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THUFUR MORPHOLOGY WITHIN THE PONOR DEPRESSION (STARA PLANINA, SERBIA)

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Abstract: Thufur (earth hummocks) are small periglacial landforms typical for subpolar latitudes, as well as for the high alpine areas at lower latitudes. Their presence in the mountains of the Balkan Peninsula was spotted during the mid-20th century. In this paper we analyze morphometry and morphology of thufur in the context of physio-geographical conditions for their formation. The main aims are to inventorize the thufur in the study area and to determine the physio-geographical factors which enabled their formation at non-zonal elevations. Statistical analysis was performed on the sample of 305 thufur mapped in the field, measuring their circumference, height, and delineating their areas. Classification of the results revealed morphological varieties in terms of horizontal and vertical development. The elevation of the sampling location Ponor is 1,410 m a.s.l., which is considerably lower than the zonal periglaciation in Serbia, at approx. 1,900 m. Therefore, the role of relief as a climate modifier is analyzed in the context of conditions for the azonal development of periglaciation process. Topographical conditions for thufur formation were analyzed through slope inclinations and vertical dissection, determined using the Digital Elevation Model over Europe with 25 m resolution.

Keywords: thufur morphology; earth hummock; periglacial morphology; Stara Planina; Serbia

1. Introduction

At the global level, periglacial geomorphological processes are present in subpolar regions, where their delineation includes both the permafrost zones and the areas of seasonal ground freezing. At lower latitudes, the areas characterized with periglacial environment are high-elevation mountains and plateaus (alpine environments). The elevation-based definition of periglaciation zone (usually above the regional tree line) is considered as a criterion for demarcation between zonal and azonal periglacial processes (Murton, 2021).

The term thufur comes from the Icelandic language (singular: thufa; plural: thufur). It is approximately synonymous with the term earth hummock and used both in permafrost and non-permafrost areas (in the latter, occurring in seasonally frozen ground). Terminology is elaborated by van Everdingen (2005), referring to the work of Thorarinsson (1951), Schunke (1975), and Scotter and Zoltai (1982). Another term used for these relatively small-sized landforms is minerogenic pounu (Van Vliet-Lanoë & Seppälä, 2002), while Grab (2005a,

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p. 140) describes them as "miniature cryogenic mounds" forming both in permafrost and seasonally frozen ground.

In the Balkan area, thufur are reported in high mountain periglaciation zones in Bulgaria (Glovnja, 1959; Maruszcazak, 1961), Romania (Marcu, 2011; Onaca et al., 2013), and Serbia, on Prokletije Mts. and Šara Mt. (Belij, 1990, 1992, 1994). Other localities of thufur in Serbia belong to azonal periglaciation (below 1,900 m a.s.l.) within various genetic types of relief depressions. The first such example was detected on Beljanica Mt. in Carpatho-Balkan Mts. in Eastern Serbia (Belij et al., 1997; Gavrilović, 1968), on Pešter polje in the Dinarides of SW Serbia (Belij et al., 2004), and in the basin of Vlasina Lake in SE Serbia (Serbian-Macedonian Massif; Milošević et al., 2015; Milošević et al., 2007). The occurrence of thufur on Stara Planina (Balkan) Mt. in Eastern Serbia was first detected by Gavrilović (1970), primarily on Kopren locality at 1,935 m a.s.l. and subsequently in Ponor depression (Gavrilović, 1990). The author listed the conditions for thufur formation in this place, one of which is temperature inversion caused by terrain morphology. The thufur of the Ponor depression were morphometrically analyzed by Belij et al. (2008) who gave the average height and diameter values (d = 60–90 cm and h = 45–50 cm), as well as the approximate number, 400 thufur. Nešić (2009) suggested the possibility that the Ponor thufur were of zoogenic origin (formed by the activity of ants).

The aims of study are: (1) to inventorize the thufur within the Ponor depression, (2) to determine the physio-geographical factors which led to their azonal development in sub-alpine periglacial environment, and (3) to improve the understanding of the relation between thufur morphological varieties and micro-location characteristics. The working hypothesis is that thufur may be regarded as indicators of microclimate-dependent micro-morphogenesis. We compare the studied locations which have been analysed with the similar ones for the purpose of building theoretical frameworks which could be used in future research and modeling.

