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SUB-ALPINE PERIGLACIAL MORPHOLOGY OF THUFUR ON THE SOUTHERN RIM OF VLASINA LAKE, SERBIA

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With 11 figures and 6 tables

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Summary: The paper elaborates on the occurrences of thufur (earth hummocks, pounus) in a sub-alpine periglacial environment of the Vlasina Lake (1210 m a.s.l.) in south-eastern Serbia. Field examination encompassed 8 sites at the southern rim of the lake, at altitudes from 1220 m to 1274 m, where 240 thufur were measured for height (av=32 cm) and diameter (av=51 cm). Parameters of topography (relative heights, gradient, aspect) and overall morphology are analysed as well. The lake basin represents an area of cool air accumulation and temperature inversions. The upper limit of this zone, where 7 out of the 8 studied sites are situated, is the highest closed contour at 1243 m. Analysis of the relation between lithology, morphology and groundwater drainage showed that thufur on poorly drained sites are well developed, whereas the sites with good drainage are characterized by relatively small thufur. Detailed study of the height/diameter relation enabled differentiation between three morphological types of circular thufur: prolate spherical domes, hemispherical domes and oblate spherical domes.

Zusammenfassung: Die vorliegende Arbeit beschäftigt sich mit dem Vorkommen von Thufur (earth hummocks, Erdbülten, pounus) in einer subalpinen periglazialen Zone des Vlasina Sees (1210 m ü.M.) im südöstlichen Serbien. Die Felduntersuchung umfasste 8 Standorte am südlichen Rand des Sees auf der Höhe von 1220 m bis 1274 m, wo insgesamt 240 Thufur nach Höhe (32 cm im Durchschnitt) und Durchmesser (51 cm im Durchschnitt) gemessen wurden. Die topographischen Parameter (relative Höhe, Neigung, Exposition) und die allgemeine Morphologie wurden auch analysiert. Das Seebecken stellt den Bereich von Kaltluftakkumulation und Temperaturinversion dar. Die obere Grenze dieser Zone, wo sich 7 von 8 untersuchten Standorten befinden, ist die höchste geschlossene Isohypse auf 1243 m Höhe. Die Analyse des Verhältnisses zwischen Lithologie, Morphologie und Grundwasserentwässerung zeigte, dass die Thufur auf schlecht entwässerten Standorten gut entwickelt sind, während die Standorte mit guter Drainage mit relativ kleinen Thufur gekennzeichnet sind. Eine detaillierte Studie über das Höhe / Durchmesser-Verhältnis führte zur Unterscheidung von drei morphologischen Typen von Kreisthufur: verlängerte sphärische Kuppeln, halbkugelförmige Kuppeln und abgeplattete sphärische Kuppeln.

Keywords: Periglacial morphology, thufur, earth hummock, Vlasina Lake, Serbia

1 Introduction

In most references elaborating on hummocky terrains in periglacial areas, the terms “thufur” and “earth hummock” are synonyms. Furthermore, the term “pounu” is used for the same landform as well. The *Glossary* edited by Van Everdingen (1998, revised 2005, 84), which is regarded as one of the basic references in permafrost and ground-ice terminology, defines thufur (an Icelandic term, plural of “thufa”) as “perennial hummocks formed in either the active layer in permafrost areas, or in the seasonally frozen ground in non-permafrost areas, during freezing of the ground“. In the same source, the earth hummocks are defined as hummocks “having a core of silty and clayey mineral soil which may show evidence of cryoturbation”. Definitions are based on the works of Thorarinsson (1951), Schunke (1975) and Scotter and Zoltai (1982). Schunke and Zoltai (1988, 231) link these forms to the areas of seasonal ground frost patterns, stressing that the process encompasses the “permanent displacement of local surface material in frost-sensitive soil in the presence of plentiful moisture under climatic conditions that generate seasonal frost penetration”. Van Vliet-Lanoë and Seppälä (2002) differentiate between peat pounu, peat mineral pounu and minerogenic pounu, only the last one being synonymous with the terms “thufur” and “earth hummock”, and containing a larger part of cryoturbated mineral core with smaller part of humified peat on top. Grab (2005a, 140) summarizes knowledge on these forms (“miniature cryogenic mounds”) and suggests that the term should apply to the mounds “...generally

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less than 1.5 m in height", which usually occur "in large groups or fields", and are "*capable* of forming in seasonally frozen ground" (as well as in permafrost environments).

Several authors define both external and internal thufur morphology. Schunke and Zoltai (1988) and Grab (1994) consider their morphometric characteristics (height and width) and report on circular and oval (elongated) thufur "in ground view" (Schunke and Zoltai 1988) or "in outline" (Kim 2008). The structure and composition of internal morphology have also been considered (usually distorted soil layers with rock fragments).

The main aim of this particular study is to contribute to the knowledge of the relation between morphology and micro-location in sub-alpine periglacial environments. The objectives of the paper are (1) to define the factors which determine the spatial distribution of thufur on the southern rim of the Vlasinsko Jezero Lake (in further text: Vlasina Lake) in south-eastern Serbia, and (2) to determine the external morphological characteristics of thufur at the studied location, including the details of the height/diameter relation. The working hypothesis is that the micro-location and topographical characteristics of the area (gradient, aspect, altitude, drainage) influence not only the existence, but also the external morphological characteristics of thufur. The role of groundwater drainage is particularly stressed, through the comparison of thufur on poorly drained and well drained locations. Within the study, eight sites (A-H) of thufur were examined, with 30 examples on each site, which makes 240 studied examples in total.

The novelty of the research lies both in the studied location and in the detailed statistical analysis of thufur external morphology (dimensions and shape). Although the paper treats a local phenomenon, its general relevance lies in stressing the position and morphology of thufur at a relatively low altitude at mid-latitudes, owing to specific micro-location.

1.1 Global distribution of thufur

Thufur are located in both the northern and southern hemispheres (Tab. 1). Their spatial distribution primarily depends on the soil temperature regime, which results from latitude, altitude and local conditions. In the southern hemisphere, thufur have been reported from alpine periglacial regions in South Africa (Grab 1994, 2005a; Kück 1996), Australia (Costin and Wimbush 1973), New Zealand (Mark 1994; Scott et al. 2008) and the Andes of central Chile (Brenning 2005). In the northern hemisphere, they are present in the zones of regional periglaciation (at high latitudes), alpine periglaciation (on the high mountains, above the tree line), as well as sporadically at lower altitudes in the sub-alpine zone, depending on local micro-climatic conditions. Reported thufur occurrences in the zone of regional periglaciation include the Arctic and subarctic areas of Canada (Tarnocai and Zoltai 1978), Greenland (Raup, 1963; Schunke 1977), Iceland (Thorarinsson 1951; Schunke 1977; Gerrard 1992; Van Vliet-Lanoë et al. 1998), Norway – Svalbard (Kvíderová et al. 2011), Finland (Luoto and Sepällä 2002a; Sepällä 2005; Hjort et al. 2007) and Russia – Taymyr (Biasi et al. 2005).

