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Geomorphometric characteristics of the high mountains in North Macedonia

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Abstract— **As a result of powerful local and regional geotectonic movements, the landscape of North Macedonia (25,713 km^2) has a typical chequerboard topography with frequent changes of mountains and depressions. There are 38 mountain ranges, of which 13 extending above 2000 m are defined as high, while the highest - Korab, reach 2753 m. Because of their geomorphological and overall significance, geomorphometric features of these 13 dominant high mountain ranges are analyzed in this work. The data are calculated from a previously prepared 15-m DEM with particular attention to hypsometry, slope gradient, aspect, and curvature. Based on these variables, a simple classification of the high mountain ranges is made.**

I. INTRODUCTION

As uplifting morphostructures mountains are the predominant elements of the landscape in North Macedonia. The highest mountain massifs are mostly found in the western and central parts (Fig. 1); there are only two from 13 mountains above 2000 m in eastern parts of the country: Osogovo (2252 m) and Belasica (2029 m). According to a peak altitude of the mountains in the Balkan Peninsula, mountains in North Macedonia are divided into three groups: high mountains (2000-2753 m) with a subgroup of very high mountains (2500-2753 m), medium-high mountains (1000-2000 m) and low mountains (below 1000 m). The lowest altitude limit for a mountain is set to 700 m of absolute elevation and 500 m of relative altitude [1]. Because of the geotectonic setting, mountains in western and central parts (in the West-Macedonian zone, the Pelagonian massif, and the Vardar Zone) have a general NW-SE direction. In contrast, in the eastern part of the country, they are E-W elongated (because of the predominant N-S extensional regime). Mountains in the west and central part are generally composed of marbles (Jakupica, Suva Gora), lime-stones (Bistra, Jablanica, Galičica, Šara), granites (Pelister) or other compact rocks. For reasons, these mountains have usually narrow, sharp ridges and peaks and deeply incised valleys. Mountains in the eastern part of the country, are dominantly composed of erodible crystalline rocks (schists) and, consequently, show a more subdued relief, rounded ridges, and peaks, and less deeply incised valleys. However, both groups of mountains were shaped during the Neogene–Pleistocene [2].

All of the above differences are well reflected in the mountain morphology, which can be seen in their geomorphometry as well. In this regard, Milevski [3, 4] perform the first morphometric analysis of the mountain ranges in North Macedonia, based on 3"SRTM DEM.

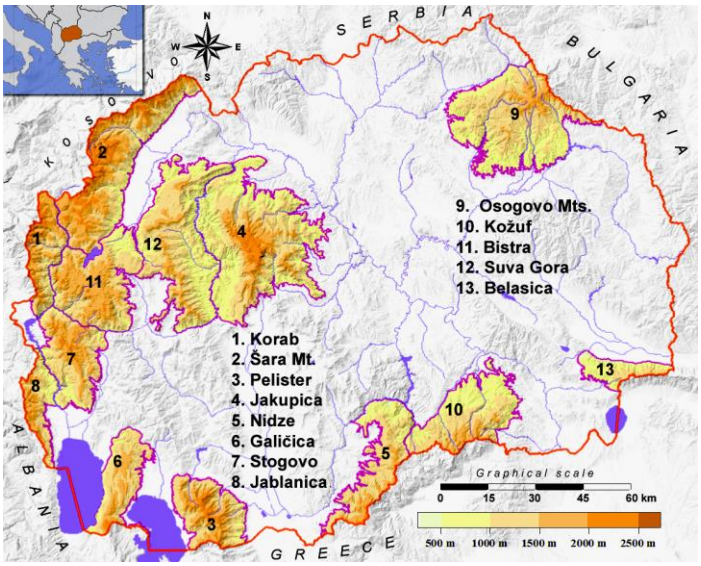

Figure 1. Geographic position of the high mountain ranges in North Macedonia

II. METHODOLOGY

In this work, geomorphometrical analyses of the high mountains in Macedonia are further improved and based on much more accurate 15-m DEM of the State Agency of Cadaster of North Macedonia. According to our tests, this model has a very good average horizontal and vertical accuracy of +/- 1.3 m, with maximum errors up to +/-4 m [5, 6]. Mountain range borders are vectorized manually with a combination of hypsometric criteria (following characteristic contours) and morphologic criteria

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(tracking clearly expressed morphological boundaries). However, it was a difficult and subjective task as the mountains in some parts gradually pass through hilly terrain to plains and valleys. After this, mountain extents are clipped from the 15-m DEM and processed to further calculations performed mostly in SAGA GIS software.