2. Study area

The Ponor depression is situated on Stara Planina Mt. at the far east of Serbia (43.2461° N, 22.8133° E), at the elevation of 1,408 m a.s.l., close to the crest of the ridge between the watersheds of the Dojkinačka Reka River and Jelovička Reka River (Figure 1). The bottom of the depression is covered with proluvial-deluvial sediments, while the slopes reveal the lithological contact of Lower Triassic sandstones and Middle Triassic limestones (Anđelković et al., 1975). The bottom of the depression is covered with more than 50 cm thick clayey-sandy deluvial soil without large rocky fragments, while the slopes are characterised by considerably thinner (up to 35 cm) ranker soil. Four streams (three large and one small) have developed on the sandstone slopes. Limestones are situated along the south-western edge of the depression, capturing the surficial streams through three ponors and directing the groundwater toward the Žuberna karst spring in the Dojkinačka Reka River watershed (Pantelić, 2017). Such geological settings have played the crucial role in morphogenesis of the depression, in terms of highly different erodibility of two main lithologies, which caused the radical change in water drainage and subsequently the morphological outcome. The limestone outcrop enabled the favorable conditions for the development of the inflow type of contact karst, turning the fluvial (stream) valleys into blind valleys. In this context, the Ponor depression with all the sinking streams (ponors—clear toponymic relation) can be defined as a multiple blind valley. Ponor depression was described for the first time by Jovan Cvijić (Cvijić, 1896). Researchers in the second half of the 20th century and early 2000s used the term “uvala” for this landform (Belij et al., 2008; Gavrilović, 1970, 1990; Gavrilović & Gavrilović, 1998; Nešić, 2009), but it is geomorphologically incorrect, because the term “uvala” refers to fully-karstic environments and includes the tectonic influence (Ćalić, 2011). In recent publications the correct terminology is used (Pantelić et al., 2018).

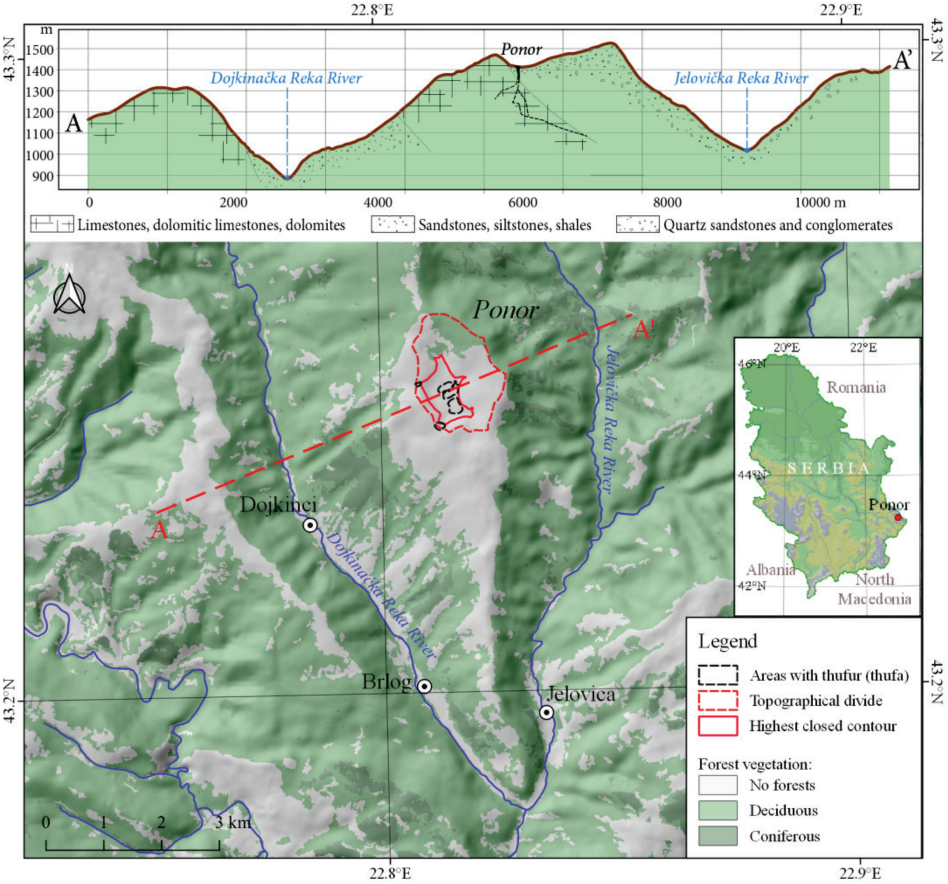

Figure 1. Position of the Ponor depression.

The climatological and hydrological measurement infrastructure of the wider area is rather poor. In the village of Topli Do, situated about 15 km to the NW from Ponor, the climatological station (at the elevation of 700 m) has not been in function since 1985 (Milovanović, 2010). The last official data from the station show that the mean monthly air temperatures were negative in three winter months (December, January, and February), which is significant, since the other stations in the wider area show the negative mean temperatures only in January. According to the isotherm map of Stara Planina Mt. presented in Milovanović (2010), the mean annual air temperature in Ponor region ranges between 4.1

and 6 °C, while Ristić Vakanjac et al. (2018) provide the expected mean temperature of 4.3 °C. These data are in accordance with Koaze et al. (1974), cited by Grab (2005a), that such air temperature conditions are suitable for thufur development. Mean monthly minimum air temperature is negative in March as well (Milovanović, 2010). There are temperature inversions on Stara Planina Mt. (Milovanović, 2010), which appear when cold air settles in depressions such as the Ponor depression. From 1961 to 1985, the average number of frost days (Tmin < 0 °C) measured in Topli Do was 110.6 in the time span September–May. From November to March, the average number of days with strong frost (Tmin < 10 °C) at Topli Do station was 12.9, while for the same period, the average number of ice days (Tmax < 0 °C) was 23.8 (Milovanović, 2010). Precipitation is measured at Dojkinci station, 3 km from the study area, the elevation of which is 600 m lower. Based on the precipitation gradient, the calculated average precipitation in the Ponor depression is 814.2 mm (Ristić Vakanjac et al., 2018). Considering the data at Topli Do, the average number of days with snow cover is 59, from the beginning of November to the end of March. Since the duration of snow cover rises with elevation (lower air temperature and higher precipitation), on the elevations of about 1,400–1,500 m the period with snow is expanded and the number of days with snow is estimated to 90–100 (Milovanović, 2010). These circumstances are followed by the decrease of soil temperature, as well as by the reduction of freeze penetration depending on aspects (Grab, 2005b). All climatological data are expected to be more extreme, as Ponor is the depression with temperature inversion.