Thufur in the zones of alpine periglaciation are reported from Japan – Hokaido (Matsumoto et al., 2001), Russia – Kazbek (Prosova and Sekyra 1960), Canada – Rocky Mountains (Scotter and Zoltai 1982), Czech Republic (Treml et al. 2010), Romania (Sircu 1978; Marcu 2011; Onaca et al. 2013), Serbia (Belij 1990, 1992) and Ethiopia (Grab 2002). In the zone of alpine distribution of thufur, their altitude increases with decreasing latitude. Distribution and factors affecting periglacial phenomena at mid-latitudes were studied in detail by Höllermann (1985). However, some locations are not actually in the zone of alpine periglaciation, but rather belong to sub-alpine areas at lower altitudes. Although the term "sub-alpine" is not precisely defined in the available climatological references, it is usually considered as an altitudinal belt below the alpine zone (below the tree line). Examples for such thufur locations are: England – West Dartmoor (Killingbeck and Ballantyne 2012), South Korea – Mt. Halla (Kim 2008), Serbia – Mt. Ostrozub (Milošević et al. 2007). Existence of thufur in the sub-alpine zone is determined by appropriate local cryogenic conditions. One of these conditions can be topography with morphological depressions (karst poljes and uvalas, volcanic craters), as well as anthropogenic lowering of the tree line.

1.2 Spatial distribution of thufur in Serbia

Several locations with thufur occur in Serbia, including mountainous parts of the country, south from the Danube and the Sava Rivers, with the total altitudinal span from 990 m to 2320 m a.s.l. The natural limit of zonal alpine periglaciation in Serbia

Tab. 1: Review of global distribution of thufur (earth hummocks, pounus)

	Country	Latitude	Altitude (m a.s.l.)	Periglaciation zone	Thufur dimensions		References
					height (h)	diameter (d)	
			SOUTHERN HEMISPHERE				
Old Man Range	New Zealand	45°20’	1640	sub-alpine	15–30	70–150	Mark (1994), Scott et al. (2008)
Snowy Mountain	Australia	36°26’	1905	sub-alpine	15	30	Costin and Wimbush (1973)
Tiffindell Ski Resort	South Africa	30°39’	2916	alpine	15	37	Kück (1996)
Mashai Valley	Lesotho	29°41’	2950	alpine	32	55x73	Grab (1994, 2005a)
			NORTHERN HEMISPHERE				
Petuniabukta, Central Svalbard	Norway	78°44‘	15	regional	/	/	Kvíderová et al. (2011)
Taymyr Peninsula	Russia	72°42‘	80-110	regional	10–30	30–50	Biasi et al. (2005)
Mackenzie Valley	Canada	65°00‘-70°00‘	≈ 100	regional	40–60	110–160	Tarnocai and Zoltai (1978)
Lapland	Finland	69°45‘	65-640	regional	70	232	Luoto and Sepällä (2002b)
Krafla	Iceland	65°42’	550	regional	90	200	Gerrard (1992), van Vliet-Lanoë et al. (1998)
High Sudetes	Czech Republic	50°44’	1430	sub-alpine	37	167x123	Treml et al. (2010)
West Dartmoor	UK	50°31”	320-440	sub-alpine	5–35	80–200	Killingbeck and Ballantyne (2012)
Aleutian Islands	USA (Alaska)	54°	150-600	sub-alpine	/	/	Schunke (1999)
Făgăraş Mountain	Romania	45°34‘	1800	alpine	50	50–100	Marcu (2011)
Mountains Ushiro-Asahidake	Japan	43°39‘	2190	alpine	/	/	Matsumoto et al. (2001)
Mt. Kazbek	Georgia, Russia	42°42‘	2150	alpine	50	50–80	Prosova and Sekyra (1960)
Mt. Prokletije	Serbia	42°40‘	2240	alpine	17	80	Belij (1990)
Mt. Halla, Jeju Island	South Korea	33°22‘	1710-1840	sub-alpine	16.9	98.3	Kim (2008)
Simen Mountains	Ethiopia	13°15’	3600	alpine	/	/	Grab (2002)

starts at 1900–2100 m a.s.l. (Belij and Kolčakovski 2000). The highest thufur in Serbia are found in this belt, along wide mountain ridges, passes and karstic uvalas of Mt. Prokletije (Rusolija area, at 2240 m) and Mt. Šara (2300 m) (Belij 1990, 1992). Thufur dimensions on these locations range from

70–80 cm in diameter and 20–30 cm in height. Thufur in Serbia exist even lower than in this natural belt. The altitudinal range from 990 to 1900–2100 m a.s.l. is the area of azonal (sub-alpine) thufur distribution. Azonal areals are a consequence of modified climate elements on a micro-level, and may be of natural or anthropogenic origin (Milošević et al. 2007). Natural sub-alpine thufur areals may be present mostly in karstic (poljes, uvalas, blind valleys) and other depressions where periglacial conditions come from air temperature inversions. The examples are blind valleys of Rečke (990 m a.s.l.) and Busovata (1020 m) on Mt. Beljanica (Gavrilović 1968; Belij et al. 1997), Peštersko polje (1165 m) (Belij et al. 2004) in SW Serbia, Ponor uvala on Mt. Stara Planina (1400 m) (Gavrilović 1990; Belij et al. 2008), Vlasina Lake (1230 m) (Milošević et al. 2007). Anthropogenic areals of thufur develop as a consequence of anthropopression – deforestation and lowering of the natural tree line. These activities and subsequent processes have lowered the natural zone of periglaciation by an additional 500–800 m. A typical example is Mt. Ostrozub, where thufur are present from 1420 to 1520 m a.s.l. (Milošević et al. 2007).