III. RESULTS

According to the data in Table 1, Šara Mt. has the highest mean altitude of 1610 m, followed by Korab with 1573 m, while the third is Pelister with 1477 m. With 1384 m, Bistra Mountain is the fourth immediately after Pelister (Baba Mountain), although by peak altitude (2163 m) it ranks eleventh. That is because of a significant area in the 1500-2000 m zone, with a large karst planation surface and few karst poljes on it. The mean altitude of all analyzed mountain ranges is 1257 m, which is 427 m more than the mean altitude (829 m) of North Macedonia [2].

Table 1. Basic morphometric features of the high mountains in North Macedonia including altitudes of the highest (Hmax) peak, average altitude (Hav), slope and area (A) of each mountain range.

	Mountain	Hmax m	Hav m	Slope °	A km^2
1	Korab	2753	1573	25.3	289.5
2	Šara Mt.	2748	1610	22.9	828.6
3	Pelister	2601	1477	23.4	396.6
4	Jakupica	2540	1127	22.1	1272.7
5	Nidže	2520	1190	22.2	460.0
6	Galičica	2288	1289	18.3	346.3
7	Stogovo	2268	1345	21.4	458.0
8	Jablanica	2256	1319	21.7	207.6
9	Osogovo Mt.	2252	1072	21.3	981.0
10	Kožuf	2165	1056	21.2	543.9
11	Bistra	2163	1384	20.8	643.7
12	Suva Gora	2061	1072	21.8	923.4
13	Belasica	2029	830	23.5	167.5
	Average	**2357**	**1257**	**22.0**	**578.4**

The data for the mean slopes show that Korab, Šara Mountain, and Pelister have the highest values (from 25.3° to 22.9°). The reasons are steep mountainsides (fault slopes), deeply incised river valleys, sharp ridges and peaks on the top shaped with strong glacial erosion during Pleistocene [7, 8]. Jakupica (22.1°) and Suva Gora (21.8°) have lower values because of large karst plains on it. Galičica Mountain have has the lowest value for mean slope (only 18.3°), due to the large karst plains with few karst poljes and uvalas. Bistra Mountain (20.8°) has an almost identical situation, but here mountainsides are almost vertically incised by the Radika Canyon, resulting in a higher mean slope [9]. Overall, the average slope gradient of the high mountains in North Macedonia is 22°, well above the average slope of the whole country of 15.1° [2].

As Figure 2 shows, the curves of mean slope against altitude are irregular, with frequent indents (representing planation surfaces and terraces) and maxima (representing steep slopes, escarpments, and sides of sharp peaks and ridges). Usually, the steepest average gradients are below 1000 m of altitude as a result of steep slopes and deeply incised valleys, as well as in the highest parts on the ridge and peak sides [4].

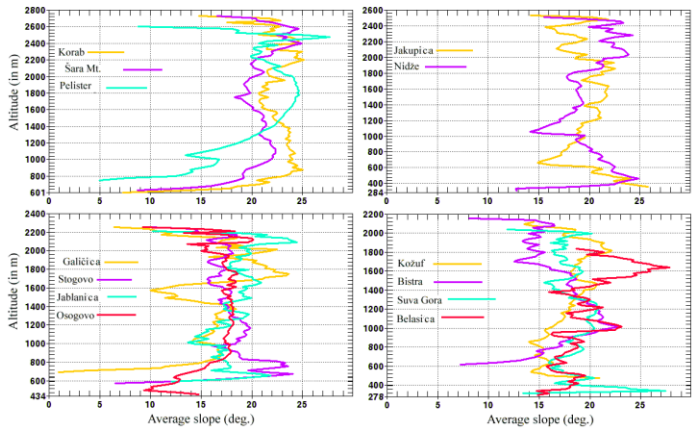

Figure 2. Average slopes against altitude of each high-mountain range in North Macedonia.

