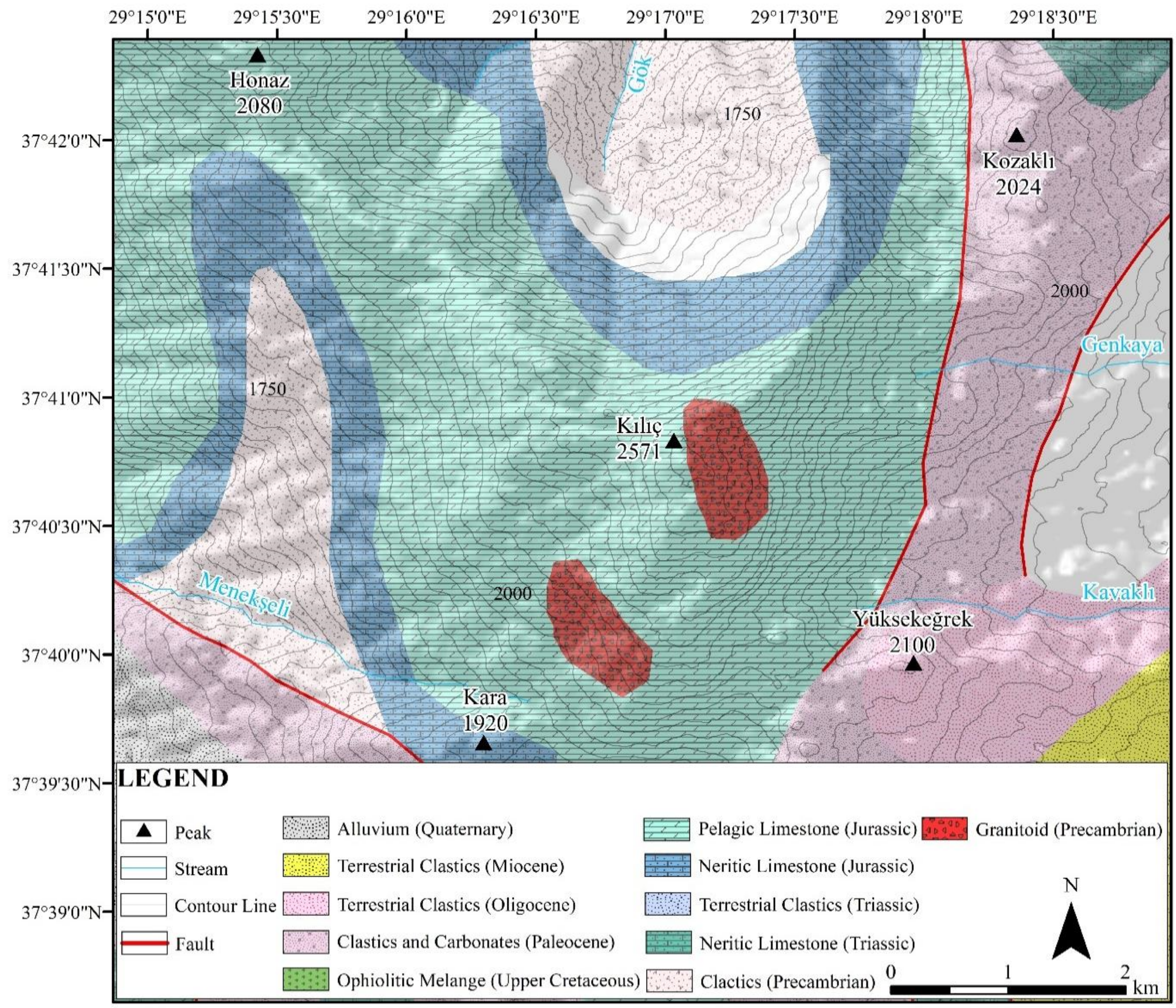

Fig.2 Topography and geological map of Mount Honaz (MTA General Directorate 1/100.000 scaled Denizli M 22 geological map and 1/25000 scaled Denizli M 22-c1, M 22-d2 topography maps of the General Directorate of Mapping were simplified and redrawn).

Acantholimon acerosum, Acantholimon androsaceum, Silene caryophylloides subsp. enchinus (Büyükoğlan 2010).

3 Methodology

3.1 Geomorphological analysis

The data sources of the study consist of topographic maps in 1:25.000 scale, geologic maps in 1:100.000 scale, GPS (Global Positioning System) measurements, climate data, fieldwork, soil sampling and mapping. To understand the environmental conditions under which periglacial landforms were formed and continued their development and explain their development processes, metric measurements (length, width, height, slope, and elevation) were taken from 125 periglacial landforms, including 25 mud circles, 25 stony earth circles, and 75 non sorted steps, which are actively developing under the effect of periglacial processes. The length is the maximum horizontal dimension of the patterns measured between the opposite centers of rough boundaries, while the width is the largest dimension in a direction perpendicular to the length and intersecting it from the center. The height is the maximum distance between the lowest and highest points on the patterns border (Křížek and Uxa 2013). The measured data were analysed statistically, and inferences about the relationship between topographic factors and their morphometric developments were tried to be performed. In the study, analyses of Pearson's correlation coefficient (r), coefficient of determination

(R^2) and least square linear regression equation were performed using the IBM SPSS Statistics 23v program to explain the morphometric development processes of periglacial landforms (IBM Crop 2015). Result outputs were created by supporting the obtained numerical data and their distributions with X-Y scatter plots. The obtained results were used inferentially assess morphological developments of the a fore mentioned landforms. Additionally, this method was used to explain the effect of topographic elements (elevation, slope) on the morphology of periglacial micro landforms. Findings that yielded results at significance levels for p<0.01 and p<0.05 were given in detail with X-Y scatter plots and supported by linear regression equations.

3.2 Soil analysis

To explain the effective periglacial processes in the study area, there were measure the soil properties of selected periglacial landforms. Soil samples were taken from a depth of 20-25 cm from the surface. The results were evaluated to explain the effective processes in the study area and the soil properties where the landforms were formed. Sampling was carried out during the fieldwork to explain the soil characteristics, periglacial processes, and soil structure in which periglacial landforms were formed. Based on the objectives, soil samples were taken from 11 periglacial landforms, including 6 mud circles and 4 stony earth circles from the southern part of the field and 1 non sorted step from the northern part (Table 1). These samples were analysed to determine their texture (sand, clay, silt), soil reaction (pH), electrical conductuvity (EC), lime, organic matter (OM), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). In this way, the effective processes in the field and the effect of soil structure on the development of landforms were evaluated.

3.3 Climate analysis

In order to determine the climate characteristics of Mount Honaz and its surroundings, climatological data recorded at the Denizli meteorological station (425 m a.s.l.) and Mount Honaz National Park automatic weather observation station (AWOS) (1190 m a.s.l.) were taken from the Turkish Meteorological Service (TMS). For this purpose, 15 climate variables were investigated, including average minimum air temperature, mean air temperature, maximum precipitation, total precipitation, maximum relative humidity, mean relative humidity, number of clear days, number of cloudy days, number of frosty days, number of snow-covered days, number of snowy days.

