THE SPATIAL DISTRIBUTION OF ROCK LANDFORMS IN THE POHOŘSKÁ MOUNTAINS (POHOŘSKÁ HORNATINA), CZECH REPUBLIC

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View of the Pohořská Mountains from the Nové Hrady Foothills
(Novohradské podhůří)

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ABSTRACT: Geomorphological mapping with an emphasis on rock landforms was carried out in the Pohořská Mountains *Pohořská hornatina*) and the positional data acquired were further processed using statistical and cartographical methods. The spatial distribution of rock landforms was investigated in relation to lithology, slope, orientation, and elevation based on an analysis using ArcGIS 9.1. The spatial distribution of rock landforms was primarily determined by the index of distribution $Wij = Xi / Yj$, where Xi is the percentage representation of landforms in the appropriate category and Yj is the percentage quotient of this category in the entire area studied, and was secondarily determined according to the sum (sum distribution) of the arithmetic mean and the average deviation.

KEY WORDS: geomorphology, rock landforms, lithology, slope, orientation of relief, elevation, Pohořská Mountains (*Pohořská hornatina*), Czech Republic

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1 Introduction

The Pohořská Mountains geomorphological subunit, which is part of the Nové Hrady Mountains (*Novohradské hory*, Figure 1), is insufficiently geomorphologically explored due to its inaccessibility in the past. The border between the Czech Republic and Austria passes through the area studied. The area was part of the Iron Curtain during the Cold War, which means that it was virtually inaccessible. This area also deserves increased attention for other reasons in addition to its particular diversity of relief. The first reason is the progressive inclusion of Czech protected areas in the European Union's nature protection system. The unique landscape of the Nové Hrady Mountains with a variety of aesthetic and natural values is protected by national law no. 114/1992 as a natural park (Collection of… 1992). The second reason is anticipated interference in the environment related to carrying out many investment projects. For these reasons, this area has become the target of multilateral and vital research (e.g., Malíček and Palice 2013; Pavlíček 2004; Rypl 2010; Rypl, Kirchner and Dvořáčková 2014; Štykar 2005).

Geomorphological mapping with an emphasis on rock landforms was carried out in the Pohořská Mountains and the positional data acquired were further processed using statistical and cartographic methods.

Other authors have also dealt with the spatial distribution of rock landforms in other parts of the world. Hjort, Etzelmuller and Tolgensbakk 2010 defined the effects of scale and data source in periglacial distribution modeling in a high Arctic environment in western Svalbard, and Marmion et al. (2008) compared predictive methods for modeling the distribution of periglacial landforms in Finnish Lapland. Ridefelt, Etzelmuller and Boelhouwers (2010) dealt with spatial analysis of solifluction landforms and process rates in the Abisko Mountains in northern Sweden. Marvánek (2010) discussed the distribution of cryogenic periglacial landforms in the Krumgampen Valley (Ötztal Alps). Křížek (2007) and Křížek, Treml and Engel (2007) defined the spatial distribution of cryogenic landforms above the alpine timberline in the High Sudetes (*Vysoké Sudety*) and in the Giant Mountains (also known as the Krkonoše Mountains). The references described were used from the viewpoint of methodological approach and to evaluate the spatial distribution of the research data obtained for comparison with other areas.

This paper discusses the distribution of geomorphological landforms in the area studied and its dependencies on the characteristics of relief and subsoil geology. The results obtained can be compared with similar areas that developed on granite rocky relief (Migoń 2004b) and can help in the study of complex solutions to problems in the structural control of evolution in granite landforms.

2 Study area

Late Variscan migmatites of the Central Moldanubian Pluton prevail in the area (represented by several types: Weinsberg granite, Freistadt granodiorite, and Mrákotín granite), being partially overlaid by cordierite gneisses and migmatites representing remnants of the pluton's mantle (Pavlíček 2004).

The prevailing relief of the Pohořská Mountains has characteristic elements of a fault-block mountain range with delimitations strongly marked by erosion, and it is also polygenetic. Here is possible to find recent forms (rounded blocks of various sizes, alcoves, and grooves) and also fossil forms that are conserved in granite rock, such as exfoliation joints, tors, and frost-riven cliffs (Demek 1964).

Tables 1 through 4 show the percentage quotient in relation to all mapped categories of relief (lithology, slope, slope orientation, and elevation) in the Pohořská Mountains.