At the base of the mountains and on the top of most peaks and ridges, the slope is lower because of the gradual flattening of the terrain. However, mountains highly affected by Pleistocene glaciation (most of them in the western part of the country), show prominent peaks of the average slope above 2000 m. That is the case with Korab (2100-2500 m), Šara (2200-2600 m), Pelister (2300-2500 m), Galičica (1900-2150 m) and Jablanica (2050-2200 m). Usually, they represent steep slopes of cirques, U-valleys, ridges, and sharp peaks. At the same time, there are distinctive indentations in higher parts of the above and some other mountain ranges related to too large karst planation surfaces. Thus, Galičica have has remarkable indents (and planation surfaces) on 1500-1600 m, 1900-1950 m, and 2150-2250 m, Bistra Mountain on 1700-2050 m, and Jakupica on 2000-2400 m. There are also indents representing large old fluvial-denudation surfaces on Korab (1600-2100 m), Šara (1600-2200 m) and Pelister (2100-2300 m). Part of these surfaces is fulfilled with glacial deposits. Bellow 2100 m, Pelister which is typical, almost symmetrical horst, has a regular curve with a broad maximum of the gradient at 1600-2000 m. This contrasts with the Kožuf Mountains which have mean gradients between 14° and 22° from the foothills to the highest parts [3].

The terrain curvature is an important morphological and geomorphometric element that indicates the shape of slopes: convex, straight or concave. Ridges and peaks have convex curvature, plains or fields and surfaces with a uniform slope have

straight curvature, while valley bottoms and depressions have concave curvatures [10]. In this work, the types of the slope are represented by the SAGA GIS convergence index which is similar to plan curvature but gives much smoother results [11]. The calculation uses the aspects of surrounding cells, i.e. it looks to which degree surrounding cells point to the center cell. The result is given as percentages, negative values correspond to convergent, positive to divergent flow conditions. Minus 100 would be like a peak of a cone, plus 100 a pit, and 0 an even slope [12]. On all mountains, the curvature changes with elevation from concave (in the lowest parts) to convex (in the highest areas).

The graph in Fig. 3 show that the high mountain ranges in North Macedonia are dominated by straight to convex curvatures. Terrains with extremely convex slopes (summits area) are found on Galičica (0.9%), Kožuf (0.8%), Jablanica (0.75%), Bistra (0.7%), Belasica (0.7%), Nidze with Kozjak (0.69%), and Osogovo Mountain (0.68%). On these, numerous non-prominent peaks appear in relation to their total areas. On the other hand, Pelister (0.2%), Šar Planina (0.3%) and Korab (0.36%), compared to their total areas have smaller numbers of peaks, but usually much sharper. Mountains with the highest relative proportion of concave slopes are Kožuf (4.5%), Osogovo Mountain (4.4%) and Bistra (4.1%).

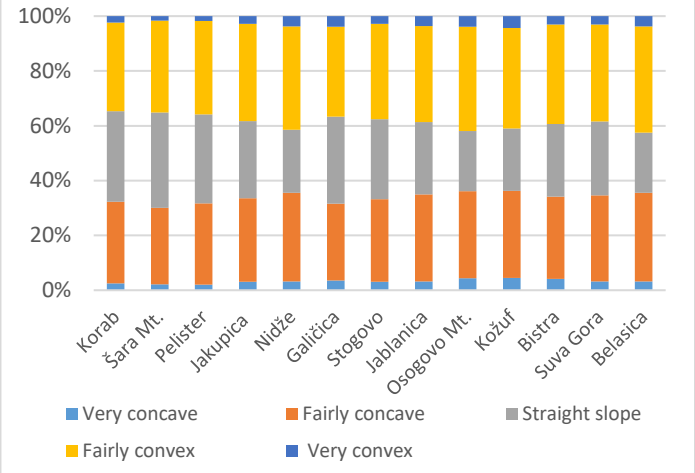

Figure 3. Graph of terrain curvature (convergence index) classes of the high mountains in North Macedonia (in %).

Aspects are an important geomorphometric element which is a result of geotectonic-structural and geomorphologic-evolutionary processes and they are important for the intensity of erosion. The high mountains in Macedonia had a high diversity of aspects as a result of dominant ridge direction, an extension of the larger river valleys, and extension of the mountain ranges in relation to the country borders. Because of the borders, a realistic view of aspect distributions is given only for the ranges which are wholly located in Macedonia: Jakupica, Stogovo, Bistra, Suva Gora and mostly Galičica range. Their aspect distributions, together with the Osogovo Mountains taken because of characteristic almost E-W stretching (as a whole, in natural borders) are presented in Fig. 4.

