MORPHOMETRIC CLASSIFICATION OF HIGH MOUNTAIN RANGES IN THE REPUBLIC OF MACEDONIA

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As a result of powerful local and regional geotectonic movements in the past, the landscape in the Republic of Macedonia is characterized by frequent alternations between mountains and depressions. There are 38 mountain ranges, of which 13 extending above 2,000 m are defined as high, while the highest - Korab – reaches 2,753 m a. s. l. Because of their geomorphological and overall significance, morphometric features of these 13 dominant high mountain ranges are analysed in this work. The data are calculated from a previously prepared 3"SRTM-based DEM model with particular attention to hypsometry, slope gradient and aspect, and vertical relief. Based on these variables, a simple supervised classification of the high mountain ranges is made.

Key words: morphometry, mountain ranges, supervised classification, 3"SRTM DEM

INTRODUCTION

Mountains are dominant morphostructural landforms in the chequerboard topography of the Republic of Macedonia. On the relatively small national area (25,713 km^2), there are some 38 mountain ranges, different in size, shape, geology and mode of formation. According to their altitude, these mountain ranges are divided into three groups: high mountain ranges (2,000 – 2,753 m a. s. l. – ibid. thereinafter), with a subgroup of 5 very high ranges (2,500 – 2,753 m); medium-high mountain ranges (1,000 – 2,000 m); and low mountain ranges (below 1,000 m). High mountain ranges are mostly found in the western and central parts; only two of the 13 mountain ranges above 2,000 m are in the eastern Macedonia: the Osogovo (2,252 m) and the Belasica (2,029 m) (MILEVSKI 2011).

Mountain ranges in the western and central parts of Macedonia geotectonically belong to Dinarides and Hellenides and its subunits: Western Macedonian Zone, Pelagonian Massif and Vardar Zone (DUMURDZANOV et al. 2005). For that reason, they have a general N-S to NW-SE strike. In contrast, the ranges in the eastern part of the country are generally E-W aligned because of the predominant N-S extensional tectonic regime (DUMURDZANOV et al. 2005). Mountains in the western and central parts are generally composed of marbles (the Jakupica, the Suva Gora), limestones (the Bistra, the Jablanica, the Galičica, the Šara), granites (the Pelister) or other very resistant rocks: these mountain ranges usually have narrow, sharp ridges and peaks, and deeply incised valleys. Mountains in the eastern part of Macedonia are dominantly composed of more erodible crystalline rocks (gneiss, schists) and, consequently, show a more subdued relief, rounded ridges and peaks, and less deeply incised valleys. However, both groups of mountain ranges were generally shaped during the Neogene-Pleistocene (KOLČAKOVSKI 2006). Great morphological significance for the high mountain ranges in Macedonia has its Pleistocene glacial phase, especially during the Last Glacial Maximum (LGM) and later Older and Younger Dryas, when numerous mountain glaciers existed (KOLČAKOVSKI 2004, KUHLEMANN et al. 2009, RIBOLINI et al. 2011). Most of them were cirque glaciers on the Pelister, the Jablanica and the Stogovo Mountains or occupied short and small U-shaped valleys downslope on the Šara, the Korab, the Jakupica and the Galičica Mountains (KOLČAKOVSKI and MILEVSKI 2012). The Equilibrium Line Altitude (ELA) was located high (1,900 – 2,100 m), elevating in W-E direction (KUHLEMANN et al. 2009), while precipitation was relatively low and decreasing in same (W-E) direction (KOLČAKOVSKI 2004). For that reasons and very weak glacial remnants, it is still doubtful if the high mountain ranges on the east, the Osogovo (2,252 m) and the Belasica (2,029 m) were glaciated (MILEVSKI 2008), while the similar problem is with the Suva Gora (2,061 m) on west. From LGM and later glacial phases many landforms have remained: cca 30 cirques generally between 2,000 and 2,400 m of altitude, U-shaped valleys with lengths of up to 2.5 km and mo-

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raines of different types: terminal, lateral, recessional etc.

All of the above differences are well reflected in the mountain morphology, which can be seen in the field, on maps or, more objectively, through a complex morphometric analysis as in this work.

In morphometrical analyses of the landscape in the Republic of Macedonia carried out in recent decades (STOJMILOV 1976, ANDONOVSKI 1995, MARKOSKI 1995 and MANAKOVIK et al. 1998), only basic variables were generally considered (hypsometry, slope gradient and aspect). Furthermore, the calculations were based on traditional cartographic approaches, with high subjectivity and doubtful accuracy. But nowadays, the need for complex quantitative landscape data is rapidly increasing. Possibilities have increased with release of the latest global, medium - to high - resolution digital elevation models (3"SRTM DEM; 1"ASTER GDEM). Recently these approaches were used in terrain analyses of the Republic of Macedonia, showing interesting results (MILEVSKI 2005, 2007 and 2011). Taking into account that Macedonia has complex mountain morphology, it is valuable to analyse the morphometry of the 13 mountain ranges higher than 2000 m (**Fig. 1**).