Table 1: Percentage quotient representation of lithology.

Lithology	Granite	Gneiss and migmatite	Sediments	Residue
Percentage quotient	56.84	30.61	11.52	1.03

Table 2: Percentage quotient representation of slope.

Slope	0–2°	2.1–5°	5.1–10°	10.1–20°	above 20.1°
Percentage quotient	9.77	19.73	48.28	20.71	1.51

Table 3: Percentage quotient representation of slope orientation.

Slope orientation	N	NE	E	SE	S	SW	W	NW	Plain
Percentage quotient	14.54	15.01	9.67	5.47	7.15	12.44	14.14	13.07	8.51

Table 4: Percentage quotient representation of elevation.

Elevation (m)	560–600	601–700	701–800	801–900	901–1,000	1,001–1,072
Percentage quotient	0.87	14.82	36.85	31.98	14.57	0.91

There are also granite areas with spectacular landforms in the Czech Republic. The Jizera Mountains (*Jizerské hory*, Figure 1) are among granite areas with extensive protection as a protected landscape area. The Giant Mountains and the Podyjí area (Figure 1) are also among granite areas with extensive protection as national parks. Although the Nové Hrady Mountains are an area with well-preserved spectacular granite landforms in the Czech Republic, there is no appropriate protection of the Nové Hrady Mountains today.

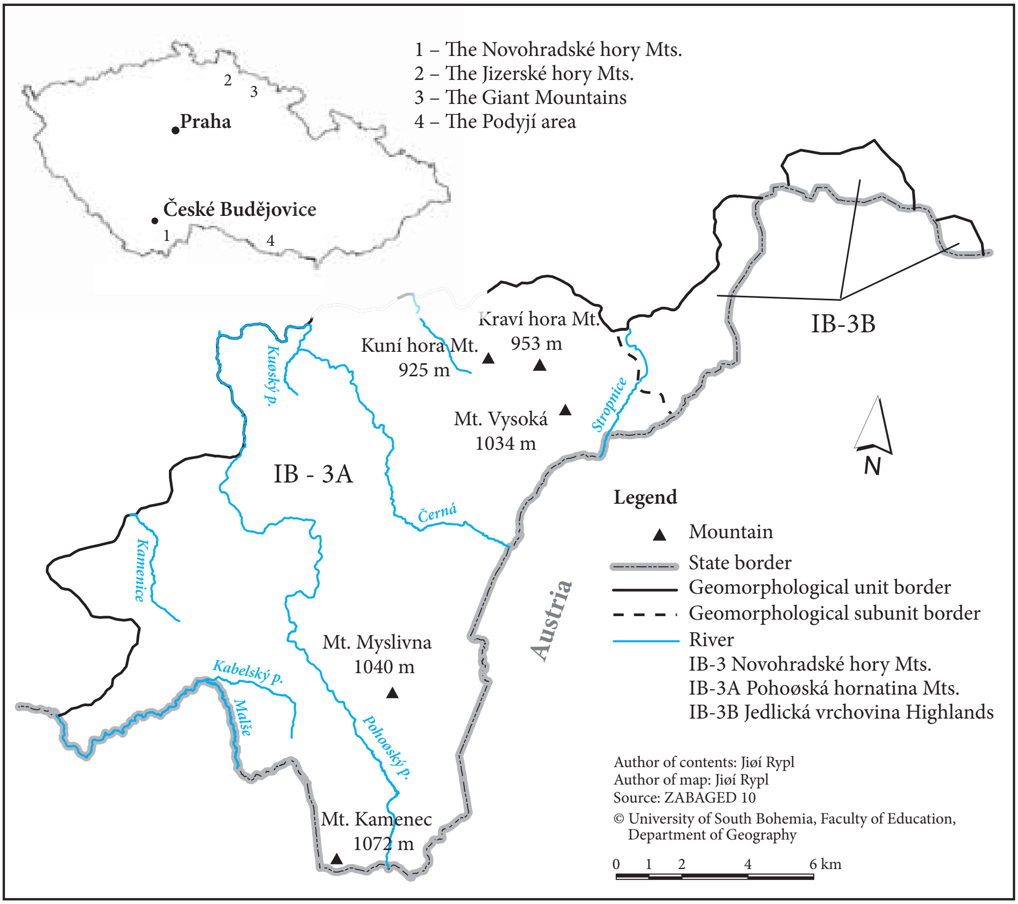

Figure 1: Location of the Nové Hrady Mountains, the Jizera Mountains, the Giant Mountains, and the Podyjí area in the Czech Republic and the basic geomorphological regionalization of the Nové Hrady Mountains.