Interestingly only the Galičica and Stogovo Mountains show distinctive bi-directional aspect distributions (W-E and SW-NE) exactly in opposite to their elongations. The reason for that is poor lateral relief dissection. On the contrary is Osogovo Mountain, where aspects distribution is the same as its elongation (ENE-WSW) mostly because of frequent valleys incised in perpendicular directions. A relatively similar situation is with Jakupica and Suva Gora, while Bistra Mountain which is without clear elongation have an uneven distribution of aspects. However, on all 6 mountains except on Suva Gora, west and east aspects are dominant. Actually, that is the same for all 13 mountains, where western aspects are dominant (by a number of ranges), followed by eastern ones (by area). This is consistent with the dominant Dinaric-Hellenidic (N-S and NW-SE) direction of most ranges in Macedonia. Exceptions are Nidže, Kožuf, Osogovo and Belasica Mountains, which are W-E oriented because of the Aegean extensional neotectonic regime [13].

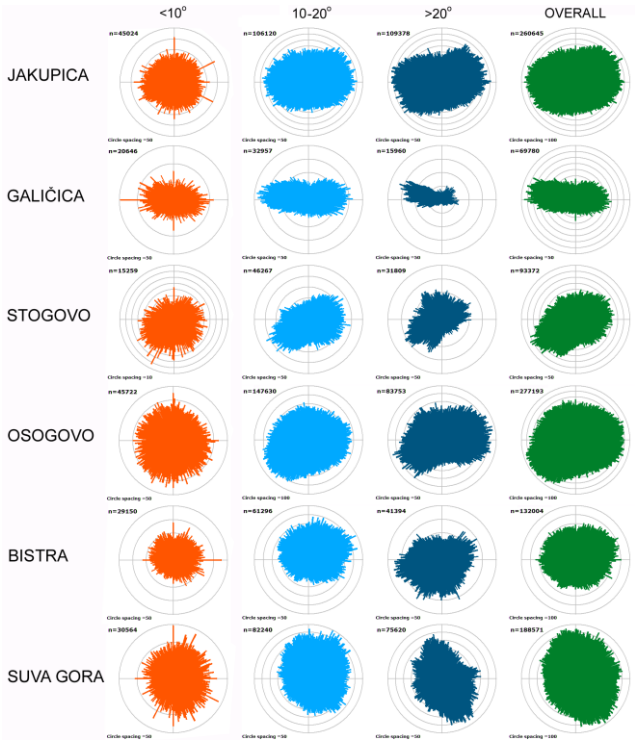

Figure 4. Aspects vs slopes for selected high mountains in North Macedonia.

With further analyses, the average gradients for each aspect were calculated. The data shows that the most common aspects do

not have the greatest slopes but the opposite. This is because a smaller slope increases the area with a given aspect. In fact, the most common aspects represent long, extensive mountain slopes that are perpendicular to the mountain direction. Aspects with the greatest slope gradients generally represent steep valley sides of rivers deeply incised into the mountain ranges, or along their rims. Steep slopes have great erosive potential, especially where facing south.

IV. CONCLUSION

Because of variable structural and geomorphic evolution, high mountains (higher than 2000 m) in North Macedonia have significant morphometric differences, clearly evident in their hypsometry, slope gradient, aspect, and convergence. According to the mean values of these variables, morphometric classification of the mountain ranges is made and they are classified into three groups. The first is a group of very high mountains (regarding the Balkan Peninsula conditions), with steep slopes: Korab, Šar Planina, and Pelister. In the second group are mountains with moderate altitude, slope, and convexity: Nidze, Stogovo, Jablanica, Suva Gora and Bistra. According to its characteristics, Jakupica (Mokra) Range lies between the first and second groups. The third group includes the lower ranges, with gentle slopes and large planation surfaces: Galičica, Osogovo, Kožuf, and Belasica. This classification is strongly related to the geotectonic position and mountain evolution. Thus, the first and second groups of mountain ranges belong to the inner Dinaric and Hellenic geotectonic belt characterized by intensive E-W tectonic compression especially during the Tertiary [14]. Numerous remnants from LGM with cirques, narrow ridges and sharp peaks extending above the karst planation surfaces (on 1600-2000 m), make distinctive morphology of these ranges. Unlike them, except for Galičica, the third group is closer to the Carpatho-Balkanic geotectonic belt, with a highly expressed N-S extensional regime of development.

Previous semi-automated geomorphometric classification is based only on the basic characteristics of 13 analyzed mountains in North Macedonia. However, with further improvements of variables and adjusting limiting values, automated classification [15] can be used at least for the high mountains on the Balkan Peninsula. Beyond purely theoretical research approaches, geomorphometric correlations may have practical significance for better structural and morphological interpretations, as well as for some erosion potential modeling [16] and geohazards indicators.

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