The absence of meteorological stations in high mountain areas complicates climate inference on these areas. However, these challenges can be eliminated using Geographic Information Systems nowadays. The IDW (Inverse Distance Weighting) method (Philip and Watson 1982; Watson and Philip 1985) (GIS) is one of the frequently used methods of mapping. Temperature and precipitation values obtained from the original data were recalculated for the peak part of the mountain using the IDW interpolation method. The IDW method produces predictions from the data obtained and works as a deterministic method with a mechanism that determines the weights of the points according to their distance from each other. If the distance between the points is small, it can produce reliable estimation results. The automatic weather observation station (AWOS) located around the study area is not too far away. For this reason, IDW was preferred with the thought that it could achieve better results. Because the Mount Honaz National Park AWOS has limited data (3 years) as of the date of study, it is not used for a detailed climate analysis. Consequently, general climate character was evaluated according to the standard atmosphere of the

Table 1 Field measurement information of soil samples from Mount Honaz

Sample code	Sample name	Coordinates (N/E)	Elevation (m a.s.l.)	Location
Hon18-01	Mud circle	37°40'33"/29°17'06"	2484	South of Kılıç Hill
Hon18-02	Stony earth circle	37°40'33"/29°17'07"	2485	South of Kılıç Hill
Hon18-03	Mud circle	37°40'40"/29°17'08"	2495	South of Kılıç Hill
Hon18-04	Stony earth circle	37°40'40"/29°17'09"	2493	South of Kılıç Hill
Hon18-05	Non sorted step	37°40'58"/29°17'09"	2445	North of Kılıç Hill
Hon18-06	Mud circle	37°40'53"/29°17'08"	2473	West of Kılıç Hill
Hon18-07	Stony earth circle	37°40'54"/29°16'48"	2348	West of Kılıç Hill
Hon18-08	Mud circle	37°40'55"/29°16'48"	2350	West of Kılıç Hill
Hon18-09	Stony earth circle	37°40'54"/29°16'47"	2346	West of Kılıç Hill
Hon18-10	Mud circle	37°40'54"/29°16'48"	2347	West of Kılıç Hill
Hon18-11	Mud circle	37°40'58"/29°16'47"	2345	West of Kılıç Hill

International Civil Aviation Organization (ICAO), (Türkeş 2022). Additionally, climatic evaluations were made based on data according to Fick and Hijmans (2017).

4 Results

On the southern slopes, in the east of Kılıç Hill, mud circles, non sorted steps, and non sorted stripes develop, while non sorted steps, mud circles, and stony earth circles spread in the south of the hill. Furthermore, on the west side of Kılıç Hill, mud circles and stony earth circles spread along the summit plain (Fig. 3). Moreover, the current periglacial limit for Mount Honaz is 2550 m a.s.l.

4.1 Periglacial geomorphology

The elevation range where mud circles occur in the study area is between 2345 m a.s.l. and 2501 m a.s.l., their average length is 55 cm, their width is 53 cm, and their height is 19 cm. The slope value of the areas where mud circles are formed is 15% on average. Stony earth circles spread between 2300 m a.s.l. and 2500 m a.s.l., their average length is 65 cm, their width is 64 cm, and their height is 17 cm. The average slope of the areas where stony earth circles are formed is 17%. Non sorted steps are formed in the northern and southern parts of the field. Topographic factors and aspect effect at the local scale cause differences in the processes experienced in the northern and southern parts of the field. Therefore, the development of non sorted steps were analysed separately, not as a group, but as non sorted steps formed in the northern and southern sections. Accordingly, the non sorted steps formed in the southern part spread between 2482 m a.s.l. and 2496 m a.s.l., their average length is 43 cm, and the average width is 96 cm. While the average plant height was determined as 21 cm, the average slope value of the

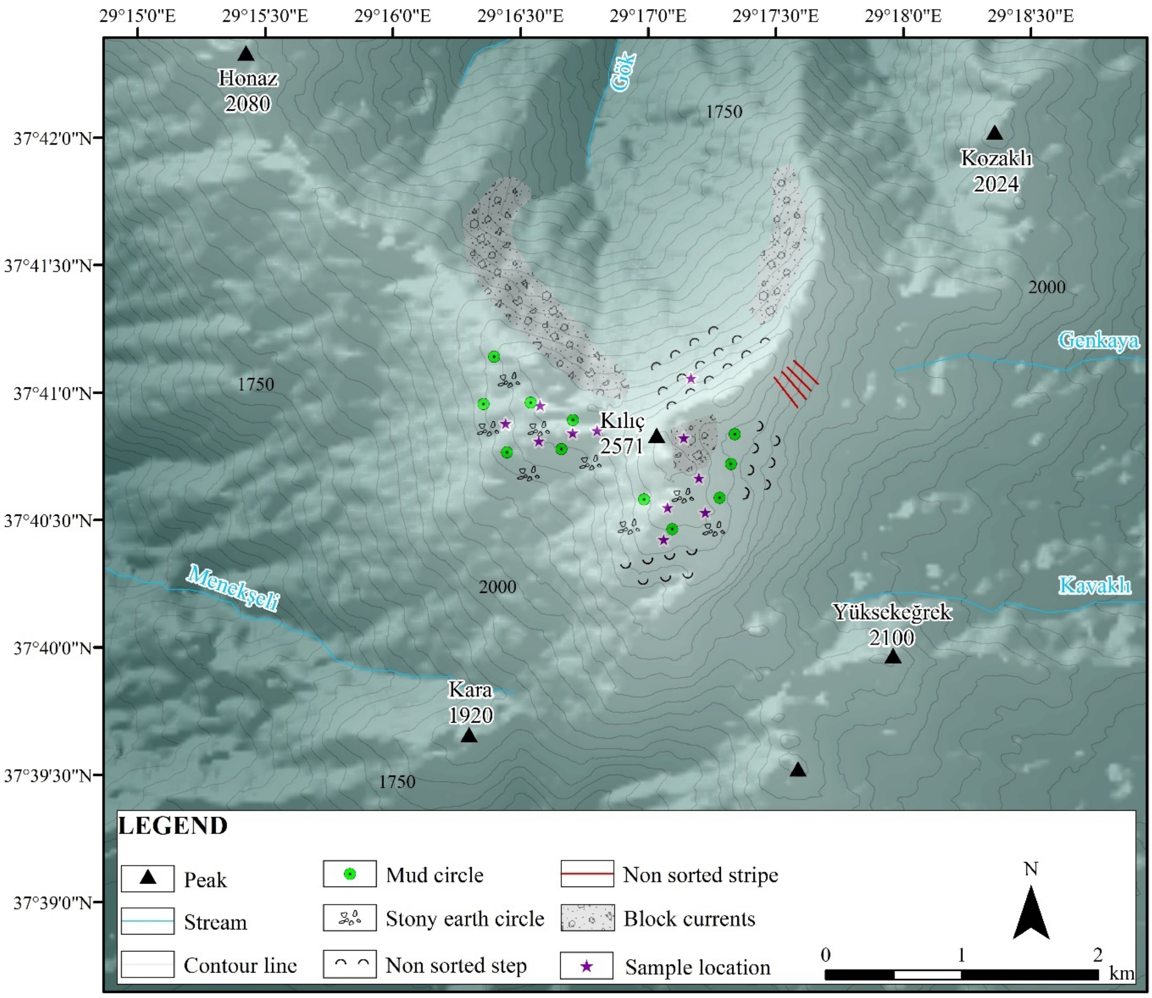

Fig. 3 Periglacial geomorphology and sample location map of Mount Honaz.

area where they developed was measured as 15%. In the northern part, where periglacial processes were more severe, non sorted steps, especially in the Gök Stream valley, displayed a more characteristic development. The landforms in this section were distributed between 2398 m a.s.l. and 2460 m a.s.l. The average length was determined as 275 m, and the average width was determined as 190 cm. While the average height of plants was measured as 32 cm, the slope of the ground on which they developed was recorded as 45% (Table 2). Non sorted stripes were detected in only one area locally on the mountain. Although these landforms developed in the direction of the slope on the southeastern slopes of the mountain, they spread between 2410 m a.s.l. and 2550 m a.s.l., and the slope values of the ground where non sorted stripes were formed were around 35% on average. It was determined that non sorted stripes occurred morphologically as coarse-grained limestone material and alpine-type plant borders alternately (Fig. 4).