3 Methods

Investigation of the spatial distribution of rock landforms in relation to geomorphological characteristics (lithology, slope inclination, orientation of slope, and elevation) may be based on division of the territory into discrete areas (e.g., squares). Dependence in the discrete area is examined using multiple statistical methods (e.g., CART, or classification and regression trees; Breiman et al. 1984) or generalized linear models such as GLM (Nelder and Wedderburn 1972). This article used another methodological approach, in which the study area is divided into categories according to its geomorphological characteristics and links to them are investigated. This method was successfully tested earlier in a similar Bohemian mountain range of the Giant Mountains (Křížek, Treml and Engel 2007).

Geomorphological mapping and GPS mapping were carried out in the Pohořská Mountains following the methodology described by Condorachi (2011), Smith, Paron and Griffiths (2011), and Voženílek et al. (2001). Mapping focused on rock relief landforms, and spatial data concerning their localization were acquired during the mapping. These spatial data were then processed using ArcGIS 9.1. Every geolocated landform was overlaid with a digital elevation model of the area studied and every feature was associated with data concerning lithology, slope, slope orientation, and elevation. Spatial statistics were calculated and it was possible to obtain the spatial distribution of rock landforms in all these categories. The spatial distribution of rock landforms was detected using the index of distribution *Wij = Xi / Yj*, where *Xi* is the percentage representation of the landform in the relevant category of the characteristic studied (e.g., in the case of slope characteristic, five categories of slopes were studied: 0–2.0°, 2.1–5.0°, 5.1–10.0°, 10.1–20.0°, and > 20.1°). *Yj* is the percentage quotient of this category on the surface of the entire area studied; this means that the percentage of surface was calculated where the relevant category of slope was identified. The example of tors is explicit: 52.5% of tors were found on slopes between 0° and 2°, and this category of slope is located on 9.7% of the area studied. The index of distribution *Wij* of tors was calculated as 52.49 / 9.79, which yields *Wij* =5.41. The index of distribution was calibrated using the sum (distribution sum) of arithmetic mean and average deviation:

$$\frac{1}{n}\sum_{i=1}^{n}\left|W_{ij}-\bar{W}_{ij}\right|$$

The distribution sum was calculated using the indices of the spatial distribution *Wij* of all rated landforms in the appropriate category of the characteristic investigated (e.g., slope 0–2° in the case of slope characteristic), its arithmetic mean, and its average deviation. From these indicators it is possible to obtain the formula:

$$Sumj=\bar{W}_{ij}+\frac{1}{n}\sum_{i=1}^{n}\left|W_{ij}-\bar{W}_{ij}\right|$$

where *n* represents the number of all landforms rated (the sum of tors, frost-riven cliffs, castle koppies, and blockfields). If the index of distribution *Wij* is equal to 1, the percentage representation of the landform in the category is equal to the proportional surface of this category in the total area studied. If the value of *Wij* is above 1, the landform has more significant representation in the relevant category. This means that the presence of this rock landform is related to the relevant category of the observed characteristic. If the value *Wij* is below 1, the occurrence of the landform in question is less significant in the relevant category and there is no clear dependence of landform localization with the relevant category. Landforms were estimated as dependent landforms based on two statistical conditions. First, the index of distribution *Wij* must be greater than 1. Second, the index of distribution must be greater than the sum of the arithmetic mean and average deviation in the category of the characteristic studied (Křížek, Treml and Engel 2007; Křížek 2007).

4 Results

Thirty-four tors were mapped in the Pohořská Mountains (see Figure 2), as well as 153 frost-riven cliffs (see Figure 3), thirty-six castle koppies, ninety-nine areas of blockfields, and a significant number of cryoplanation surfaces and terraces. This landforms are defined in global research as cryogenic landforms (Traczyk and Migoń 2000). According to Demek et al. (2006), the territory of what is now the Czech Republic was located not far from the frontal part of a continental glacier in Pleistocene sequence, where the climate

Figure 2: Tor on Mount Kamenec.