Despite the lack of climatological data, it can be assumed that the thermal characteristics and the freezing/thawing dynamics determine the genesis and existence of thufur. According to the existing calculations, the seasonal frost occurs in Ponor depression during the winter period, which enables the thufur development. In the absence of the official data, the earth hummocks and other frost-snow landforms present on Stara Planina Mt. offer the indirect information on climate conditions at higher elevations and they are valuable from the climatological aspect (Milovanović, 2010).

In accordance with the above physio-geographical conditions, there is specific runoff, the values of which, in the broader area of Ponor depression (according to Urošev et al., 2020), vary from 6 $l/s/km^2$ to 16 $l/s/km^2$. These values are obtained from the rainfall-runoff model, since this is an area without hydrological stations – the nearest one is at Visočka Ržana, 10 km to the south from the study area.

The vegetation consists mostly of natural meadows with perennial grasses, occasionally grazed by livestock owned by local population. The most typical grasses are *Sesleria coerulans* Friv, *Agrostis rupestris* and *Festuca supina* (Lakušić & Ćetković, 2007). At the northern outskirts of the depression there is a small wood community of moesian beech (*Fagus sylvatica* subsp. *Moesiaca*). The bottom of the depression is characterised by hydrophilic vegetation. The most significant is the European purple lousewort *Pedicularis palustris* L. subsp. *Palustris*, having the endangered/vulnerable (EN/VU) Regional IUCN status (Lakušić & Ćetković, 2007). Ponor is its only location on the entire Stara Planina Mt. The swampy locations of Ponor also host *Drosera rotundifolia* L. (having EN–VU status), *Epipactis microphylla* (Ehrh.) Swartz (EN), as well as the association of bittercress *Cardamino amarae-Rumicetum balcanici* R. Jov. 1971 (Lakušić & Ćetković, 2007). It is notable that the majority of thufur are owergrown by breckland thyme (*Thymus serpyllum*, *Thymus praecox*).

3. Data and methods

Field examination showed that the thufur are present in the Ponor depression as discontinuous features, grouped in five areas (DA, DB, DC, DD, and DE; Figure 2). Within each area, measurement of height, length, and width was carried out for randomly chosen thufur, summing up to 305 samples with determined morphometric characteristics. Hand-held GPS receiver was used to delineate particular areas in Gauss-Krueger projection, 7th zone. The analysis of the topographical characteristics of the depression was carried out on the basis of the Digital Elevation Model over Europe (EU-DEM, 2018) with 25 m resolution. Raster analysis in QGIS software (Version 3.14 'Pi') was used to obtain the inclinations, vertical dissection, and Topographic Wetness Index (TWI) of thufur areas. At the open lithological profiles at the bottom of the depression, the proluvial-deluvial sediments were observed, which may be regarded as an addition to the data of the Basic geological map (1:100,000), sheet Pirot.

Thufur morphometric characteristics (height—h, shorter diameter—d_1, and longer diameter—d_2) were measured, their relations defined as h/d_1 and h/d_2, while the indices were calculated. These five variables were analyzed using methods of descriptive statistics (minimum, maximum, mean, standard deviation, and median), as well as inferential statistics for homogeneity tests (one-way ANOVA, followed by post hoc Tukey test; Kruskal-Wallis followed by post hoc Mann-Whitney test; and Epps–Singleton test). All tests were performed with the significance level $\alpha = .05$. Despite the outliers found through the descriptive statistics analysis, the whole sample of 305 thufur was further analyzed.

For the distribution of thufur characteristics, five classes were made according to class ranges determined with sigma rule division of probability of occurrence (Upton & Cook, 2014):

$$P = \bar{x} \pm n\sigma \tag{1}$$

where P is probability of occurrence, $\bar{x}$ is mean value, n is the number of standard deviations and σ is the standard deviation. The obtained values of P were treated as class ranges.

In order to calculate the eccentricity of ellipsoidal thufur base, we have used the following expression:

$$\mathrm{e} = \sqrt{1 - \frac{\left(\frac{d_2}{2}\right)^2}{\left(\frac{d_1}{2}\right)^2}} \tag{2}$$

where e is ellipse eccentricity, d_1 shorter diameter and d_2 longer diameter. These analyses were performed in MS Excel and PAST softwares.