2 Study area

Vlasina Lake is an artificial lake in the south-eastern part of Serbia (42˚40' N; 22˚21' E; Fig. 1), close to the state border with Bulgaria. It is situated on a fluvial levelled surface in the upper part of the Vlasina River basin, at 1210 m a.s.l. Construction of the 34 m high embankment dam in 1949 marked the beginning of water accumulation, which submerged the former Vlasina peat bog. The volume of the lake is 107 x 10^2 m^3, and the maximum depth is 22 m in the northern part, close to the dam (Rakićević, 1964). The lake has a shoreline of 132.5 km. Geomorphological research of the wider area was carried out by Cvijić (1896) before the establishment of the lake, as well as Rakićević (1964) and Milić (1984) after the lake had formed. The subject of their studies was morphogenesis of the Vlasina region. Cvijić (1896) considered that the levelled surface is of tectonic origin with the Vlasina peat bog representing the last evolutionary phase of a palaeo-lake. On the other hand, Rakićević (1964) and Milić (1984), judging from the indented

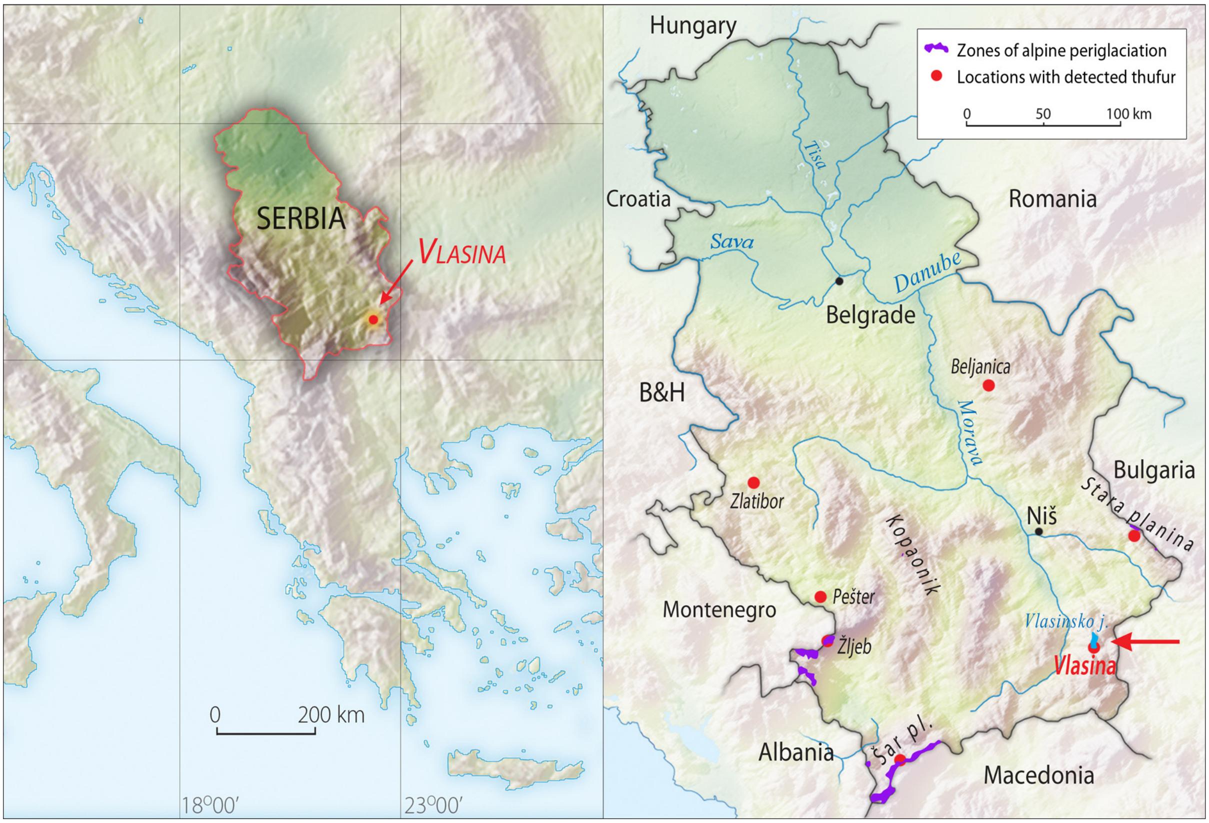

Fig. 1: Periglaciation zones and thufur locations in Serbia, with the position of the study area

coastline and the hydrographic network, interpret the area of Vlasina as a vast fluvial levelled surface. As a consequence of frequent flooding, a swampy area was formed, which evolved into the Vlasina peat bog. None of these authors mention the presence of thufur, probably due to the fact that the focus of their research was on larger-scale landforms. The length of the fluvial levelled surface in the N-S direction is 16.3 km and the maximum width (in the E-W direction) is 3.5 km. A large part of this area is covered by the lake (14 km^2). The hinterland of the Vlasina levelled surface is mountainous with peaks exceeding 1500 m: Gramada (1721 m), Čemernik (1638), Vardenik (1874 m) and Milevska Planina (1738 m).

This paper analyzes eight locations with thufur (sites marked A–H; Figs. 2 and 3) on the southern and south-western rim of the lake. The whole area where the studied locations are situated covers 5.3 km^2, before 1210 m and 1280 m a.s.l. Lithological composition includes Cambrian chlorite schists in the southern part and mica-schists in the SW part (Petrović et al. 1973; Dragišić 1997; Vasković 2002). The southern part, at 300–800 m horizontally from the lake shoreline, is covered with hillslope deposits of Quaternary age. The mean annual air temperature (1961–2010) of the Vlasina meteorological station, which is situated within the study area, is 5.9 °C. Negative mean monthly temperatures occur in December, January and February. Autumn months are warmer than those in spring. As a consequence of morphological isolation, minimum air temperatures exceed -30 °C (the absolute minimum of -31.2 °C was measured on January 13th, 1950; Hydrometeorological Survey of Serbia). Negative minimal daily air temperatures in June, July and August occur as well (Tab. 2). Snow occurs regularly, mostly during December–February, with monthly average depths of up to 27 cm (February average during the period 1950–1987). The insulating effect of snow inhibits freezing of the adjacent ground (Sepällä 1994; Grab, 2005b), therefore the best conditions for thufur development are present in March/April and October/November, when negative air temperatures are generally not accompanied by the snow.