Figure 3: Frost-riven cliff on Mount Kuní.

was cold and cryogenic processes took place. This geomorphological processes formed cryoplanation terraces with frost-riven cliffs, tors, castle koppies, and blockfields (Demek et al. 2006). These landforms also developed in the Pohořská Mountains. They stand next to the Bohemian Forest (*Šumava*), a mountain range covered by an alpine glacier in the late Pleistocene sequence (Demek et al. 2006). Tors and castle koppies were formed during the same process (Migoń 2006) and they are mainly distinguished by their shape and proportions. Landforms with height greater than length were mapped as tors, and landforms with length greater than height were defined as castle koppies.

The cryoplanation terraces in the study area were not included in the analysis due to the scale of the maps used (1:25,000; the maps used covered the entire study area) and due to the size of cryoplanation terraces, which was smaller than other rock landforms. The thickness of the regolith was not considered in the research because the regolith was removed by etching during Saxon tectogenesis and a planation surface with a stripped etchplain was created (Migoń 2004a; Demek et al. 2006). The study area is practically without regolith originating from chemical weathering in the Paleogene. The percentage occurrence of cryogenic landforms in relation to various categories of relief is shown in Figures 4 through 7. The index of distribution, the arithmetic mean, the average deviation, and the distribution sum are shown in Tables 5 through 8.

Table 5: Index of distribution, arithmetic mean, average deviation, and distribution sum in relation to lithology.

Lithology	Tors	Frost-riven cliffs	Castle koppies	Blockfields	Arithmetic mean	Average deviation	Distribution sum
Granite	1.71	1.53	1.71	1.51	1.62	0.09	1.71
Gneiss	0.10	0.13	0.00	0.33	0.14	0.06	0.20

Table 6: Index of distribution, arithmetic mean, average deviation, and distribution sum in relation to slope.

Slope	Tors	Frost-riven cliffs	Castle koppies	Blockfields	Arithmetic mean	Average deviation	Distribution sum
0.0–2.0°	5.41	0.40	2.27	0.10	2.05	1.80	3.85
2.1–5.0°	0.15	0.17	0.42	0.05	0.20	0.11	0.31
5.1–10.0°	0.24	0.39	0.23	0.75	0.40	0.17	0.57
10.1–20.0°	1.28	2.68	1.60	2.15	1.93	0.49	2.42
> 20.1°	3.89	12.11	16.56	11.30	10.97	3.54	14.51

Table 7: Index of distribution, arithmetic mean, average deviation, and distribution sum in relation to slope orientation.

Slope orientation	Tors	Frost-riven cliffs	Castle koppies	Blockfields	Arithmetic mean	Average deviation	Distribution sum
N	0.20	0.90	1.15	0.76	0.75	0.28	1.03
NE	0.19	0.70	0.74	0.81	0.61	0.21	0.82
E	1.22	0.42	0.86	1.15	0.91	0.27	1.18
SE	1.61	2.27	1.52	1.48	1.72	0.27	1.99
S	0.00	2.10	0.39	1.70	1.05	0.85	1.90
SW	0.95	0.95	0.89	1.62	1.11	0.26	1.37
W	0.00	1.20	0.98	0.93	0.78	0.39	1.17
NW	0.67	0.75	0.43	0.85	0.68	0.13	0.81
plain	6.22	0.38	2.61	0.19	2.35	2.07	4.42

Table 8: Index of distribution, arithmetic mean, average deviation, and distribution sum in relation to elevation.

Elevation (m)	Tors	Frost- riven cliffs	Castle koppies	Blockfields	Arithmetic mean	Average deviation	Distribution sum
560–600	0.00	0.00	0.00	0.00	0.00	0.00	0.00
601–700	0.00	0.04	0.00	0.20	0.06	0.04	0.10
701–800	0.16	0.50	0.15	0.90	0.43	0.27	0.70
801–900	1.11	0.94	0.96	1.45	1.12	0.17	1.29
901–1,000	2.42	2.74	3.24	1.04	2.35	0.67	3.02
above 1,001	25.86	12.21	18.31	2.21	12.76	7.44	20.20