4. Results

4.1. Macro-location

All mapped thufur areas are situated either in the central part or at the rim of the Ponor depression. Its outline can be determined using two criteria. The first follows the topographical divide and we label it as the depression *sensu lato*. Its orthogonal area is 2.3 km^2, with the height difference of 176 m between the lowest and highest point (Figure 2).

The depression *sensu stricto* is determined by the highest closed contour at 1,441 m a.s.l. Since the lowest point is at 1,408 m, it can be calculated that the *sensu stricto* volume is 15 × 10^6 m^3 (Table 1).

Table 1. Morphometric characteristics of the Ponor depression

Ponor definition criteria	Elevation (m a.s.l.)			Inclination (°)			Area (km^2)
	min	max	mean	min	max	mean	
Topographical divide (*sensu lato*)	1,408	1,584	1480	0	23	8.2	2.3
Highest closed contour (*sensu stricto*)	1,408	1,441	1425	0	23	7	0.5

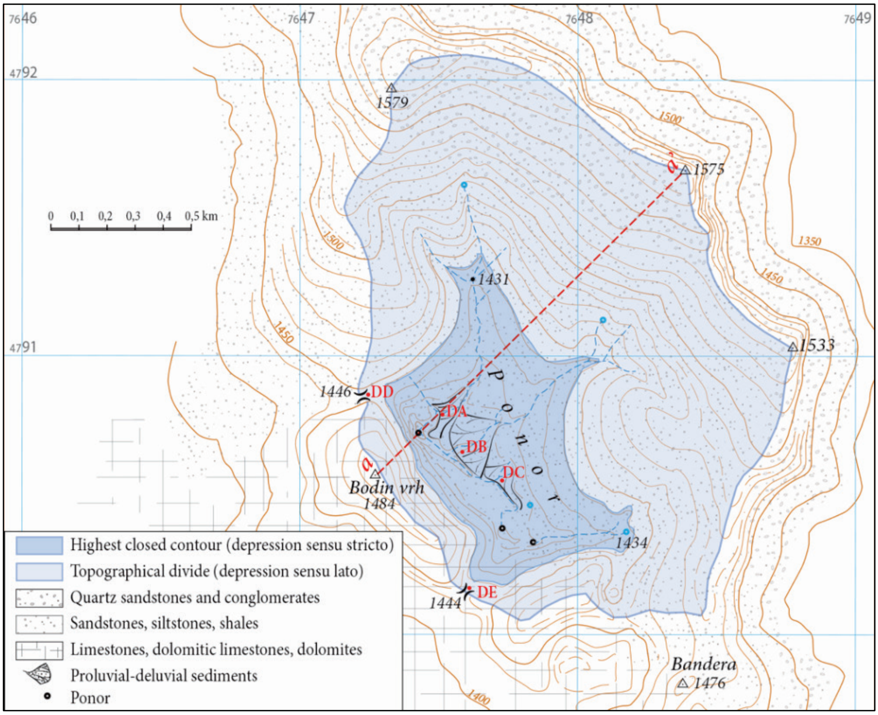

Figure 2. Ponor depression outlines and lithological composition.

4.2. Topography

Topographic analysis included the elevation, inclination, and vertical dissection of thufur areas (Table 2). All the areas are situated in the hypsometric belt between 1,412 m and 1,445 m a.s.l. Thufur are present on the inclinations ranging from 1° to 9°. The lowest inclination is present in the DA area (average 3.5°), while the highest (average 6°) is found in DC. The inclinations are in accordance with the previous studies (Grab, 2005b; Marcu, 2011; Milošević et al., 2015). Regarding the vertical dissection, thufur are developed on the areas dissected up to 10 m/2,500 m^2 (Figure 3). This means that they are present on poorly drained terrain sections that keep the soil moisture for longer time.

Topographic Wetness Index (TWI) was used for the analysis of potential wetness and it showed that the largest part of the depression area has the low index values—up to three (very dry) and up to six (dry). At the very bottom of the Ponor depression, the TWI values are highest, up to the maximum of 15.7 (very wet). Among the zones of thufur occurrence, the highest TWI is in the zone DA (11) and the lowest in DE (7).

Table 2. Morphometric characteristics of thufur areas

Area	Elevation (m a.s.l.)			Inclination (°)			Topographic Wetness Index (TWI)			Vertical dissection (m/2,500 m^2)
	min	max	mean	min	max	mean	min	max	mean	
DA	1,412	1,432	1,418	1	5	3.5	7.5	13.3	10.9	5
DB	1,412	1,436	1,422	2	9	5	7	12.9	8.9	8
DC	1,413	1,435	1,423	2.5	8	6	6.9	10.9	7.9	10
DD	1,445	1,449	1,447	1	7	3.5	6.7	8.9	8.0	9
DE	1.437	1,445	1,441	1	7	4.5	6.1	8.8	7.0	10