In this section, the results from correlation coefficient (*r*) and the determination coefficient (R^2) analysis are used to assess the relationship between variables as the essential interconnected metrics. On the other hand, while both coefficients serve to quantify statistical relationships, they differ in their focus. The correlation coefficient quantifies nature and magnitude (i.e., direction and strength) of a linear relationship between two sets of variables, ranging from -1 (perfect negative correlation) to 1 (perfect positive correlation), while the coefficient of determination represents the variance proportion in the dependent variable explained by the independent variable, ranging from 0 (no explained variance) to 1 (complete explained variance). R^2 equals square of the correlation coefficient. Because coefficient of determination shows only magnitude of the relationships, and not whether that association is statistically significant or not, both R^2 and Pearson's correlation coefficient (*r*) were assed in this section. Significance level of the associations was shown based on the significance test of the *r* values according to a two-sided Student *t* test.

According to the results, because the measurements were obtained from two parts of Mount Honaz, a moderate positive correlation at a rate

Table 2 Descriptive statistics and correlation matrices of the data obtained from the Kılıç Hill location of Mount Honaz

a1) Descriptive statistics for mud circle (*n*=25)				
	Mean	StD	Variance	CV (%)
Length (cm)	55.40	17.17	295.00	30.99
Width (cm)	53.24	16.18	261.94	30.39
Height (cm)	19.60	9.49	90.08	48.41
Slope (%)	15.80	8.67	75.33	54.87
Elevation (m a.s.l.)	2444.84	52.17	2722.05	2.13
b1) Descriptive statistics for stony earth circle (*n*=25)				
	Mean	StD	Variance	CV (%)
Length (cm)	65.08	15.49	240.16	23.80
Width (cm)	64.60	13.91	193.50	21.53
Height (cm)	17.00	8.82	77.91	51.88
Slope (%)	12.52	8.52	72.59	68.08
Elevation (m a.s.l.)	2459.60	50.94	2594.83	2.07
c1) Descriptive statistics for non sorted step south of Kılıç Hill (*n*=20)				
	Mean	StD	Variance	CV (%)
Length (cm)	43.10	11.23	126.20	26.05
Width (cm)	96.25	24.10	581.25	25.03
Height (cm)	21.05	10.36	107.52	49.21
Slope (%)	15.10	1.91	3.67	12.64
Elevation (m a.s.l.)	2488.45	4.43	19.62	0.17
d1) Descriptive statistics for non sorted step north of Kılıç Hill (*n*=55)				
	Mean	StD	Variance	CV (%)
Length (cm)	275.56	30.36	921.73	11.01
Width (cm)	190.84	46.41	2154.10	24.32
Height (cm)	32.13	13.01	169.37	3.11
Slope (%)	45.76	7.84	61.48	17.13
Elevation (m a.s.l.)	2432.69	18.84	355.18	0.77

a2) Correlation coefficients for mud circle (*n*=25)					
	Length	Width	Height	Slope	Elevation
Length	1	0.714**	0.232	-0.401*	-0.776**
Width		1	0.117	-0.372	-0.555**
Height			1	-0.274	-0.178
Slope				1	0.482*
Elevation					1
b2) Correlation coefficients for stony earth circle (*n*=25)					
	Length	Width	Height	Slope	Elevation
Length	1	0.500**	0.483*	-0.206	-0.452*
Width		1	0.416*	-0.187	-0.684**
Height			1	-0.175	-0.337
Slope				1	0.315
Elevation					1
c2) Correlation coefficients for non sorted step south of Kılıç Hill (*n*=20)					
	Length	Width	Height	Slope	Elevation
Length	1	-0.459*	0.384	-0.284	-0.976**
Width		1	-0.633**	-0.401	-0.502*
Height			1	-0.341	0.462*
Slope				1	0.180
Elevation					1
d2) Correlation coefficients for non sorted step north of Kılıç Hill (*n*=55)					
	Length	Width	Height	Slope	Elevation
Length	1	-0.186	-0.784**	0.846**	0,998**
Width		1	0.525**	-0.268	0,187
Height			1	-0.760**	-0.785**
Slope				1	0.861**
Elevation					1

Note: (*), (**): Statistically significant correlation coefficients at the 0.05, 0.01 significance levels, respectively.

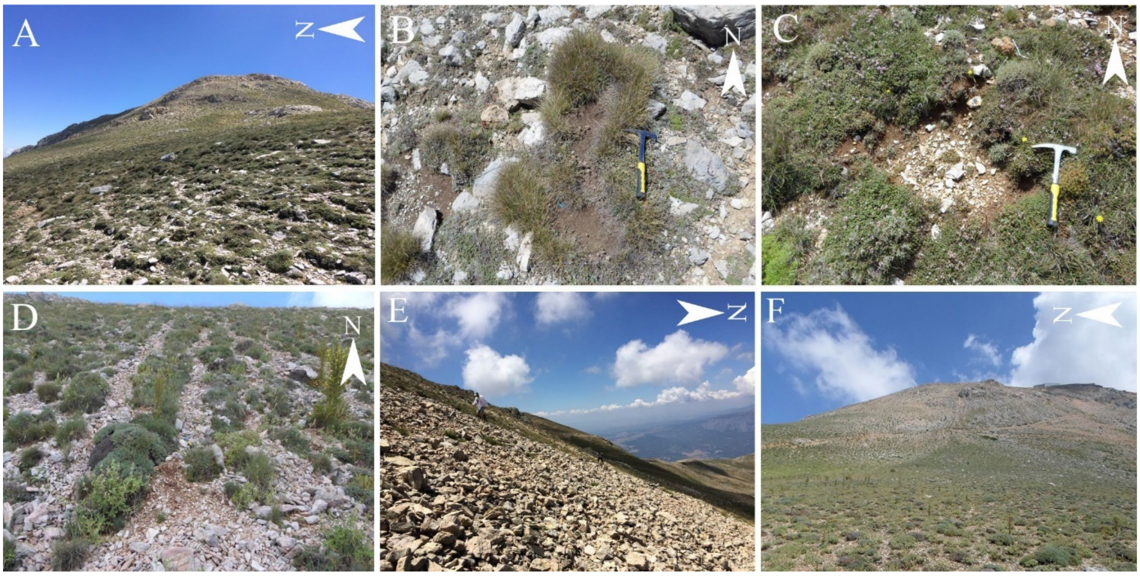

Fig. 4 General views of periglacial landforms at the top of the Mount Honaz (A: Non sorted step, B: Mud circle, C: Stony earth circle, D: Non sorted stripe, E: Block currents, F: Peaksbelt-Kılıç Hill (2571 m a.s.l.).

of 51% (significance level of *r* is 0.01) was determined between the width and length of the mud circle landforms formed on the southern, eastern, and western slopes of Kılıç Hill. Accordingly, it was revealed that the length and width of mud circles increased in direct proportion to each other, and their morphological development was statistically significant. In the length and slope analysis, a low negative correlation at a level of 16% ($p<0.05$ for r) was detected. It can be said that the mud circle morphology lost its characteristics with a significant change in slope values. Considering that the slope values of the areas where landforms are spread are 15% on average, these results are also compatible with the field observations. According to the morphology of the landforms, 60% ($p<0.01$ for r) negative significance was found between the length and height, and 30% ($p<0.01$ for r) negative significance was revealed between the width and height. Especially the disappearance of environments with the decrease in the elevation of these landforms makes sense when the climate and periglacial processes are effective in the field, considering the elevation level.