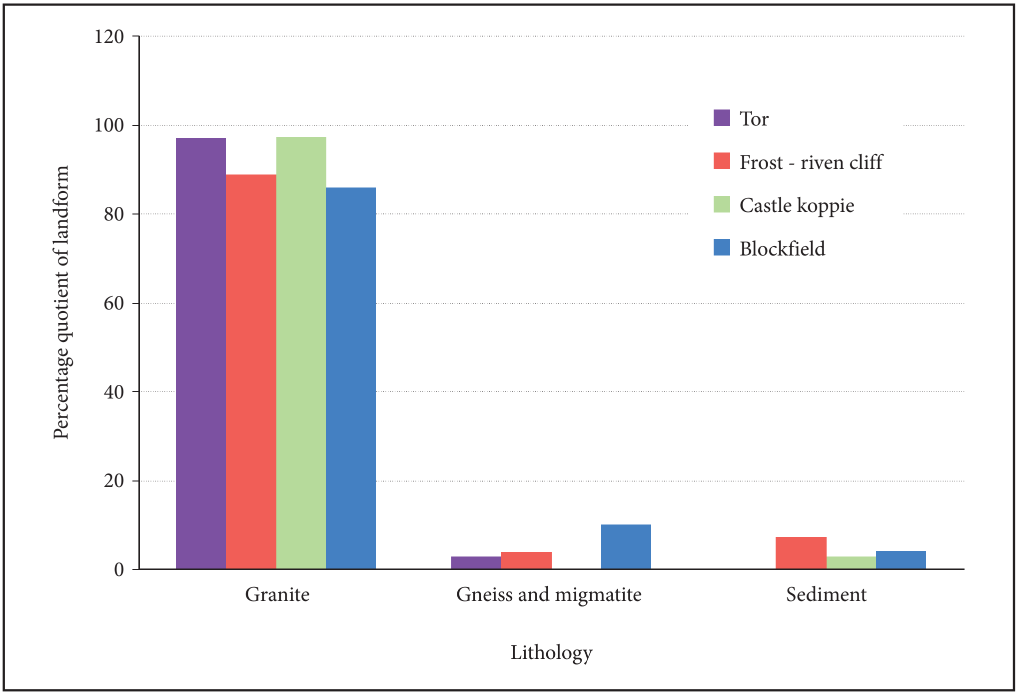

Figure 4: Occurrence of rock landforms in relation to lithology.

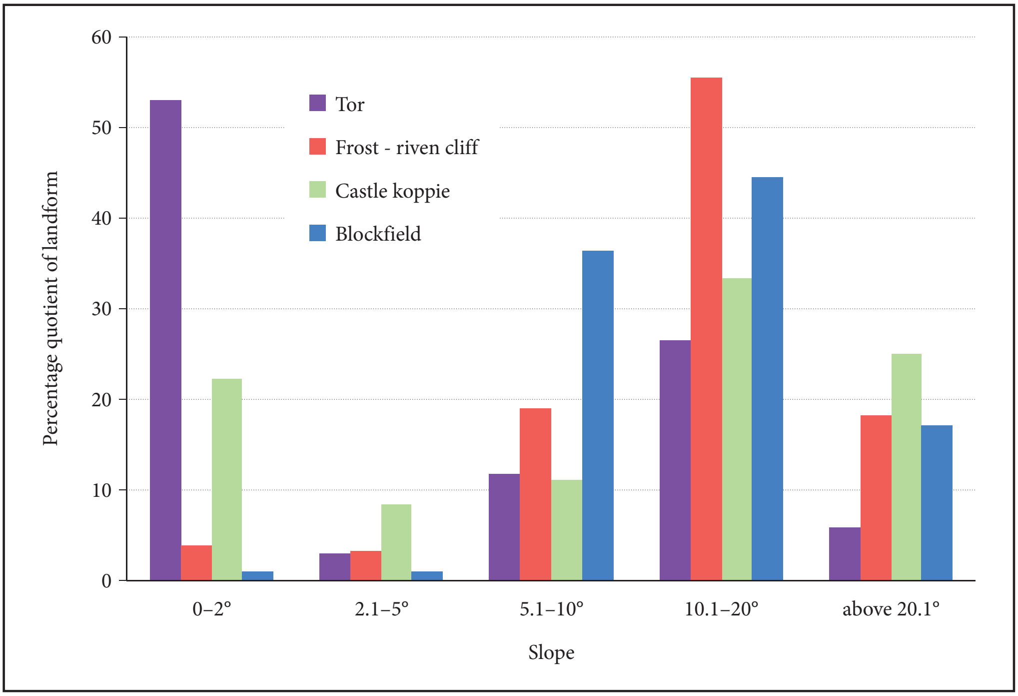

Figure 5: Occurrence of rock landforms in relation to slope.