METHODOLOGICAL APPROACH

In this paper, 3"SRTM (Shuttle Radar Topography Mission) DEM is used for morphometric analyses. Worldwide research suggest that vertical and horizontal errors of this model are tolerable (GAMACHE 2004, GONÇALVES and FERNANDES 2005, KOCH et al. 2002) for medium-scale geomorphometric procedures. Because of international coverage, there are possibilities for comparison of results with other areas and countries. Depending on the region and latitude, the resolution of this model ranges from 30 m to 90 m. After the initial release of the model in 2004, its quality was gradually improved by software algorithm corrections. Thus, for our research version 3 is used (JARVIS et al. 2006). The 30m ASTER GDEM and a 20m National DEM were also available for Macedonia, but the first has some quality issues (HENGL and REUTER 2011), while the second is highly priced and unavailable for entire area.

First of all, for software purposes, selected DEM area of Macedonia is re-projected and re-interpolated to a 70 m square grid in the UTM coordinate system. According to our tests, this new SRTM-based model has average horizontal and vertical accuracy of +/- 5 m, with maxi-

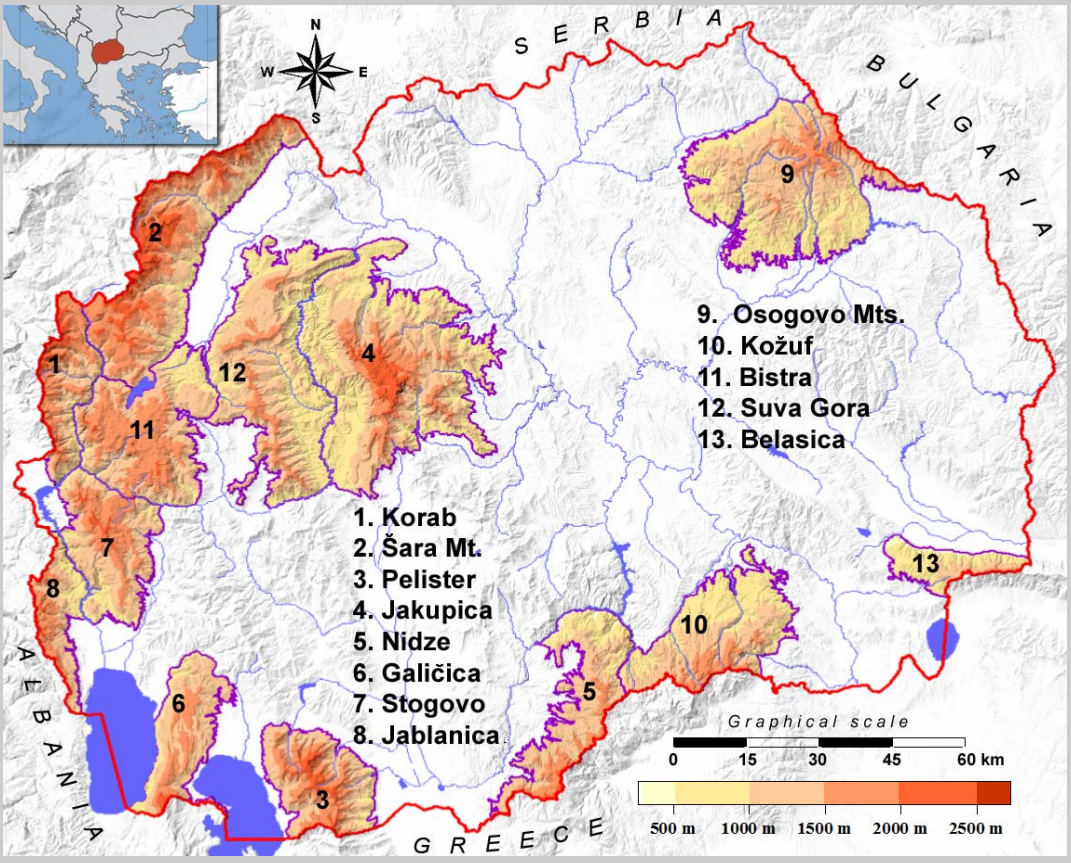

Fig. 1 Geographic position of the high mountain ranges in the Republic of Macedonia

mum errors up to +/-15 m. Such height inaccuracies are generally due to the resolution of the model, and the location of DEM points around the prominent peaks. To minimize the effect of these shifts, in some morphometric procedures as for slope gradient, empirical correction coefficient was used (explained in slope gradient section).