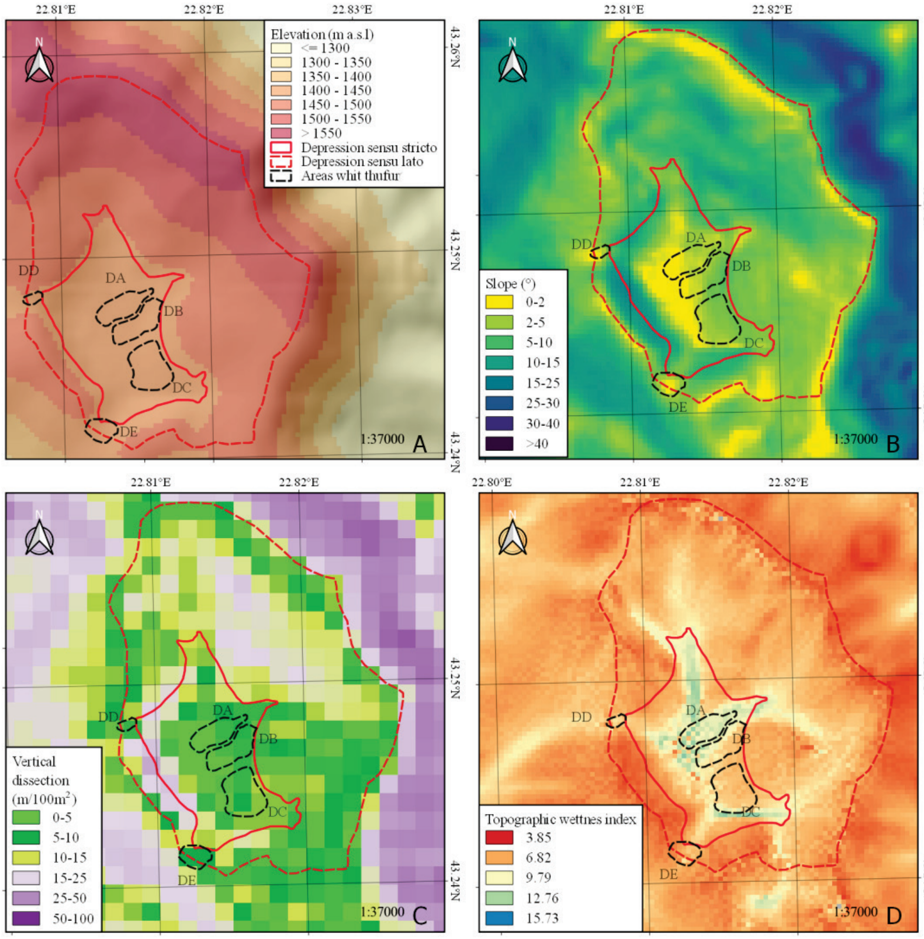

Figure 3. Morphometric characteristics of thufur areas: Elevation (A), Slope (B), Vertical dissection (C), TWI (D).

The spacings between the individual thufur were analyzed for the reason of the comparison between the sites. The input data were based on the sketches created in the field and/or reconstructed from the photo-documentation. Two types of distances were selected for the analysis: average maximum distance *ΔLmax* (cm) and average minimum distance *ΔLmin* (cm) between the thufur, supplemented by the calculation of the thufur density per 100 m^2. At all sites, the distances are proportional to the density, except at the largest site DB, where the *ΔLmax* is slightly higher than at the site DA. Larger thufur distances and smaller density at the sites DD and DE are in accordance with the lower TWI.

Table 3. The spacings between the individual thufur

Site	Average distance (cm)	Average max. distance *ΔLmax* (cm)	Average min. distance *ΔLmin* (cm)	Thufur density /100 m^2
DA	195	237	153	27
DB	187	239	135	28
DC	220	283	157	21
DD	287	350	224	13
DE	310	380	240	8

4.3. Thufur morphology

Within the whole sample, the average thufa height is 30.54 cm, while the average shorter diameter (d_1) is about 59 cm and the average longer diameter (d_2) is about 62 cm. The maximal observed thufa height and diameters, and others morphometric characteristics are presented in Table 4. These data are consistent with the data published by Belij et al. (2008). In comparison with the thufur on Vlasina Lake measured by Milošević et al. (2015), the thufur on the Ponor site are lower, but wider and longer in diameter.

Table 4. Descriptive statistics of thufur morphometry (whole sample, n = 305)

Statistics	h (cm)	d_1 (cm)	d_2 (cm)	h/d_1	h/d_2
Min	17	38	38	0.28	0.24
Max	48	104	115	0.98	0.82
M	30.54	59.37	61.95	0.52	0.50
SD	5.79	10.98	13.43	0.10	0.09
Mdn	30	60	60	0.52	0.50

The analyzed variables (height, shorter diameter, and longer diameter) are distributed with the majority of samples in the class range between one standard deviation around the mean value. In the positive direction (higher values), there are two classes, and in negative direction (lower values), considering the diameters, there is one class (Figure 4). In view of the height, there are two classes, but in the second one, there is just one sample.

Within each site, descriptive statistic parameters are more homogenous and there are just several outliers presented in Figure 4. The highest thufur are located at the site DD, the shorter diameter (d_1) is the highest at the site DE, and at the sites DD and DE have the highest values of longer diameter (d_2). The smallest thufur by both variables (height and diameters) are at the site DC. At the same site, all the variables, except height, vary the least. Considering h/d_1 index the highest values are at site DD, and with the respect to h/d_2 index, the thufur at the sites DA, DC, and DB have the highest values. The lowest values are present at the sites DD and DE. Differences between sites related to variables size are proven by homogeneity tests.