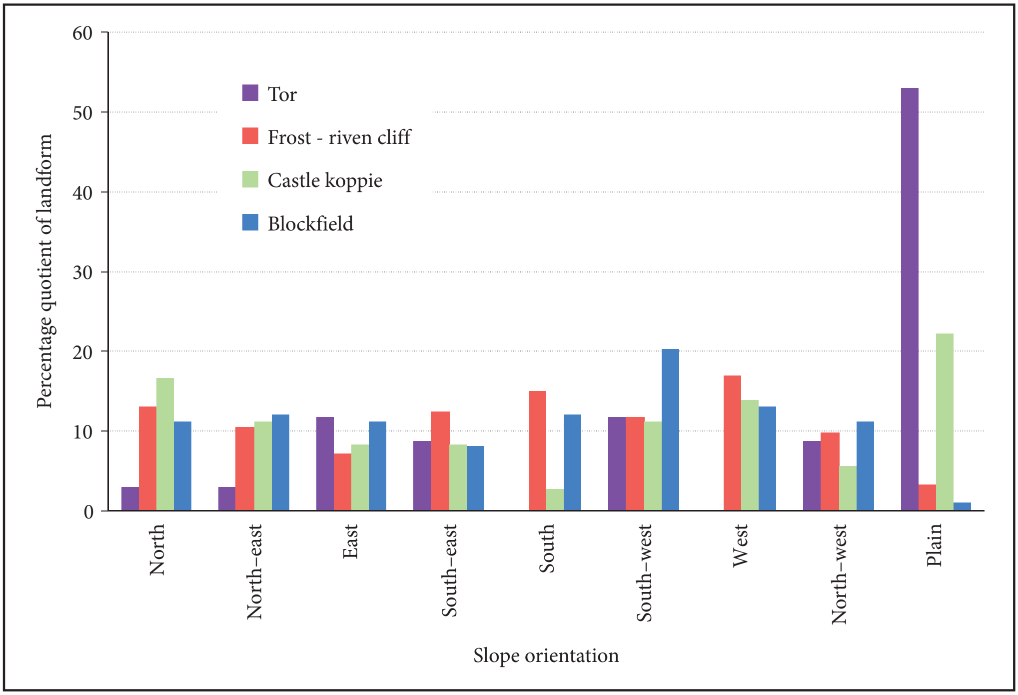

Figure 6: Occurrence of rock landforms in relation to slope orientation.

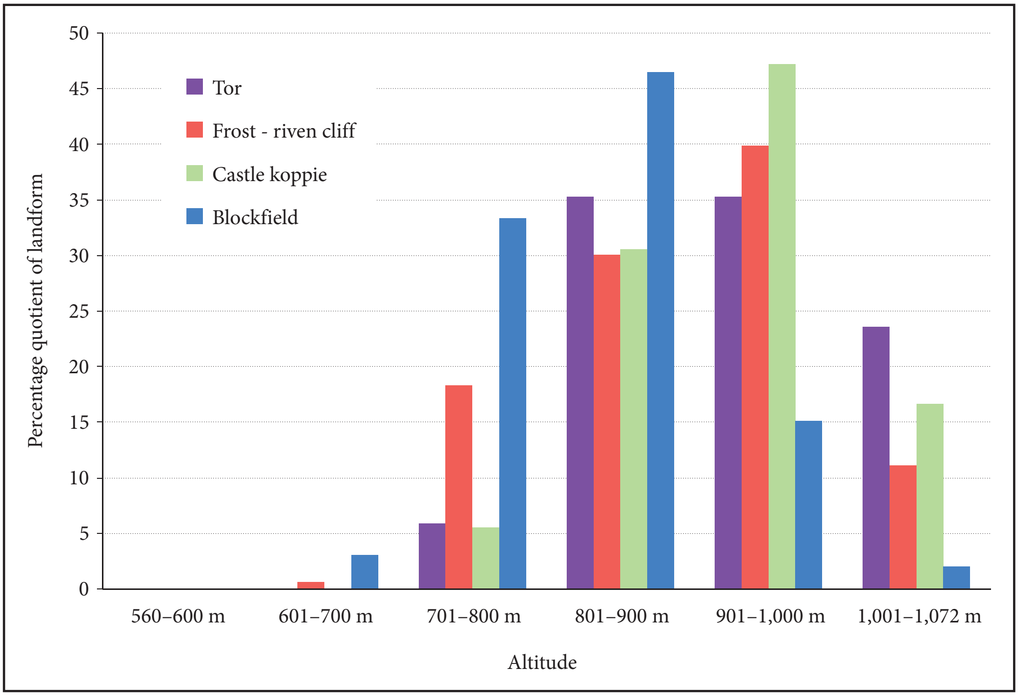

Figure 7: Occurrence of rock landforms in relation to elevation.