According to the statistical results for stony earth circles, positive relationship was determined between their length and width. Therefore, there is a low-level linear relationship of 25% ($p<0.05$ for r). It was determined that the measured variables of landforms developed in direct proportion to each other and were compatible with the developmental morphology. The length-height relationship is found at a level of 23% ($p<0.05$ for r) and the positive width-height relationship is at a level of 17% ($p<0.05$ for r).

By evaluating the other micro-morphologic measurements, it is revealed that the relationship between length and height is in the negative direction at a low rate of 20% ($p<0.05$ for r). Again, when the relationship between width and height is evaluated, there is a moderate negative relationship at a rate of 46% ($p<0.01$ for r). According to these results, it is concluded that stony earth circles lost their original structures and development environments with an increase in height. These results agree with field observations. With an increase in elevation, the bedrock emerges as bare surfaces, and the fact that it does not support soil formation appears as a factor preventing the formation of these landforms (Fig. 5).

A negative linear relationship of 21% ($p<0.05$ for r) was found between the length and width of the non sorted steps developing on the southern slopes. Although this linear relationship is low, it indicates that the width begins to deteriorate as the length increases. Since the length of the non sorted steps on the southern slopes is not very long, the relationship between them and their width remains low. One of the important factors that reveal this negative relationship is slope conditions. Increases in slope conditions in the field cause deterioration in the original structure of landforms. The fact that the slope is not high on the southern slopes causes the deformations on the landforms to be less. Therefore, both the lengths are not long and the slope values are not high, which is

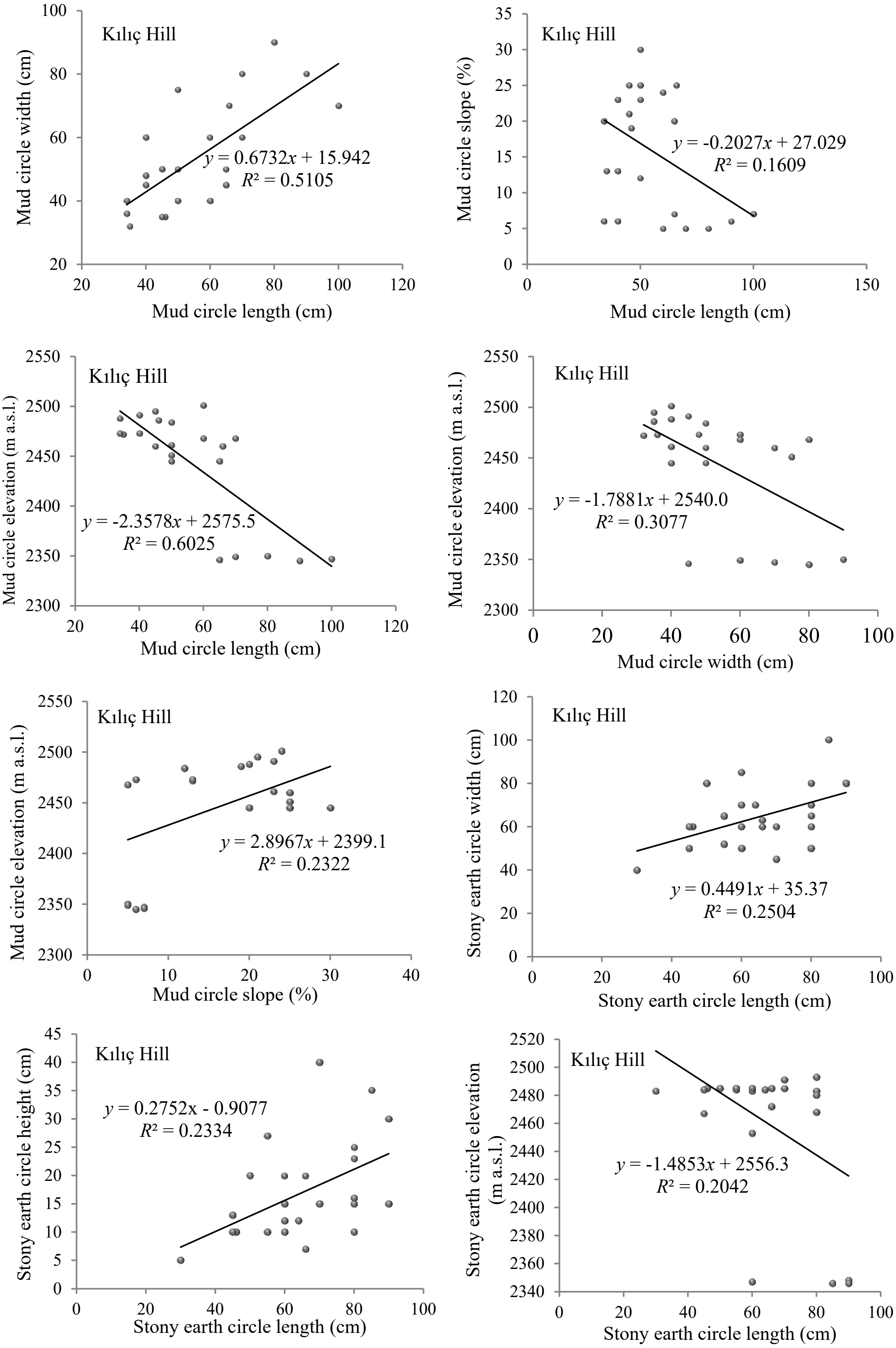

Fig. 5 XY scatter plots showing the statistically significant linear relationships between various properties of the mud circle and stony earth circle landforms on the Mount Honaz.
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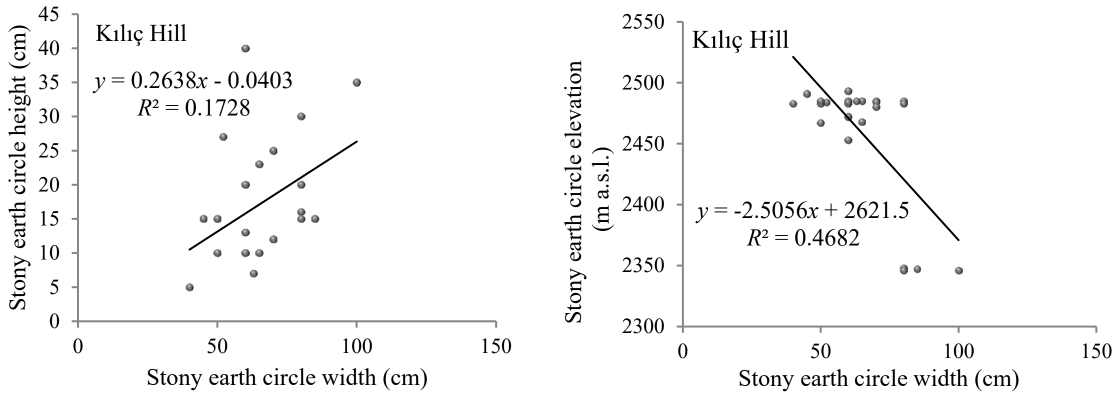

Fig. 5 XY scatter plots showing the statistically significant linear relationships between various properties of the mud circle and stony earth circle landforms on the Mount Honaz.

explained by the low level of negative relationship between these two parameters. A remarkably high negative correlation is also detected between the length and height at a rate of 95% (p<0.01 for r). Although the aspect is effective here, the decrease in alpine-type plants growing in front of the landforms causes their morphology to be adversely affected and results in the loss of their original appearance. Another element that yields clear results is the width-height relationship. In this series, in which a moderate negative relationship is found at a rate of 40% (p<0.01 for r), there are findings similar to other results. It was determined that the plant height started to decrease in the areas where the width of non sorted steps increased, which is compatible with the statistical results. The high slope values are effective here. As a result, although the plant height is developing, it is buried due to the movement of the debris material behind it. There is a low positive correlation at a rate of 25% (p<0.05 for r) between the width and height. At higher altitudes, the lengths of landforms are appositively affected. Accordingly, despite its low explanatory power, it was determined that the width of locally disintegrated steps increased with the accumulation of debris material at certain points due to the length deformation. There is a low negative correlation at a rate of 21% (p<0.05 for r) between the plant height and topographic elevation. Despite the tendency of non sorted steps to move in the slope direction, it is clear that field observations and geostatistical results are compatible.