A very difficult step in this research was the exact identification of range boundaries because very often the lower slopes gradually pass into hills or basins. Despite of some newest automated and semi-automated approaches of mountain range delineation (CHAUDHRY and MACKANESS 2008, DRĂGUŢ and EISANK 2011), in our methodology this task is accomplished by careful combination of hypsometric criteria (following characteristic contours) and morphologic criteria (tracking clearly expressed morphological boundaries).

After determination of range borders, their individual and comparative morphometry is analysed. In addition to the basic elements: hypsometry, slope gradient and aspect, the type and length of slope, as well as horizontal dissection and vertical relief (roughness) are calculated. These procedures are generally performed with SAGA GIS v2.07 and MicroDEM v12 software.

BASIC MORPHOMETRIC FEATURES

Basic morphometric features of the high mountain ranges in the Republic of Macedonia are shown in **Tab. 1** and graphically in **Fig. 2**. They include: altitudes of the lowest (Hmin) and highest (Hmax) points, overall relief (Hrel), average altitude (Hsr), map area (P) and volume (V) above lowest point of each mountain range.

HYPSOMETRY

Hypsometry of the high mountain ranges in the Republic of Macedonia was calculated from the 70 m digital elevation model according to elevation zones 500 m wide. The output values were compared with test areas on topographic maps at a scale of 1:25000, showing acceptable deviations up to 5%.

According to the data in **Tab. 2**, only the Korab and the Šara Mountains have a largest area in modal class at 1,500 – 2,000 m. On the other hand, the Jakupica, the Osogovo, the Kožuf and the Belasica Ranges have largest area in a much lower modal altitude class of 500-1000 m. It is interesting to consider mean altitude (**Tab. 1**) which is the average value of all points of the digital elevation model (70 m grid) for that range. Thus, the Šara has the highest mean altitude with 1603 m, followed by the Korab with 1565 m, while the third is the Pelister with 1480 m. Remarkably, the Bistra Range is fourth: with 1385 m it comes immediately after the Pelister (the Baba Mountain), although by peak altitude (2163 m) it ranks eleventh. That is because of a significant area in the 1,500 – 2,000 m zone, with a large karst planation surface and few karst poljes on it. The mean altitude of all analyzed mountain ranges is 1248 m, which is about 416 m more than the 832 m mean altitude of the Republic of Macedonia (MILEVSKI 2007).

SLOPE GRADIENT (STEEPNESS)

The slope gradient of the high mountains in Macedonia is calculated with the Terrain Analysis / Morphometry module in SAGA software, from the 70 m digital elevation model. To minimize deviations arising from resolution

Mountain	Hmin	Hmax	Hrel	Hsr m	P km^2	Vkm^3	iV/P
Korab	589	2753	2164	1564.9	289.5	282.6	0.98
Šara Mountain	590	2748	2158	1602.7	828.6	839.1	1.01
Pelister	740	2601	1861	1480.3	396.6	293.7	0.74
Jakupica	316	2540	2224	1127.2	1272.7	1032.4	0.81
Nidže	272	2520	2248	1197.3	460.0	425.5	0.93
Galičica	693	2288	1595	1294.3	346.3	208.2	0.60
Stogovo	570	2268	1698	1345.8	458.0	355.3	0.78
Jablanica	574	2256	1682	1314.2	207.6	153.6	0.74
Osogovo Mt.	424	2252	1828	1074.8	981.0	638.5	0.65
Kožuf	449	2165	1716	1058.5	543.9	331.6	0.61
Bistra	587	2163	1576	1384.9	643.7	513.6	0.80
Suva Gora	301	2061	1760	1070.7	923.4	710.8	0.77
Belasica	268	2029	1761	843.6	167.5	96.3	0.57
Average	**490**	**2357**	**1867**	**1248.3**	**578.4**	**452.4**	**0.77**
Total	-	30644	-	-	7518.8	5881.2	-

Tab. 1 Basic morphometric indicators of high mountain ranges in the Republic of Macedonia