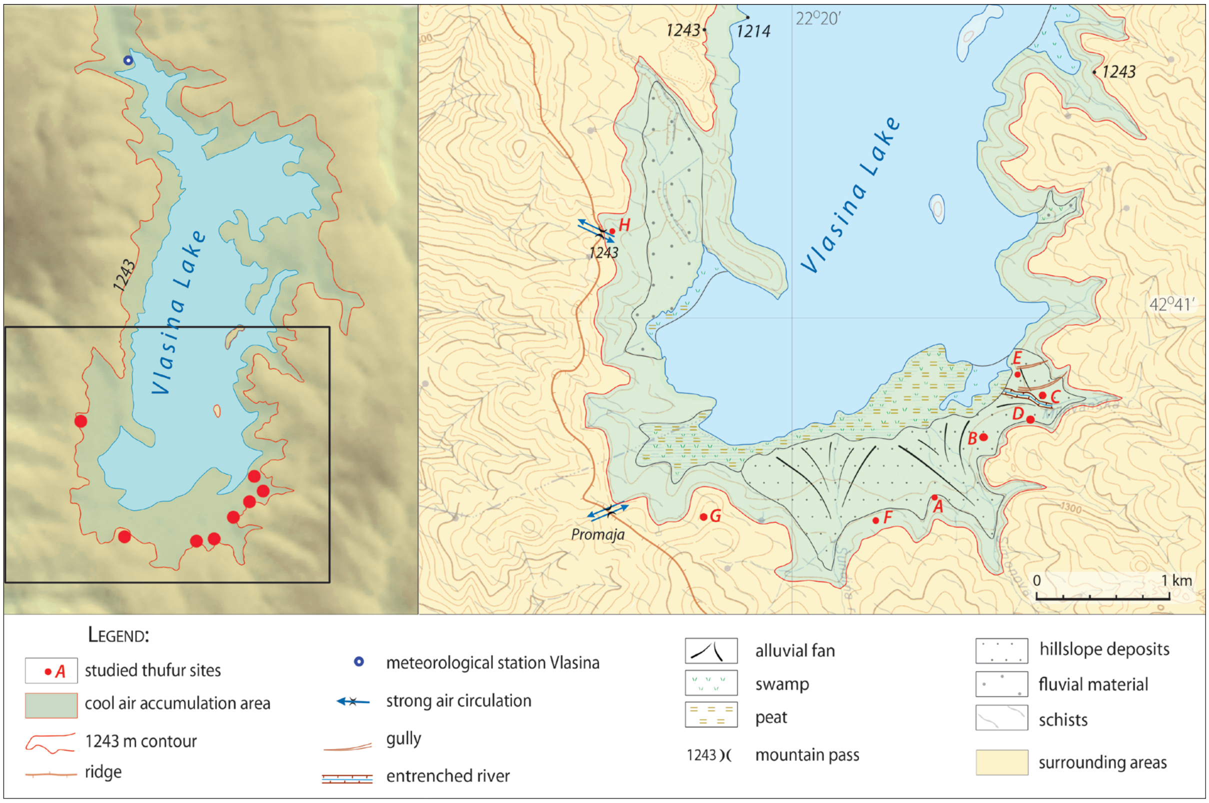

Fig. 2: Positions of the studied thufur sites next to the Vlasina Lake, with geomorphological and lithological characteristics (lithology after Petrović et al. 1973)

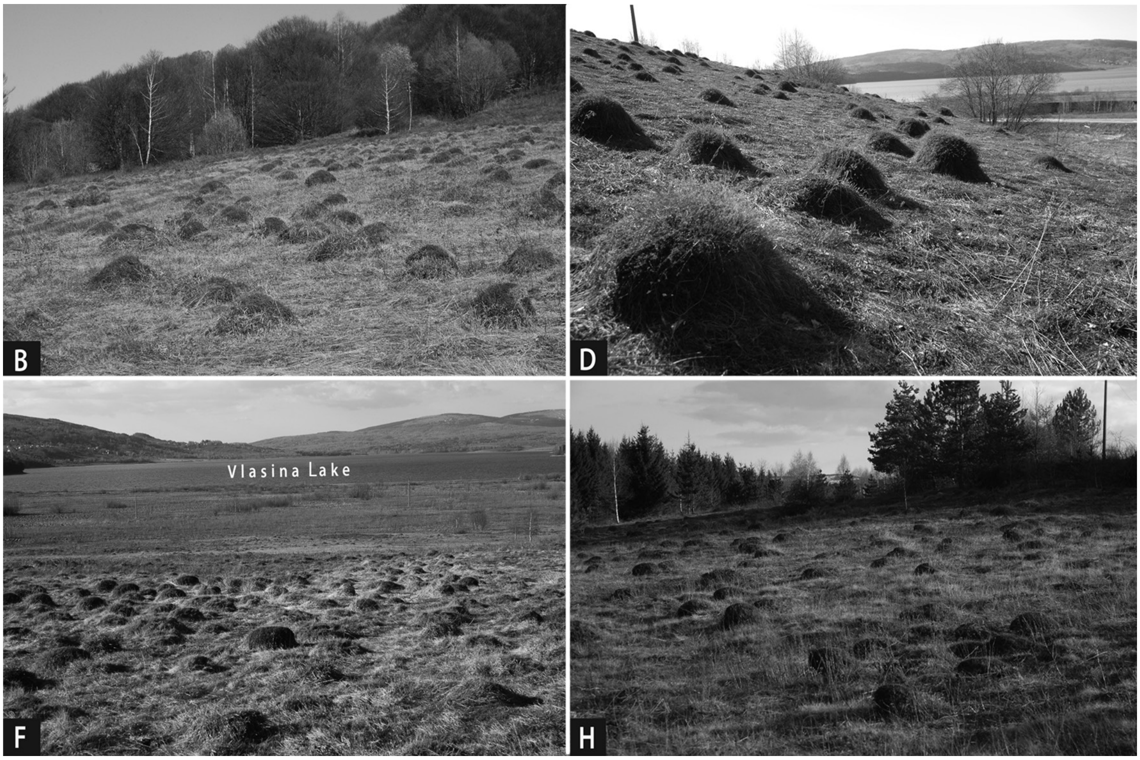

Fig. 3: Thufur by the Vlasina Lake. The letters denote the mapped sites

3 Methods

Eight discontinuous thufur sites (A–H) were mapped in the field: seven on the southern rim of the Vlasina Lake (A–G) and one on the SW rim (H). Precise locations were determined by a hand-held GPS receiver *Trimble Juno*. A high-resolution digital elevation model was created using the topographical maps at a 1:25,000 scale, by digitizing at 10 m and 5 m contour intervals (using the *Intergraph MicroStation 97* software package). Lithological composition was included by digitizing the Basic geological map (Petrović et al. 1973). The GIS package *IdrisiAndes* was used for rasterization of the vector-based input data into a 50 x 50 m grid. Since the details of irregularly-shaped outlines of A–H fields are not relevant to the study, it was approximated that each A–H site refers to one grid cell (closest by its GPS-determined position). Raster-based analysis provided the data on topographic (gradient, aspect, altitude) and lithological characteristics for each thufur site (A–H). *GlobalMapper 12* software was used for subsequent highest closed contour generation on the digital elevation model.

Quantitative analysis of thufur morphometric characteristics included the measurement of height (h) and diameter (d), as well as calculation of their relation (determined by the ratio between the height and the diameter, called the “h/d index”). At 8 sites (A–H) we measured 30 randomly selected thufur per site, which makes 240 observed examples in total. Thufur density was calculated for each site by counting the number of thufur on representative areas 10 x 10 m.