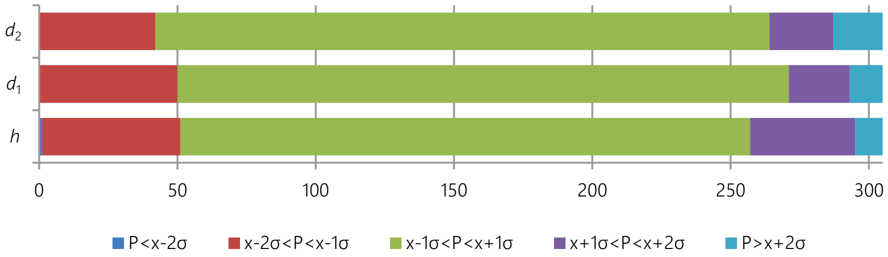

Figure 4. Studied thufur height (*h*), shorter diameter (d_1), and longer diameter (d_2) size distribution.

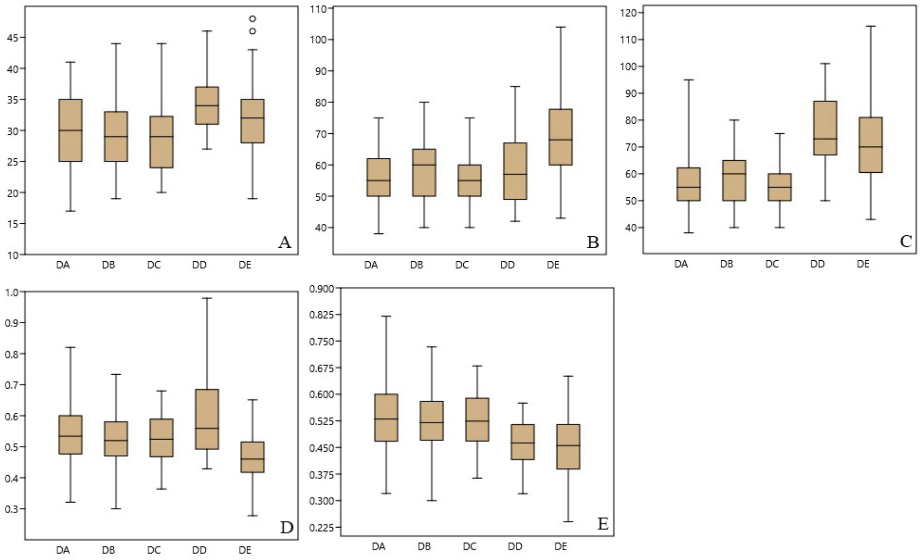

Figure 5. Thufur morphometry: height—*h* (A), shorter diameter—d_1 (B), longer diameter—d_2 (C), height/shorter diameter index (D), height/longer diameter index (E).

Note. Short and long diameters are the same in the case of circular thufur.

Considering the height, thufur at sites DA, DB, and DC significantly differ from thufur at site DD, and thufur at sites DB, DC, and DD significantly differ from thufur at site DE (Figure 5). Shorter diameter at site DE is significantly different from shorter diameters at all other sites. Regarding longer diameter, h/d_1 index, and h/d_2 index, thufur at sites DA, DB, and DC differ from thufur at sites DD and DE. In addition, with respect to h/d_1 index thufur at site DD significantly differ from those at site DE. During the field work it was obvious that some thufur samples are elongated. This implied that thufur with forms of spherical domes (with circular base) and thufur with forms of elongated domes (with ellipsoidal base) had to be analyzed separately.

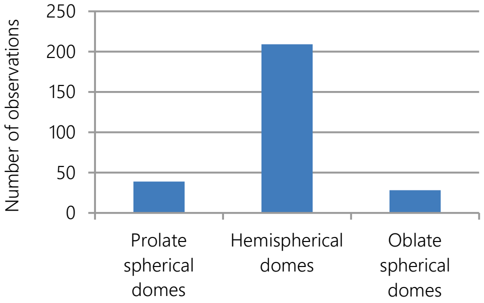

Figure 6. Frequency distribution of studied thufur forms (with circular base).

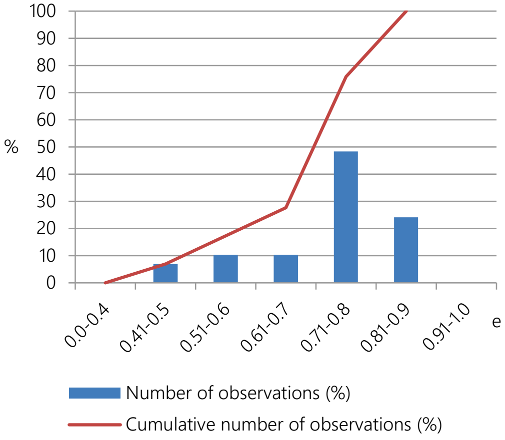

Figure 7. Distribution of elongated thufur's eccentricity.