Non sorted steps on the northern slopes of the study area are the most characteristic landforms in the field. Based a result of their analysis, a high positive correlation at a rate of 73% (p<0.01 for r) was detected between the length and slope values. The most important criteria in this area are the better development of the soil formation and more suitable topographic conditions for the development of landforms. The relationship non sorted steps between the length and height differs from the results obtained on the southern slopes. The main reason of this very strong positive correlation at a rate of 98% (p<0.01 for r) is that of they differ from non sorted steps formed on the southern slopes with a more humid environment and debris provides a more suitable environment for the formation of alpine-type plants (e.g., Matsuoka 1996; Jaesche et al. 2003). Another significant relationship is detected between the width and height. There is a low positive correlation at a rate of 20% (p<0.05 for r). On the southern slopes, this relationship is negative. Although it is low on the northern slopes, the main reason why it is positive is that the plants that limit non sorted steps have a better growth environment.

Despite the tendency of non sorted steps to move in the slope direction, the density and holding power of alpine plants are higher. The plant burial process causing to be slower and the height to be higher. These assessment and statistical analysis results agree with the situation observed in the field. There is a negative correlation between the slope and plant height. This correlation is moderate at a level of 57% (p<0.01 for r). It is concluded that with the increase in the slope values, the plant formation environments begin to deteriorate, affecting their morphology. These data, indicate that it is effective in areas where slope values exceed 50% in the field. The elevation data are similar to non sorted steps on the southern slopes. For these variables, which are in a moderate negative correlation at a rate of 61% (p<0.01 for r), it can be interpreted that the plant height begins to decrease with the increase in elevation. The same result is valid for the periglacial micro-scale landforms formed in other parts of the field. Since the slope of these landforms is over 60%, it does not provide a suitable environment for the formation of micro-scale landforms (Fig. 6).

4.2 Soil properties

These surfaces are considered areas where slope development processes are effective. According to the analysis results of the soil samples taken from the study area, there is a strong correlation between periglacial landforms and lithology. Additionally, it has been determined that the northern slopes are more humid on the local scale and the southern slopes are more deprived of moisture, and the severity of periglacial processes is more intense along the north-facing slopes.

Most soils are classified as loam and clay loam. The amount of organic matter (OM) in mud circles varies between 10% and 26%, which corresponds to the highest rates. This result is related to the plant borders, effective in the development of the mud circle morphology. It has been observed that organic matter is at the level of 6% in non sorted step formations. Plant formation is considered an important element in the formation of these landforms. While the OM content in stony earth circle varies between 8% and 16%, the lime content varies between 3% and 49%. It is seen that vegetation does not have an effect on the formation of stony earth circle, but rather the parent material factor (Table 3, Fig. 7).

4.3 Climate properties

The areas where periglacial landforms develop on the summits of Mount Honaz, especially the higher parts of the northern slopes, reflect the humid temperate mountain climate. The annual average minimum air temperature on the summits of Mount Honaz is 0.8°C. While the annual mean air temperature is 2°C-4°C. It has been determined that these climate variables are below zero only in winter and early spring months (December, January, February, and March) (Fick and Hijmans 2017). The annual precipitation amount of the peak section of the Mount Honaz is calculated as 775 mm. When evaluated seasonally, most precipitation (297 mm) occurs in the winter season (December, January, February). During the period covering March and April-May, 230 mm of precipitation was measured on Mount Honaz. Snow cover in the peaks is effective in December, January, February, and March Mount Honaz. Snow cover in the peaks is effective in December, January, February and March (Fick and Hijmans 2017). While the climate type in the summits of Mount Honaz is evaluated as semi-humid, the vegetation type has been determined to be dry forest (Fig. 8).

5 Discussion

5.1 Statiatical properties of periglacial landforms

Cold climate processes support the formation of distinctive landforms in the areas where they are effective (Thorn and Hall 1980). Mud circles, non sorted steps, stony earth circles, non sorted stripes and block currents among these special landforms are identified on Mount Honaz. In general, periglacial processes are effective at 1900 m a.s.l. and above on Mount Honaz (Serin 2019).

Severe weathering due to periglacial processes in the study area causes the formation of periglacial landforms. Weathering and mass movements associated with freeze-thaw are the main processes that control the development of slopes in periglacial regions (Matsuoka et al. 1997). These landforms, which emerge as steep walls, especially along the Gök Stream valley opening to the north, cover an average of 1 km².

Mud circles are formed by swelling of the ice lenses in the soil during the winter months, with a diameter of up to three meters (Peterson and Krantz 2003). Mud circles with coarser material or plant boundaries and finer-grained soil characteristics are formed by the movement of ice-rich soils (Hallet and Prestrud 1986). Seasonal freezing processes, local climatic factors, and vegetation are the most important determinants in the formation of these landforms (Josefsson 1988).

Stone patterns, originally composed of evenly dispersed stones, transform into stony earth circles in the freeze-thaw cycle and gradually merge with adjacent ones (Li et al. 2021). Stony earth circles were formed in the same environments as mud circles. Considering the morphology of stony earth circles, it was concluded that landforms would increase in height because of freeze-thaw processes and development over time, and the development