Measurement data were processed using statistical procedures from the two major categories: descriptive statistics and inferential statistics, using the software packages *MS Excel* and *PAST 3.0*. Within the group of descriptive statistics, we used the measures of central tendency, as well as the measures of dispersion (standard deviation). In order to estimate the distribution of the chosen variables (h; d; h/d), their frequency and probability of occurrence, 3 x 240 data series were established. Then, for the thufur classification by height and diameter, five classes were made according to class ranges determined with sigma rule division of probability of occurrence:

$$P = \bar{x} \pm n\sigma \qquad (1)$$

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

Inferential statistics encompassed the randomness analysis (the consecutive differences

Tab. 2: Mean air temperature (1961–2010), mean minimal air temperature (1950–1989), mean absolute minimum air temperature (1961–2010) and absolute minimum air temperatures for each month at the Vlasina meteorological station

	J	F	M	A	M	J	J	A	S	O	N	D
Mean temp.(°C)	-3.7	-2.9	0.7	5.4	10.3	13.3	14.8	14.7	11.0	7.0	2.5	-1.9
Mean min. temp.(°C)	-8.3	-7.3	-4.1	0.5	5.1	7.8	8.9	8.9	6.0	2.3	-1.4	-5.4
Mean abs. min. temp.(°C)	-19.1	-17.8	-14.0	-5.9	-1.2	2.0	3.1	3.1	-0.7	-4.9	-11.0	-15.2
Abs.min. temp. °C)	-31.2	-28.0	-26.6	-10.5	-7.1	-2.5	-1.0	-2.5	-6.4	-9.2	-20.0	-25.0
Year	1950	1991	1987	1996	1978	1990	1993	1981	1977	1991	1989	1953

test – Neyman's test), homogeneity analyses (one-way ANOVA, Mann-Whitney, Student's t-test and Fischer's F-test), cluster analysis and correlation analysis. All tests were performed with the significance level $\alpha=0.05$.

4 Results

4.1 Topography

Topographic analysis includes the gradient, aspect and altitude. In the areas inclined below 2°, within 100 m to 300 m distance from the lake shore, there are no occurrences of thufur. The studied sites closest to the lake are E (110 m from the lake) and B (223 m from the lake). Minimal gradient of thufur area is at the site B (4°). Other sites have the gradients within the interval 5–12° (Tab. 3). These gradients are in accordance with the intervals reported in recent studies: <20° (Grab 2005a), <15° (Killingbeck and Ballantyne 2012) and <15° (Marcu 2011), although partially opposed to previous results (e.g. up to 6°; Schunke and Zoltai 1988). The general aspect of the southern rim of Vlasina Lake is northerly (337°–22°), except for the outskirts with western (C, E) and eastern (H) aspect.

Altitudes of particular sites, ranging from 1220 to 1274 m a.s.l. are given in table 3. Regarding the relative heights, all sites are located within the zone up to 27 m above the mean level of the lake, except the G field, which is at 67 m above the lake.

In order to emphasize the position of small landforms on large-scale landforms, the notion of a "host-form" is introduced. Small relief forms (in this case thufur) are situated on or within larger relief forms, which act as host-forms. Host-forms may be regarded through several orders (levels). A landform of the 1st order is the largest and hosts all subsequent orders of forms superimposed one above the other. The 1st order host-form, where all the studied thufur fields are situated, is the fluvial levelled surface of the Vlasina River. Superimposed on the 1st order host-form, there are 2nd order host-forms: alluvial-deluvial fan and the eluvium zone. Most of the studied sites are situated on the fan (A, B, C, D, E), whereas other sites are within the eluvium zone (F, G, H). The sites C and E are characterized by their positions next to 3rd order forms – a river valley and a gully cut in the alluvial-deluvial fan. Close to the site C, the fan is cut by the valley of the Milovanska Reka stream, and next to the site E, an unnamed stream has cut a gully (Fig. 2, Fig. 7). The reason why this kind of position is analysed is to contribute to the knowledge on hydrogeological characteristics (drainage) of thufur sites, because relevant references stress the relation between thufur morphology and groundwater drainage (e.g. Van Vliet-Lanoë and Seppälä 2002). Due to decomposition of schists and mica-schists, regolith of 2–5 m thickness was formed. Lithologically, this cover is composed of sands and clays with fragments of quartz, feldspars of various granulations and fine grains of other minerals. Such lithological structure led to the formation of intergranular aquifer with poor filtration characteristics (Dragišić 1997). In the gully, which is cut through the hillslope material, it is possible to see the traces of groundwater seepage through the deposits towards the recipient (gully thalweg). Further elaboration on this issue is given in the discussion section.

Plant communities on thufur locations correspond to typical pasture vegetation (e.g. *Festuco-Nardetum strictae* and *Diantho-Armerietum rumelicae*). A large number of thufur are overgrown with *Thymus praecox*. In the narrow belt around the southern rim of the lake there are neither agricultural activities nor buildings. Cattle breeding is not present to a considerable extent. Unfavourable climatic conditions

Tab. 3: Parameters of topography

Site	Altitude (m a.s.l.)	Aspect (°)	Slope (°)	Distance from ground-water recipient (m)	Thufur density (no./m²)
A	1231	359	5	860	0.28
B	1232	304	4	223	0.26
C	1231	202	5	78	0.08
D	1235	10	12	139	0.13
E	1220	244	6	89	0.16
F	1234	345	6	770	0.30
G	1274	299	9	580	0.18
H	1237	90	5	472	0.17

contribute to generally high depopulation in the area (Milošević et al. 2010).

4.2 Thufur external morphology

Standard statistic parameters for the whole group show that the average thufa height is 32 cm and the average diameter is 51 cm. With such dimensions, they are smaller than thufur in Arctic and subarctic regions (Gerrard 1992; Van Vliet-Lanoë et al. 1998), but similar to those located in regions at lower latitudes (Biasi et al., 2005), including the southern hemisphere (Costin and Wimbush 1973). The maximal observed thufur height is 53 cm, and the maximal diameter is 78 cm.

Descriptive statistic parameters for each variable (height – h, diameter – d, and h/d index) for each mapped site are presented in figure 4.

Analyzing these results, it can be concluded that the thufur with greatest height dimensions can be found at sites F and A, and the widest thufur at site A. Minimal dimensions are characteristic for thufur at site C. At all sites, thufur vary less in diameter than in height. With respect to h/d index, sites H and F have examples with the highest values, and site C has the lowest values. Detailed results of homogeneity tests related to size parameters at particular sites are given in table 4.

The thufur size distribution is presented in figure 5. The majority of examples are in the class that ranges between one standard deviation in both directions, whereas the others are divided into four groups, two in each direction. In both variables h and d, thufur are normally distributed.