4.3.1. Spherical domes

After the classification of thufur forms given by Milošević et al. (2015), which refers to the thufur with a circular base, all three types of thufur appear in Ponor depression. Hemispherical domes dominate (Figure 6 and 11).

4.3.2. Elongated domes

Thufur with ellipsoidal base have different base eccentricity. The analysis of the relation between thufur's diameters (eccentricity) shows the range from 0.43 to 0.87 (Figure 7). This means that the relation between diameters are such that longer diameter is maximal twice as large as the shorter diameter. Only one of the observed thufur has such eccentricity, i.e., longer diameter twice larger than shorter diameter. One-third of the observed elongated thufur have eccentricity up to 0.7 which means that longer diameters are up to 25% longer than shorter diameters. The majority of the observed elongated thufur (48%) have the eccentricity between 0.7 and 0.8 which means that the longer diameters are about 50% longer than shorter diameters.

Thufur morphology depends on their base. Thufur with circular base are spherical domes, while those with ellipsoidal base are elongated domes (Table 5). Theoretically, with respect to vertical profile, which can be prolate, semicircle and oblate (Figure 8), both groups can be prolate, hemispherical, or oblate (Table 5).

Table 5. Morphlogical classification of thufur

Thufur shape		
Vertical profile	Horizontal profile (base)	
	Circular ($d_1 \approx d_2$)	Ellipsoidal ($d_1 \neq d_2$)
Prolate ($h > d/2$); $h/d > 0.6$	Prolate spherical dome	Prolate elongated dome
Semicircular ($h \approx d/2$); $0.4 < h/d < 0.6$	Hemispherical dome	Hemispherical elongated dome
Oblate ($h < d/2$); $h/d < 0.4$	Oblate spherical dome	Oblate elongated dome

Analysis of elongated thufur in the Ponor depression shows that there are no prolate elongated domes, and that there are slightly more hemispherical than oblate elongated domes (Figure 9). This kind of distribution can be related to the fact that if the horizontal dimension is more developed, the vertical one is reduced. Therefore, there are oblate and hemispherical elongated domes (with dominantly developed horizontal dimension) and no prolate elongated domes (with both horizontal and vertical dimension developed).

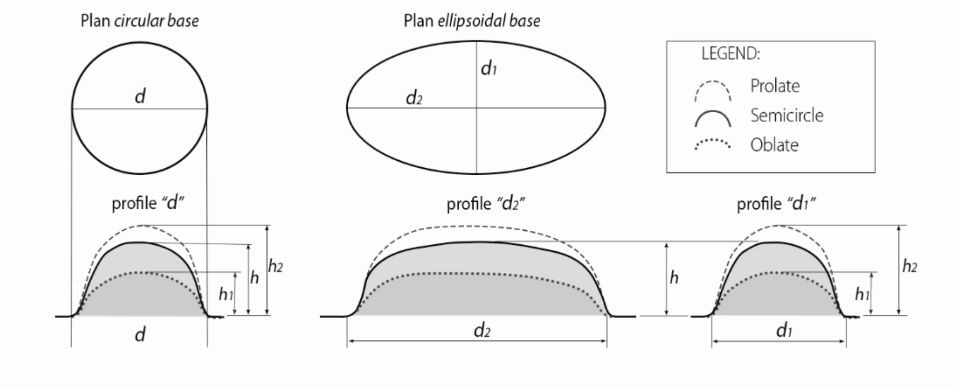

Figure 8. Relations between plan and profile views of different thufur types.

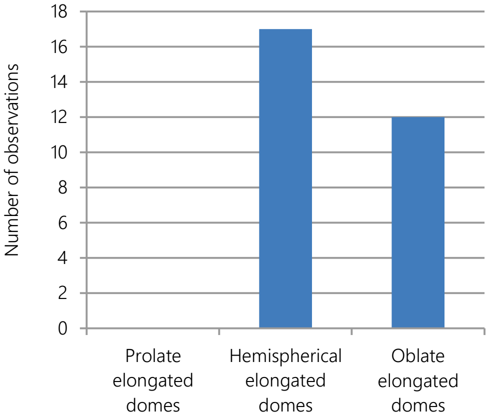

Figure 9. Frequency distribution of the studied thufur forms (with ellipsoidal base).

5. Discussion

The occurrence of thufur in the Ponor depression is of azonal character, considering the fact that they are present in the span from 1,412 m and 1,449 m n.v. The occurrence of thufur at lower elevations was also mentioned by Jahn (1975), Wahsburn (1979), Treml et al. (2010), Killingbeck and Ballantyne (2012). The landform hosting the thufur (DA, DB, and DC) is a depression which is fully closed up to the 1,441 m contour (depression *sensu stricto*). If we consider the elevation of the depression bottom (1408 m), we can conclude that there is a vertical span of 30 m thickness in which the conditions for cold air accumulation exist (Figure 10), including the occurrence of temperature inversions. In the published calculation of the mean annual air temperatures in Ponor (Ristić Vakanjac et al., 2018), this factor was not taken into account, but only the linear dependence of air temperature gradient to the elevation. This means that even the lower mean annual air temperature than the calculated 4.3 °C could be expected, which is in accordance with the maximum average air temperature enabling thufur formation (Grab, 2005a; Kim, 2008; Koaze et al., 1974).