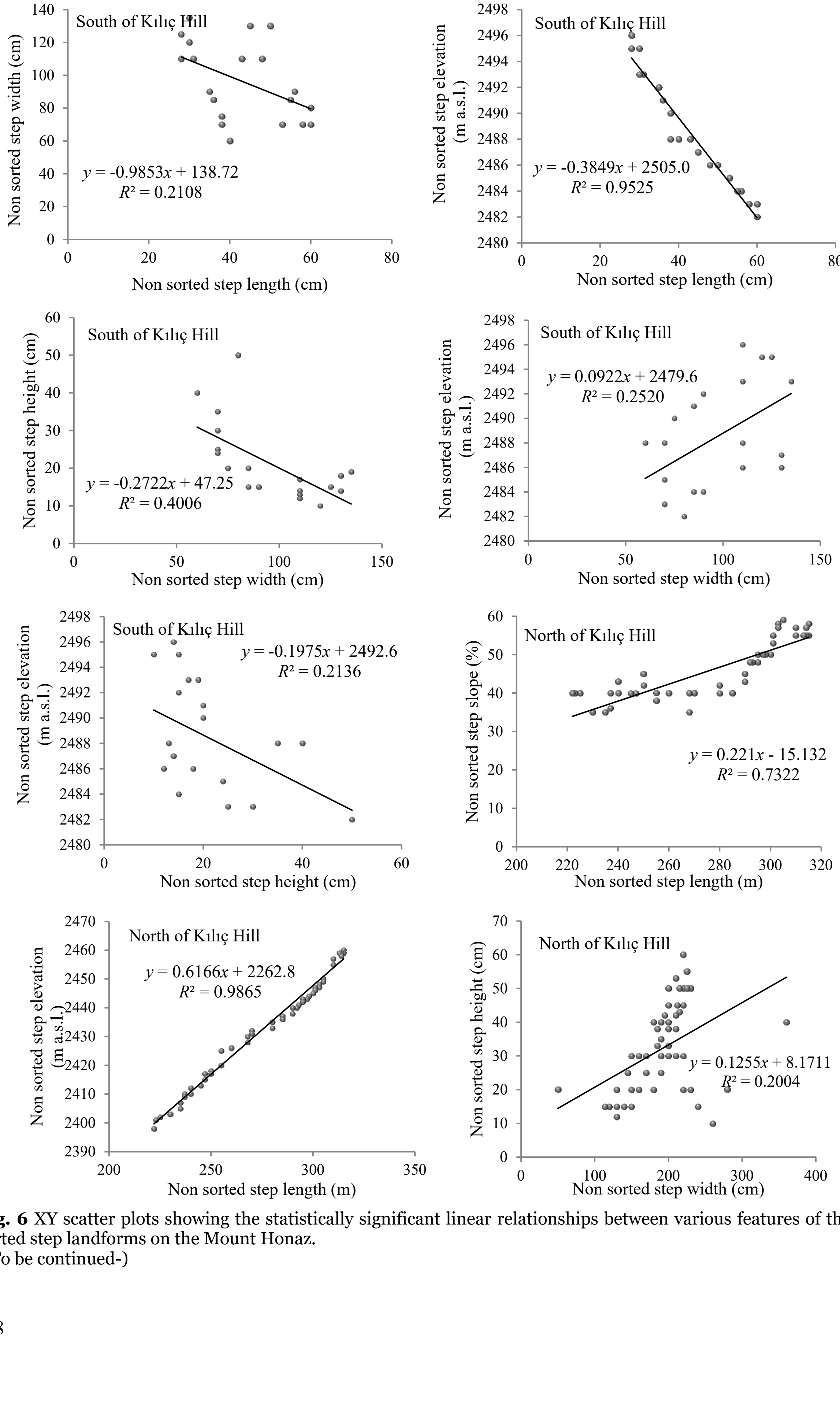

Fig. 6 XY scatter plots showing the statistically significant linear relationships between various features of the non sorted step landforms on the Mount Honaz.
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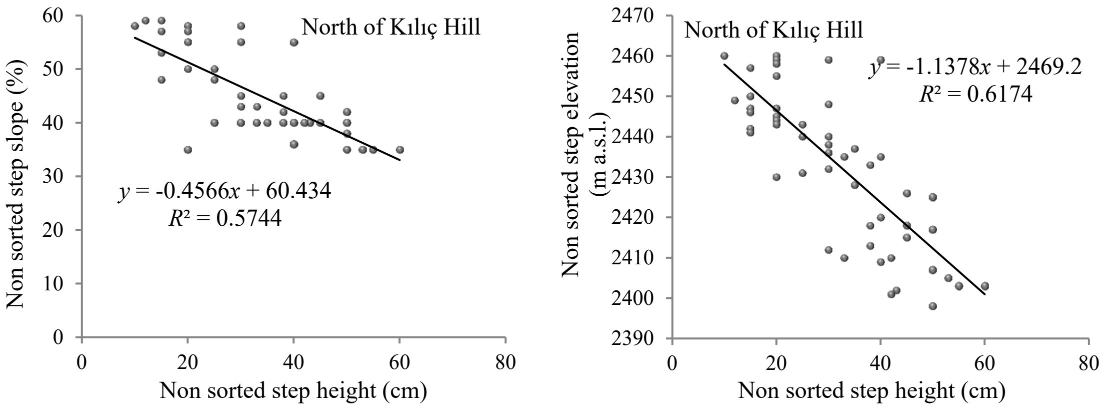

Fig. 6 XY scatter plots showing the statistically significant linear relationships between various features of the non sorted step landforms on the Mount Honaz.

mechanism would comply with geostatistical results (e.g., Mullin 2000; Yamagishi and Matsuoka 2015).

Solifluction structures, (related to soil movement in periglacial environments), frost creep and the soil development and its backward erosion, are common in these environments (Matsuoka 2001, 2010; Hjort et al. 2007). Non sorted steps develop on both the southern and northern slopes of the site. The measurement parameters of the non sorted steps developed on the southern slopes, the relationships between the size significant ones were evaluated.

According to the results obtained in Mount Kaz, the height and width of mud circles are as r=0.67 and 0.89, according to separate samples and analyses made in different locations, and in non sorted steps, r=0.78 and r=0.54 results were obtained (Türkeş et al. 2023). Results in accordance with the specified values were also obtained on Mount Honaz. Values of R^2=0.51 were obtained between mud circle lengths and widths, and R^2=0.60 values were obtained between heights and lengths.

Two different morphologies of large rows of circles around Mafadi-Njesuthi peak have been described (based on pattern sizes) as 'large circles' and 'very large circles'. The centers of the large circles (n=10) have an average diameter of 74 cm and the average border diameter is 63 cm. The centers of very large of circles (n=6) have borders with an average diameter of 100 cm (max. 190 cm) and a width of 80-100 cm (Grab et al. 2021). For Mount Honaz, these average values were found to be 55 cm in diameter for mud circles.

5.2 Physicochemical properties of periglacial landforms

Modern research have shown that continuous or discontinuous permafrost probably existed at different times throughout the region during the Quaternary. This has significant implications for ground permeability and strength of sediments and soils, and this has undoubtedly influenced landscape development (Whiteman 2024). Although characteristics such as location, elevation and aspect cause different climate processes among the areas where periglacial processes are effective, it has been revealed that there are similarities between the areas where these processes are dominant and Mount Honaz. In this respect, new data have been obtained for the Anatolian Mountains. As a result of the analysis of the soils obtained from the Mount Kaz, the soils developed under the periglacial processes were defined in the Entisol order. While the texture classes of the soils formed on the mass are sandy loam, very few of them are sandy clay loam. While the amount of clay varies between 7.50%-24.27%, the amount of sand varies between 56.74% and 82.55%. Although the average amount of organic matter is 9.51%, it is between 0.29% and 30.90% (Türkeş et al. 2023). In the soil samples taken from Ilgaz Mountains, it was determined that acid reaction, slightly alkaline and all soils were salt-free. It has been determined that the organic matter levels of the soils are above 3% (Dede et al. 2020). While it was determined that the texture structure of the soils where the periglacial landforms developed on Mount Honaz were formed mostly in the loam and clay structure, it was determined that the EC values changed between 0.06 and 0.24, and the OM values changed between 6.56% and 25.77%. In addition, it has been found that there is a significant decrease in OM