5 Discussion and conclusion

The determination of regularities in the spatial distribution of rock landforms is based on a comparison of the indices of distribution and arithmetic averages, or corresponding distribution sums. Each value of the index of distribution that is greater than the corresponding arithmetic mean of all the indices of distribution of the category shows that the occurrence of the specific type of rock landform is above average with regard to the mean. The data in Tables 5 through 8 show that the criterion related to the distribution sum is more stringent. This is because the criterion corresponds to only some values of the distribution indices that belong to the set of values greater than the arithmetic mean of the corresponding indices.

The elimination of a number of values is caused by calculating the variability of all rock landforms in the category, which also involves the error of minimalization potentially caused by variance in irregularly distributed values (Křížek, Treml and Engel 2007; Křížek 2007).

The spatial analysis of cryogenic landforms shows that all rock landforms are related to the presence of granite in all cases in which *Wij* > 1 (Table 5). The analysis did not prove dependence on another type of rock from the area studied. The dependence of cryogenic landforms on granite results from its easier conservation as solid rock (French 2007; Migoń 2006; Summerfield 1991) and was also studied in the Giant Mountains (Křížek, Treml and Engel 2007).

With regard to slope (Table 6), the dependence between tors and a slope of 0 to 2° was confirmed. This dependence is primarily based on the genesis of these cryogenic landforms (French 2007; Migoń 2006; Summerfield 1991). An above-average occurrence on slopes with an inclination of 0 to 2° was also discovered for castle koppies. The dependence of castle koppies and relief with a slope greater than 20.1° is interesting. This dependence is mainly explained by the low percentage quotient of occurrence of this landform in the area studied. The dependence of occurrence of frost-riven cliffs was proved for relief with a slope of 10.1 to 20° and an above-average occurrence of such cliffs was identified for relief with a slope of 20.1° and greater. This dependence and the above-average occurrence can be explained by the genesis of these cryogenic landforms (French 2007; Migoń 2006; Summerfield 1991). In the case of blockfields, no dependence was found, but only an above-average occurrence for two slope categories: 10.1–20° and > 20.1°. It is not possible to compare the dependence and above-average occurrence of landforms with the results of this relief category in the Giant Mountains because Křížek, Treml and Engel (2007) specified different slope categories in their work.

With regard to slope orientation (Table 7), the dependence of tors and the above-average occurrence of castle koppies on plains was confirmed. This dependence and above-average occurrence is connected to the genesis of cryogenic landforms (French 2007; Migoń 2006; Summerfield 1991). The dependence of tors extends to the eastern slope orientation, and the dependence of castle koppies to the northern slope orientation. Frost-riven cliffs are mainly distributed on slopes with a warm exposure (W, S, SE) owing to the intensive dynamics of cryogenic processes (Czudek 2005). This is why the blockfields also depend on slopes with a warm exposure, especially on slopes with a south (S) and southwest (SW) aspect. In this case, it is also difficult to compare the dependency and above-average occurrence of landforms with the results of this relief category in the Giant Mountains because Křížek, Treml and Engel (2007) specify four principal orientations in their work (N, E, S, W).

Above-average occurrences (Table 8) of destructive landforms (tors, frost riven cliffs, and castle koppies) were found at elevations above 901 m (climate conditions at this elevation are favorable for the significant expansion of tors; this is cold climatic zone CH7, based on Quitt 1971). Dependences and above-average occurrences of accumulation landforms (blockfields) were found at elevations between 801 and 900 meters (Table 8). Dependences and above-average occurrences with relation to elevations are a result of the genesis of these cryogenic landforms (French 2007; Migoń 2006; Summerfield 1991). In the Giant Mountains dependences and above-average occurrences of destructive cryogenic landforms depend on higher elevations (1,400–1,500 m), whereas in the case of accumulation landforms this dependence was found for relatively lower elevations (1,100–1,300 m; Křížek, Treml and Engel 2007).

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