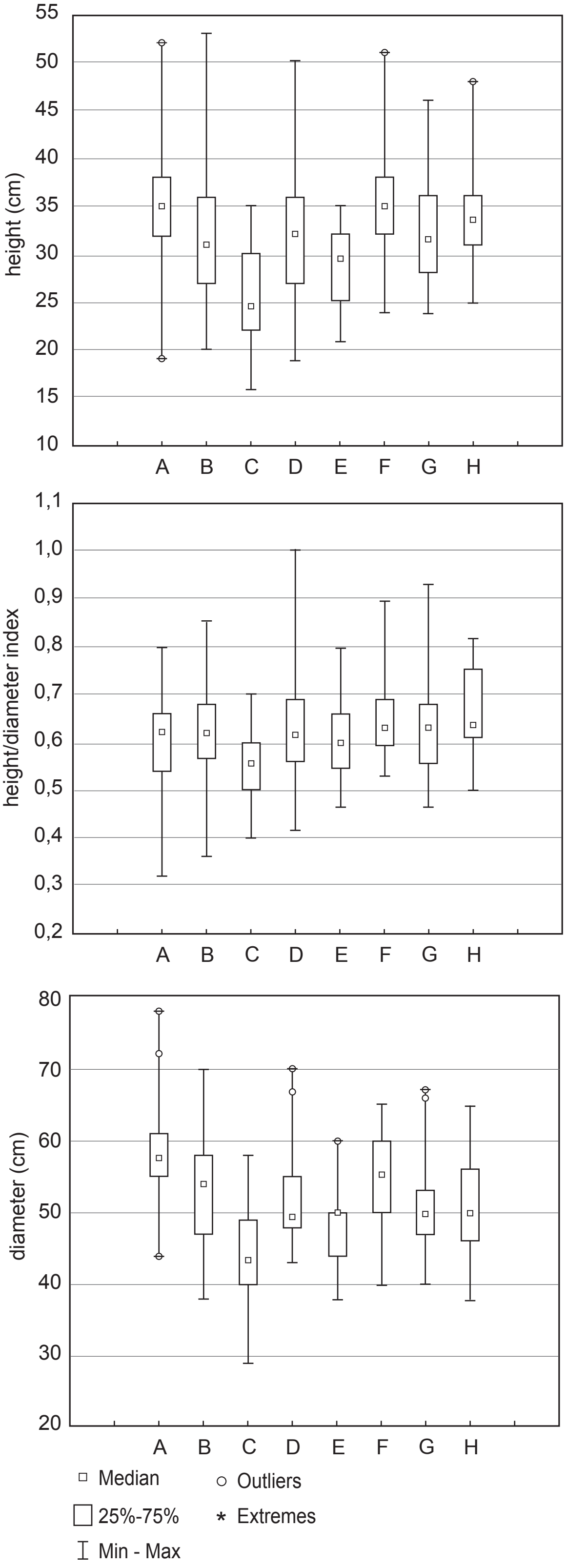

Fig. 4: Descriptive statistics of thufur morphometry

Tab. 4: Results of the inferential statistics tests (α=0.05)

Criteria	Test used	Results
Randomness	Neyman's test	Data series are random at all sites except: - height at B - diameter at F - h/d index at A and D
Homogeneity	Mann-Whitney	Height: - C and E (small) differ from all others - F (high) differs from G Diameter: - A (widest) differs from all others - C (narrowest) differs from others except E - F (wide) differs from all others except B and H h/d index: - H (prolate majority) differs significantly from A, B, C, E - C (hemispherical majority) differs significantly from A and E
	ANOVA	Height: - A (highest) differs from C and E (small) - C (smallest) differs from D, F, G, H - E (second smallest) differs from F and H Diameter: - A (widest) differs from all others except F - C (narrowest) differs from all others except E h/d index: - C (hemispherical majority) differs from F, G, H
	t-test and F-test	- C and E (small) differ from others in all parameters - A (widest) differs in diameter

The Thufur density varies between 0.08/m² (site C) to 0.30/m² (site F), with an average of 0.20/m². These values are far from those in arctic and sub-arctic areas, where the distance between thufur is smaller than their diameter (Tarnocai and Zoltai 1978; Grab 2005a), but relatively similar to those in sub-alpine areas (Killingbeck and Ballantyne 2012; Kim 2008).

5 Discussion

5.1 Topography

Thufur in general occur in the areas where the mean annual air temperature does not exceed 6 °C (Koaze et al. 1974; Grab 1994, 2005a; Kück 1996; Kim 2008). This primary condition is met on the Vlasina Lake, where the mean annual air temperature is 5.9 °C. The reason why thufur are not present within a wider area around the lake but only in its close vicinity, lies in the fact that the bottom of the morphological depression is the accumulation zone of cool air descending from the mountainous hinterland. The temperature inversion determines the existence of periglacial conditions. Similar occurrences of thufur in morphological depressions in the sub-alpine zone are reported by Kim (2008) and Matsumoto et al. (2001) in volcanic craters, as well as by Belij (1997, 2004, 2008) in karst depressions (karst poljes, blind valleys, uvalas).

In order to define the cool air accumulation zone, we supposed that it should be approximately outlined by the highest closed contour. It was derived from the DEM, at 1243 m a.s.l, with a min-

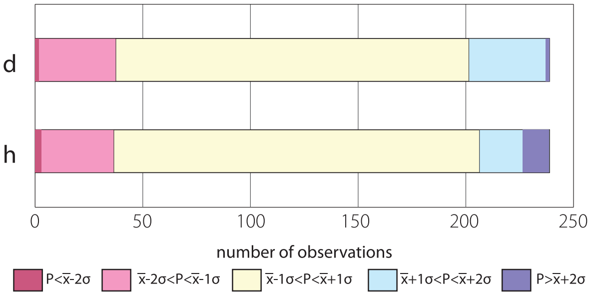

Fig. 5: Studied thufur height (h) and diameter (d) size distribution

imal break in the area of the Vlasina River outflow. Seven out of eight studied sites are situated below this contour, which indicates that they are within the cool air accumulation zone. Above the highest closed contour, there is the site G, at the direct windward position in relation to the pass called Promaja (meaning: the draught, in Serbian language). French (2007) stresses the influence of wind on microclimate in azonal periglacial areas, and Treml et al. (2010) state that thufur may be found at places highly exposed to strong wind. The wind also contributes to snow deflation during winter, which reduces the snow insulation effect.

Topographic gradients of thufur covered surfaces range from 4° to 12°. We did not find any correlation between gradient and morphometric elements (height), as some authors report (e.g. Grab 1994). The smallest, but also the largest dimensions of thufur were observed on topographic gradients of 5° and 6° (sites C, E, A, F). These results suggest that the gradient alone is not a key factor of thufur development.