Table 3 Physicochemical properties of soil samples

Sample Code	Sample Name	pH	EC (mS/cm)	OM	Lime	N	P	K	Ca	Mg	Sand	Clay	Silt	Texture
					(%)			(mek/100g)				(%)		
Hon18-01	Mud circle	6.28	0.12	12.17	2.1	0.61	7.18	188	3.4	431	30	28	42	Clay Loam
Hon18-02	Stony earth circle	7.65	0.14	8.1	3.9	0.41	2.29	92.5	4.2	376	20	32	48	Silty Clay Loam
Hon18-03	Mud circle	7.61	0.16	21.28	34.4	1.06	4.28	155	5.2	108	44	20	36	Loam
Hon18-04	Stony earth circle	7.59	0.19	11.27	49.8	0.56	0.39	123	5.4	134	50	18	32	Loam
Hon18-05	Non sorted step	5.7	0.06	6.56	1.4	0.33	1.68	95.3	2.4	377	24	40	36	Clay Loam
Hon18-06	Mud circle	7.09	0.12	25.77	2.8	1.23	9.26	341	6.9	363	34	24	42	Loam
Hon18-07	Stony earth circle	7.45	0.15	8.75	5.3	0.44	7.42	245	5.3	79.1	24	36	40	Clay Loam
Hon18-08	Mud circle	7.2	0.24	15.06	2.3	0.75	18.77	633	5.7	378	26	38	36	Clay Loam
Hon18-09	Stony earth circle	7.55	0.23	15.45	16.3	0.77	1.14	130	7.1	165	42	22	36	Loam
Hon18-10	Mud circle	7.5	0.07	26.4	24.4	1.32	4.16	308	9.8	226	40	18	42	Loam
Hon18-11	Mud circle	7.5	0.21	10.73	8.1	0.54	7.5	178	5.6	233	39	21	40	Loam

Note: pH: Soil reaction; EC: Electrical conductivity; OM: Organic matter; N: Nitrogen; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium.

Fig. 7 General view of periglacial landforms from which soil samples were taken at the top of the Mount Honaz.

and clay formation with the increase in altitude, and this is due to the decrease of bio-chemical reaction as well as geo-physico-chemical reaction (Dede et al. 2021). It has been determined that there are significant positive correlations between dehydrogenase activity and soil organic matter content in soils where

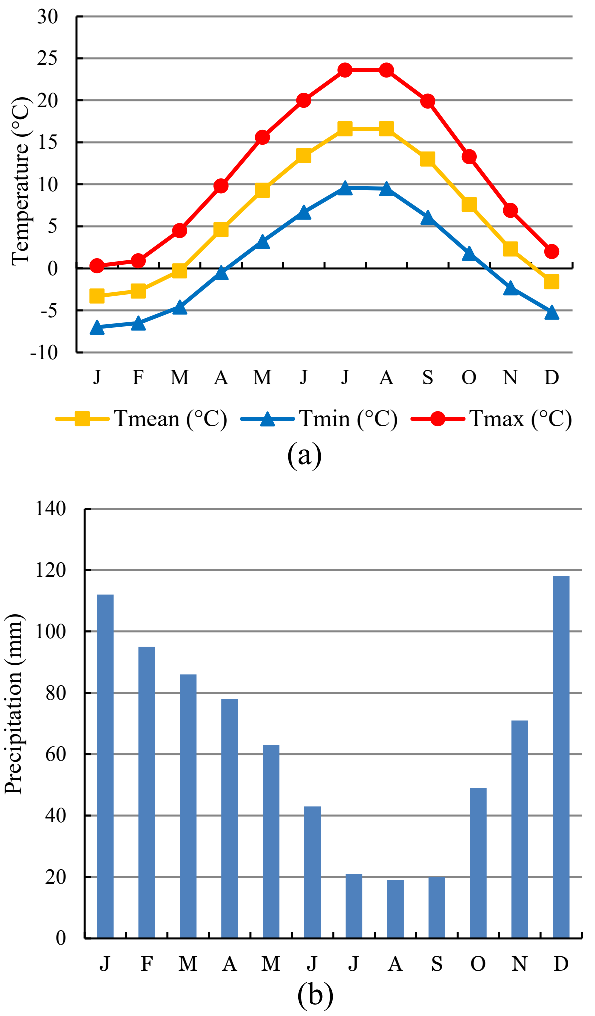

Fig. 8 Temperature and precipitation characteristics of the Mount Honaz peaks. (a) Annual Minimum, Maximum, Average Temperatures (°C); (b) Monthly Total Precipitation (mm)).

periglacial landforms are formed, and significant negative correlations between height and dehydrogenase activity (Kızılkaya et al. 2019). Soil horizons formed in periglacial regions are associated with deformation, degradation and material displacement of soil components due to deep seasonal frost conditions. It has been determined that these areas have a cold, dry, seasonal frost climate and soil materials with different frost sensitivity (Rodriquez-Ochoa et al. 2019). According to Fitzpatrick (1978), it has been determined that there is an important relationship between landforms and vegetation developing in periglacial environments. According to the results obtained, it was determined that the organic matter content was high in the A1 horizon, which decreased with depth in all soils. According to Kokelj et al. (2002), it was determined that the OM rate in the permafrost active layer decreases from the surface to the depths (3-25%). It has been determined that the soil properties of the periglacial processes that occur with similar climatic conditions also show remarkable similarities. From these results, it is thought that the micro-periglacial landforms were formed in a closer chronology to the present day and continued their motion. In some physicochemical properties of the soils formed on the periglacial landforms consisting of non sorted steps, mud circles and stone earth circles spreading on Mount Ilgar, the average value of DO was 32.16, SSI value was 23.50 and CF value was 22.25. In addition, the AS values of the soils were determined as 53.39%. The accuracy rates of erodibility parameters (DO, CF and SSI) estimated by ANN were determined as 79% for DO, 82% for CF and 72% for SSI (Dede et al. 2022b).

According to the soil analyses made from the periglacial landforms developed in Mount Cin, the average soil erosion susceptibility factors, namely structural stability index (SSI), dispersion ratio (DR) and crust formation (CF) were calculated as 29.65%, 28.36% and 40.72%, respectively. According to the regression results of soil erosion susceptibility factors using ANN, the highest prediction rate was obtained for SSI (78%) and the lowest prediction rate was obtained for DR (57%) (Dede et al. 2022a). It is pointed out that the processes experienced in periglacial areas and erosion processes are also important criteria. As a matter of fact, it has been determined that one of the effective processes in Mount Honaz is the washing process.

Comparable results apply to non sorted steps. On the other hand, the fact that this value is lower in stony earth circle landforms (8%-15%) is compatible with morphological development. While the samples taken from the mud circle and stony earth circle landforms along the southern slopes of the field are evaluated as slightly alkaline (6.28-7.65), the sample taken from the non sorted step from the northern slope is classified as moderately acidic (5.7), (e.g., Musso et al. 2020). Upon examining the EC values, it is seen that all of the samples are salt-free (0.12-0.24), while it has been determined that the lowest and different sample in this value gives a result (0.06) on the northern slopes. Lime rates vary between 2.1% and 34.4% for mud circles, and their average value is 12%. This rate varies between 3.9% and 49.8% for stony earth circles, and it is 18% on average. The fact that the parent material is a limestone formation and stony earth circles are mostly composed of the parent material also affects these results. Another remarkable result obtained from the sample analyses is for non sorted steps. The lowest lime content of 1.4% obtained in these samples is related to more effective washing processes experienced on the northern slopes. In general, it has been concluded that the southern slopes are more moisture deprived areas on the micro scale, while the northern slopes are humid. However, while washing and sweeping activities are effective on the field, it is possible to say that this effect rate is higher on the northern slopes.