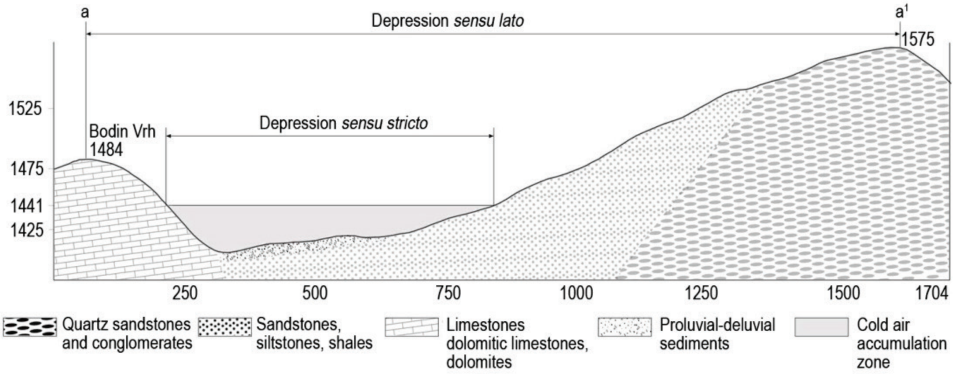

Figure 10. Ponor depression—cross section (see Figure 2 for the direction).

The lack of forest vegetation in the depression also points out to the alternation of microclimatic conditions. The lowest beech areas are present a bit higher than 1,440 m elevation contour (Figure 1). Two remaining areas (DD and DE) are situated on the saddles—the lowest points of topographical divide (depression sensu lato). We suppose that these are the points of "overflow" of cold air from the depression toward the Dojkinačka Reka River valley, thus providing the specific microclimatic "thufur-prone" conditions (Milošević et al., 2015). Local winds cause the deflation of the snow from the saddles, thus decreasing the snow insulation effect and, accordingly, the soil temperature (French, 2007; Treml et al., 2010).

Regarding the topographical conditions, thufur should theoretically be present in the zone of proluvial-deluvial sediments, on the inclinations from 1° to 9°. However, this is not sufficient, due to the impact of vertical dissection. In the central part of the Ponor depression there are flat areas without the presence of thufur, the dissection of which ranges from 15 to 25 m/2,500 m^2. The water draining process is more intensive and the soil moisture necessary for thufur formation is decreasing (Milošević et al., 2015). Therefore, they are present only in the zone with up to 10 m/2,500 m^2 of vertical dissection. Furthermore, the dissection causes smaller dimensions, which is obvious in the area DC, having the smallest thufur among all the analyzed areas. Considering the significance of soil wetness for thufur existence, TWI values may provide valuable information. Morphologically best developed thufur are present in the areas DA and DB, having high TWI, while the smallest thufur dimensions are present in the areas DC and DE, with the lowest TWI. Although the maximum values are present in the lowest parts of the depression (TWI 15; Figure 3), the thufur are lacking, probably due to exceptionally high soil water content.

Figure 11. Thufur—hemispherical dome (site DB).

Average morphometric characteristics of the Ponor thufur are: height of 30.54 cm, shorter diameter (d_1) of 59 cm, and longer diameter (d_2) of 62 cm. Compared to thufur dimensions in the polar areas (Luoto & Sepällä, 2002; Tarnocai & Zoltai, 1978), Ponor thufur are considerably smaller (in height up to 100% and in diameter up to 300%), thus being similar to other examples reported from the middle latitudes (Grab 1994; Marcu, 2011; Mark, 1994), varying in size for +/– 10%–30%. Regarding the morphology, it is significant to point to the presence of elongated thufur, which is the first observed example in Serbia. On the global level, this morphological type is described and explained by coalescence of neighboring thufur (Grab, 2005b). In Ponor depression, such forms have been determined in the areas DD (20 examples) and DE (8 examples), in the cold air overflow zones. Their forms are either oblate or hemispherical, while prolate elongates examples have not been noticed. As the thufur’s long axis is in accordance with this direction, we can suggest that this is one of the factors that had the impact on elongation, although for now this is just a hypothesis to be questioned in further research of this morphological type.

6. Conclusion

Azonal development of thufur in the Ponor depression is caused by relief-related modifications of microclimatic conditions. Accumulation of cold air at the bottom of the depression leads to temperature inversion, with significantly lower temperatures than at the outskirts. Therefore, the thufur existence may be an indicator of thermal regimes equivalent to periglacial areas.

Thufur morphometry is directly related to soil wetness, in terms that the higher wetness contributes to the larger dimensions of thufur. The soil wetness has been indirectly analyzed through the vertical dissection of relief and TWI.

Two morphological types of thufur have been observed—circular and elongated. In the case of elongated thufur, we suppose that their shape is influenced by the airflow through the mountain saddles, thus decreasing the soil temperature, which needs to be elaborated in further studies. Our research may be regarded as a contribution to stressing the significance of future monitoring and studying of periglacial processes and landforms, in the context of the present and future climate-related challenges.

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