We used cluster and qualitative analyses of groundwater recipient distance, in order to explain the differences in the thufur size. Two clusters are observed: sites C and E as one cluster and all the remaining sites as another, based on the data on height, diameter and h/d index (Fig. 6). We exclude the theoretical possibility that these differences are due to chance, and suppose that one of the main factors of cluster differentiation is the drainage of a site, conditioned by the morphological position of thufur on other landforms ("host-forms"). Hierarchy of host-forms served as a basis for determination of groundwater recipients for all sites (A–H). Sites C and E are situated next to 3rd order host-forms – on the edges of a small river valley and a gully, which are the groundwater recipients draining the thufur areas. The relative height of site C above the river valley is 3 m, whereas site E is 1.2 m above the gully bottom. Thufur at these two sites are less than 100 m from these recipients, as opposed to other sites where the recipients are farther away. These characteristics indicate the sites within cluster 1 are better drained than sites within cluster 2. Although some references (e.g. those cited in Van Everdingen 1998) claim that thufur growth is favoured by "reasonably good drainage", others state that drainage does not stimulate their development (Tarnocai and Zoltai 1978; Schunke and Zoltai, 1988). Our findings point in favour of the latter statement. Thus, the Vlasina Lake is the recipient for the sites on 1st and 2nd order host-forms (A, B, D, F, G, H), which are poorly drained and thufur well developed. The 3rd order host-forms are the recipients for sites C and E (Milovanska Reka and the gully, respectively) – these sites are well drained, the quantity of groundwater in the upper portions of soil is smaller, and thufur are smaller in size. (see Fig. 7 and Fig. 8)

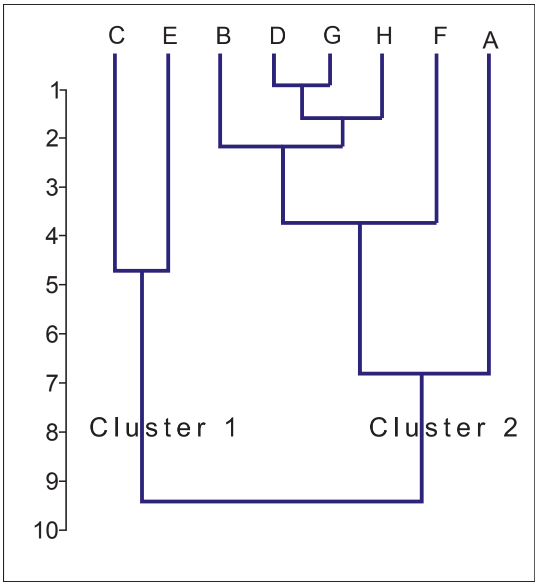

Fig. 6: Tree cluster of sites A–H, based on thufur morphometry (Euclidean distance)

5.2 Thufur external morphology

At the study sites, the h/d index ranges from 0.32 to 1, with an average value of 0.62. There is a considerable difference of Vlasina thufur average h/d index in comparison with other locations in Serbia and abroad. It is three times larger than the h/d index on Mt. Maja Rusolija in southern Serbia (0.21; Belij 1990) and twice as large as that on Sudeti Mts. in Czech Republic (0.32; Treml et al. 2010). The average h/d indices reported in many papers (Grab 1994; Kim 2008; Marcu 2011; Killingbeck and Ballantyne 2012) are also smaller than those of Vlasina thufur.

Given the large h/d index interval (0.32 to 1), it is possible to differentiate thufur forms not only morphometrically, but also by their morphology. Generally, by planar shape, thufur (their flat bottom) can be circular ($d_1=d_2$) or elongated (oval; $d_1 < d_2$). Vlasina Lake thufur may be considered circular because the differences between their diameters never exceed 10%. Considering vertical profile, thufur are

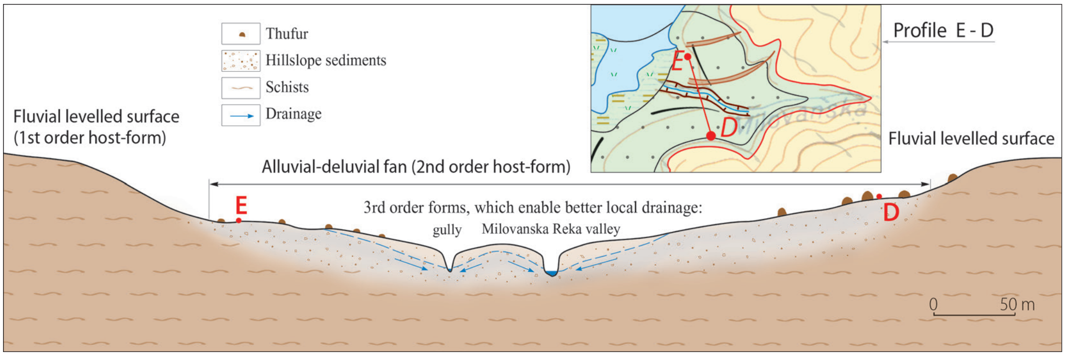

Fig. 7: Cross section showing the position of the thufur sites E and D in relation to other landforms in the study area (with three orders of host-forms hierarchy). Incised forms (gully and the Milovanska Reka valley) have enabled better groundwater drainage, which have led to smaller size of the thufur. See text for details

Fig. 8: View from the site B towards the sites C and E, with the adjoining groundwater recipients

never larger in height than in diameter. Their h/d index can be 1:<1 or 1:1, which enables us to define morphological classes (Tab. 5, Fig. 9). Thus, thufur with a circular base are defined as: hemispherical domes (those whose diameters are twice as large as height, i.e. with the range of h/d index between 0.4 and 0.6), prolate spherical domes (those whose height is larger than half of the diameter, i.e. h/d index higher than 0.6) and oblate spherical domes (those whose height is smaller than the diameter, i.e. h/d index is lower than 0.4). Ideal hemispherical domes have an h/d index of 0.5, but in this study, the h/d index range for hemispherical domes is expanded for 0.1 in each direction (between 0.4 and 0.6).

Tab. 5: Morphological classification of circular thufur

Vertical profile	Thufur shape
Prolate $(h > d/2)$ $h/d > 0.6$	Prolate spherical dome
Semicircle $(h \approx d/2)$ $0.4 < h/d < 0.6$	Hemispherical dome
Oblate $(h < d/2)$ $h/d < 0.4$	Oblate spherical dome