Current periglacial boundary is 2100 m a.s.l. in the Aladağlar and 2700 m a.s.l. in the Bolkar Mountains (Altın 2006; Çiner et al. 2017; Sarıkaya et al. 2017). The current periglacial boundary on Mount Honaz was determined as 2100 m a.s.l., which is compatible with the lower limit of periglacial processes in the Taurus Mountains. These similar conditions support the occurrence of periglacial processes in areas with suitable climatic conditions and above 2000 m a.s.l. throughout the range of Ilgaz Mountains. It has been determined that the periglacial border in the study area varies depending on the aspect factor. On the northern slopes, the limit is 1900 m a.s.l., and on the southern slopes it is 2100 m a.s.l. appears to be at levels. They determined that the physico-chemical and mineralogical properties of the soils showed significant differences between the shapes and stated that the reason for this was the effects of both the altitude (1943-2398 m a.s.l.) and the geological material (marl, limestone and sandstone), as well as the effect of the micro topography of the landforms (Dede et al. 2020, 2024). According to soil analysis from periglacial landforms, the dominant soil texture is sandy loam with clay between 5.61% and 16.79% and sand between 48.61% and 76.72% of Mount Ilgar (Dede et al. 2022b). It can be said that these differences, which are determined to be different from each other in terms of formation and size of stony earth circles, which are periglacial landforms formed in Çadır and Göze Mountains, may be due to the effects of slope, aspect and elevation change (Dede et al. 2023). While it is stated that the high organic matter content in the soils formed on periglacial landforms causes crust formation and therefore physical degradation remains at very low levels. Uludağ is one of the mountains where periglacial processes and landforms are investigated in detail. Periglacial landforms begin at 1950 m a.s.l. and spread to the summits. The results of geostatistics for the periglacial landforms in Uludağ (e.g., Türkeş and Öztürk 2008, 2011) and the analysis results for Mount Honaz are largely compatible. Accordingly, it can be said that the processes experienced in Mount Honaz and Uludağ are quite similar, and the development of landforms is similar in this direction. Studies conducted in the Anatolian Mountains and around the world show that the periglacial processes and landform formations experienced in Mount Honaz have similar morphometric developments under similar conditions.

5.3 Climate properties of periglacial areas

Climatic conditions are among the most principal factors in the formation of periglacial landforms. Increasing trends were observed in the monthly and annual maximum temperature, average maximum temperature, minimum temperature, average minimum temperature and mean air temperature series. It has been revealed that similar results of the break and increase trends in these temperature series were effective after 1990 (e.g. Türkeş et al. 2016; Erlat and Türkeş 2017; Türkeş and Erlat 2018; Türkeş 2020; Erlat et al. 2021).

The average annual temperatures in moderate and severe periglacial zones are 2.4°C and 0.6°C, respectively, meeting the globally determined criteria of below 3°C. The total annual precipitation ranges from 618 to 808 mm, with precipitation increasing from weak to severe zones. Weak periglacial zones are covered in snow for an average of 3.3 months per year, while severe periglacial zones are covered for 6.4 months. This strengthens periglacial processes and leads to the formation of periglacial zones in mountainous regions of Anatolia (Öztürk and Taşoğlu 2024). The current temperature values of the areas where periglacial processes are actively experienced at the summit of Mount Honaz are on average 2°C-4°C annually. The annual minimum average temperature value is 0.8°C. It was determined that the average annual total rainfall is around 775 mm. These results are important since they are compatible with the mean values of the current periglacial zones (e.g., French 2007). However, due to a rapid increase in global temperatures, the permafrost layer is rapidly melting with a significant increase in the temperature values in periglacial regions (Nigrelli and Chiarle 2021).

It has been determined that the periglacial forms that develop in the summits of the Mount Kaz is formed in the Mediterranean climate, under humid temperate mountain climate conditions (Türkeş et al. 2023). In the Ilgaz Mountains in Northern Anatolia, the temperature between the altitudes where periglacial landforms occur is determined to be 2.5°C-5°C on average annually (Dede et al. 2021). The annual average temperature values were determined as 6.2°C. It is stated that the temperature conditions on Mount Cin are 4°C-6°C. It has been concluded that the mountainous region can be considered humid and semi-humid (Dede 2023). It has been state that the temperature values in areas experiencing periglacial processes, typical of the Alpine belts, range between -2°C and 2°C (Aalto et al. 2017). Aalto et al. (2017) stated that there is a relationship between periglacial landforms and the thermal state of the ground in areas where cold climate processes prevail. Again, depending on these processes, it has been determined that the landforms in these regions were formed during the Holocene (Uxa et al. 2017). It is known that the current climate temperatures in Mount Honaz are around 2°C-4°C (GDM 2023). It is thought that the landforms developed during the Holocene. Climate plays a determining role in ecosystems at increasing altitudes. Increasing altitude, vegetation weakens and causes cryoturbation (D'Amico et al. 2015). Salvucci et al. (2023) found that the average annual ground surface temperature (MAGST) in periglacial environments in the Majella Massif, central Apennines, Italy varies between 1.76°C and 3.15°C. The annual average temperature values of the periglacial regions on the Mount Erciyes are -2°C, and the periglacial climate zone decreases to 1400 m a.s.l. (Sayhan 1999). In Mount Palandöken, the soils freeze in December, January, February, and March, while the annual average temperature is 3°C. Thufur formations occur with severe freeze-thaw activity in the field (Çakır and Kopar 2017). Those who have suitable conditions in the mountainous areas separated from the mountain ranges of Anatolia and have been formed as a single mountain are severely affected by periglacial processes.

6 Conclusions

Mount Honaz (2571 m a.s.l.) is one of the areas where periglacial processes are experienced severely in Türkiye. There are two basic periglacial processes on the Mount Honaz. These are mass movements and slope development processes. Climate, lithology, and topographic factors have affected the development of periglacial landforms.

On Mount Honaz, the annual average temperature value of the parts where the periglacial zone is effective is 2°C-4°C. The annual average minimum air temperature is calculated as 0.8°C. The annual minimum air temperatures (November, December, January, February, March, and April) on Mount Honaz are calculated to be below 0°C. These minimum air temperatures are thought to favor the development of periglacial landforms.

Topographic factors play an significant role in the development of periglacial landforms, and differences in these factors are effective in the morphological changes of the landforms. With the morphometric analysis results were obtained between the width-length, height-length, height-width, elevation-slope, and slope-length parameters of mud circles. Significant results were found for the width-length, height-width, height-length, elevation-length, and elevation-width parameters of stony earth circles. On the other hand, results were obtained in terms of the width-length, height-length, height-width, elevation-height, height-width, slope-length, and slope-elevation parameters of non sorted steps.

According to the results of soil samples taken from periglacial landforms, it was determined that most of the soil had a loamy and clay loam structure. It was also found that the leaching and sweeping processes played a more active role on the north-facing slopes of the study area.

While it has been revealed that mud circles, non sorted steps, stony earth circles, and non sorted stripes continue to move under current climatic conditions, descending to 1900 m a.s.l. in the Gök Stream valley was formed under cold past conditions due to their inactive state nowadays. It has been revealed that periglacial processes currently continue and landforms are in development.

Acknowledgments

The authors thank the editor and anonymous reviewers for their constructive comments and suggestions.

This publication was produced from the responsible author's master's thesis titled “Periglacial geomorphology of Mount Honaz (Denizli)”, prepared at Bilecik Şeyh Edebali University, Social Sciences Institute in 2019.

Author Contribution

SERİN Soner: conceptualization, data curation, formal analysis, methodology, writing original draft, visualization, writing-review and editing. UNCU Levent: field work, editing and review. DEDE Volkan: conceptualization, data curation, formal analysis, methodology, writing original draft, visualization, writing-review and editing. TÜRKEŞ Murat: some little writing, editing and review.

Ethics Declaration

Availability of Data/Materials: Data will be made available on request. Researchers interested in accessing the data can contact the corresponding author.

Conflict of Interest: The authors declare no competing interests.

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