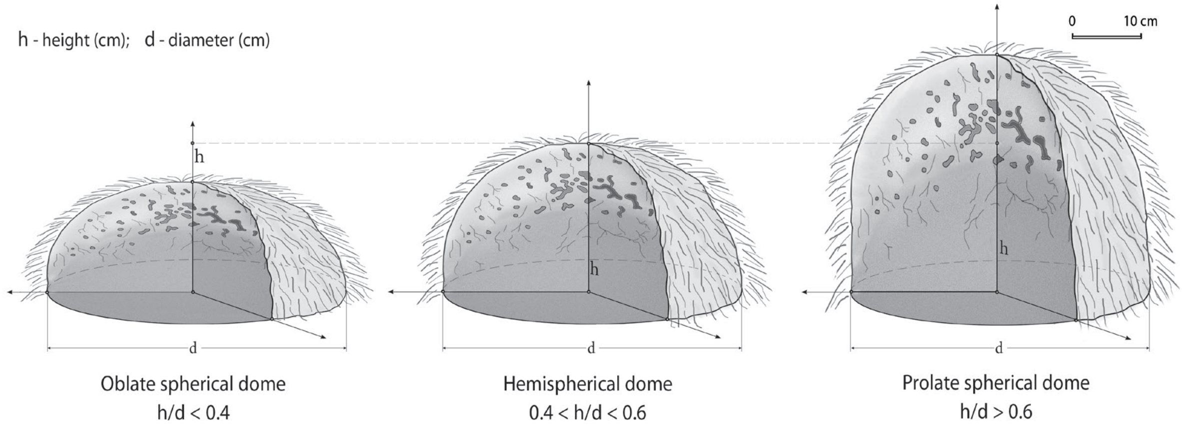

Fig. 9: Dome-shaped circular thufur

The majority of the Vlasina Lake thufur are prolate spherical domes with h/d index greater than 0.6 (Fig. 10). They are most numerous at the site H, followed by the site D, and their smallest number is at the site C. At the site D, we have observed a thufa with "ideal" shape (equal height and diameter) whose h/d index is 1 (D16, Fig. 11). Hemispherical thufur are also widely distributed. They are most numerous at site C, followed by site E. These sites were also singled out through the ANOVA and Mann-Whitney tests. The number of oblate spherical domes is relatively small. Relations of shapes and particular sites is given in table 6.

Within the studied population, there are even thufur which are non-dome-shaped, but resemble crater-like mounds, because of their mature stage of development (cf. Kim 2008). This feature is noticed on thufur A14 (Fig. 11), A12 and B13, and these have the lowest h/d indices (0.32, 0.33, 0.36, respectively). This is in accordance with published data related to patterned ground (sorted nets and sorted polygons; Treml et al. 2010), where the mounds have low h/d indices (even below 0.2) and are considered relict.

Thufur with an elongated base may be defined as ellipsoid domes. Their short diameter (d_1) and height can have the same relations as with circular domes, whereas their long diameter (d_2) is always larger than their height. In vertical sections, almost all thufur observed at the Vlasina Lake are symmetrical. Vertical asymmetry was noticed only at several thufur at site D (Fig. 3), where the topographic surface gradient is 12°, and the downslope side is longer by rule. These examples have a slight tendency towards the category of elongated thufur, but the differences between their diameters are 10% at maximum. Thufur elongation on slopes has also been reported by other authors (Van Vliet-Lanöe and Seppälä 2002; Grab 2005b). The internal morphology of site D thufur does not show the elements characteristic for the category of "slope hummocks" (sub-parallel bands deformed in the downslope direction; *sensu* Lewkowicz and Gudjonsson 1992; Lewkowicz 2011).

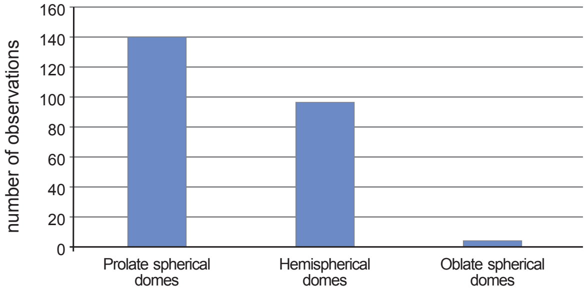

Fig. 10: Frequency distribution histogram of the Vlasina Lake thufur forms

6 Conclusion

The southern rim of Vlasina Lake is a subalpine periglacial zone with thufur occurrences. Thufur vertical distribution is limited primarily by the 1243 m contour line, but also by specific micro-climatic conditions at certain localities above this altitude. Thufur horizontal distribution is determined by lithological composition (regolith of schists and mica-schists), gradient (4°–12°), poor groundwater drainage, as well as pasture vegetation.

Significantly, smaller dimensions and smaller h/d indexes of thufur at the study sites C and E, in comparison to all other locations, are conditioned

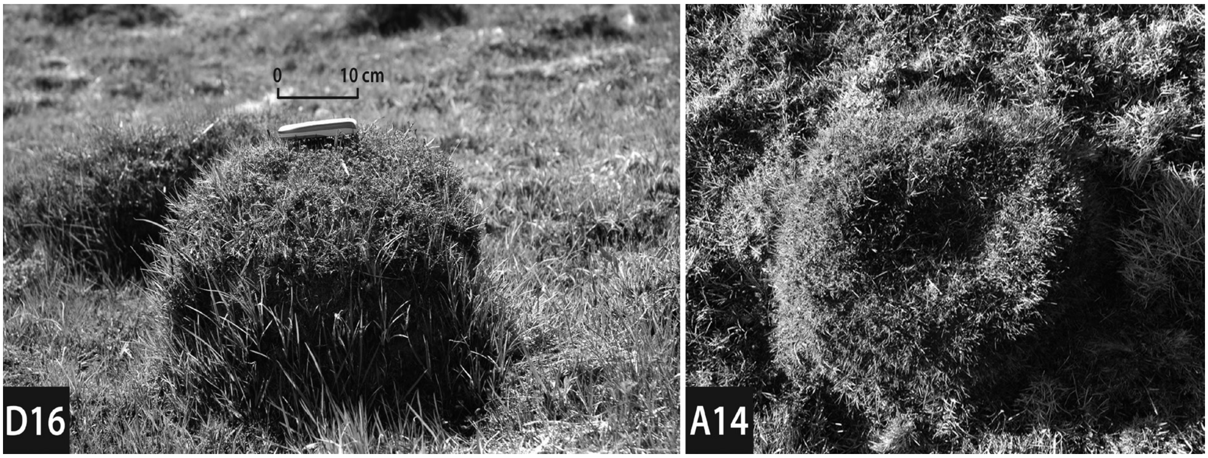

Fig. 11: Left: thufa (D16) with equal height and diameter; Right: thufa (A14) in mature stadium, with a crater-like hollow on top

by better groundwater drainage of these locations. Such drainage is a consequence of the small horizontal distance to the groundwater recipient, and of topographic vertical dissection.

The h/d index defines both morphometry and external morphology. There are three morphological types of circular thufur: prolate spherical domes, hemispherical domes and oblate spherical domes. Further research is needed in order to determine the factors which influence the development of particular types.

Thufur covered areas are only passively utilized by the local population – only as pastures. Thufur in subalpine areas may be regarded as the indicators of microclimatic conditions which are unfavourable for agricultural plant cultivation.

Tab. 6: Distribution of thufur shapes at particular study sites

	Prolate spherical		Hemi-spherical		Oblate spherical		Total
Site	no.	%	no.	%	no.	%	no.
A	17	56.7	11	36.7	2	6.7	30
B	18	60.0	11	36.7	1	3.3	30
C	8	26.7	21	70.0	1	3.3	30
D	20	66.7	10	33.3	0	0.0	30
E	15	50.0	15	50.0	0	0.0	30
F	19	63.3	11	36.7	0	0.0	30
G	18	60.0	12	40.0	0	0.0	30
H	24	80.0	6	20.0	0	0.0	30
Total	139		97		4		240

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