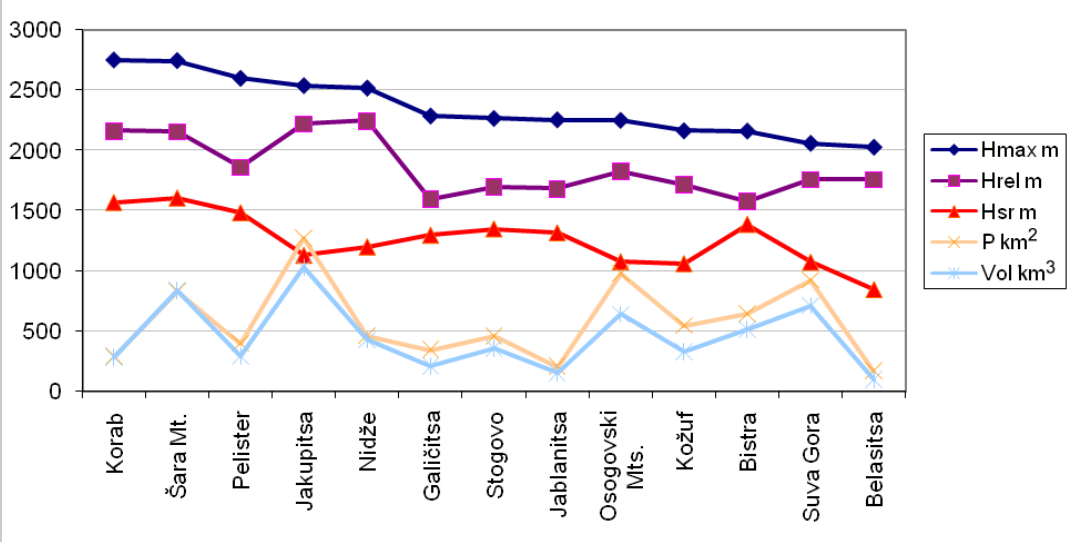

Fig. 2 Graph of the basic morphometric indicators of the high mountain ranges in the Republic of Macedonia: maximal altitude (Hmax), relative height above the base (Hrel), average altitude (Hsr), total area (P) and volume from the base (Vol)

of the SRTM-based model, and to make results consistent with the 1:50000 scale topographic map, an further empirical correction of slope values (S) is made in form:

$$S' = S * (1 + S / 150).$$

With such procedure, generally underestimated slopes (because of the DEM resolution) are corrected to accuracy of +/-5% (MILEVSKI 2005). The final results are presented in **Tab. 3**.

The results show that highest ranges: the Korab, the Šara Mountain and the Pelister, also have the steepest mean slopes (from 25.8° to 24.1°). The reasons for that are geotectonically predisposed steep slopes with deeply incised river valleys, while on the top are sharp ridges and peaks modeled with strong glacial erosion during Pleistocene (KUHLEMANN et al. 2009). The Jakupica (21.6°) and the Suva Gora (21.1°) have lower values because of many planation surfaces and weakly expressed glacial remnants. The Galičica Mountains have the lowest values for mean slope (only 17°), due to the huge summit karst planation surface with few karst poljes and uvalas. The Bistra Mountains (19.7°) have an almost identical situation, but here mountain sides are almost vertically incised by the Radika Canyon, producing a higher mean slope. Overall, the average slope gradient of the high mountain ranges in the Republic of Macedonia is 20.9°, significantly larger than the average slope in the whole country which is 13.5° (MILEVSKI 2007).

Mountain	<500	500-1000	1000-1500	1500-2000	2000-2500	>2500	Total
Korab	0.0	25.4	97.0	124.9	40.5	1.7	289.5
Šara Mountain	0.0	104.7	224.7	319.4	171.1	8.7	828.6
Pelister	0.0	28.2	188.6	140.2	39.1	0.6	396.6
Jakupica	14.6	582.3	428.2	178.2	69.2	0.1	1272.7
Nidže	15.3	85.7	273.0	76.8	9.1	0.1	460.0
Galičica	0.0	48.7	205.8	84.7	7.1	0.0	346.3
Stogovo	0.0	78.3	226.2	138.5	15.0	0.0	458.0
Jablanica	0.0	47.7	92.2	60.2	7.5	0.0	207.6
Osogovo Mt.	3.8	432.8	427.6	114.2	2.6	0.0	981.0
Kožuf	1.6	270.6	199.3	70.6	1.8	0.0	543.9
Bistra	0.0	104.5	274.3	259.0	5.9	0.0	643.7
Suva Gora	15.0	393.2	409.5	105.5	0.2	0.0	923.4
Belasica	18.9	100.9	40.8	6.9	0.0	0.0	167.5
Total	**69.1**	**2303.0**	**3087.2**	**1679.0**	**369.2**	**11.1**	**7518.7**

Tab. 2 Hypsometry of the high mountain ranges in the Republic of Macedonia (in m and km^2)

Mountain	0-10	10-20.	20-30	30-40	40-50	>50	Pkm^2	Average
Korab	19.1	70.3	103.2	69.1	22.5	5.3	289.5	25.8
Šara Mountain	64.2	269.9	289.6	149.1	48.8	6.8	828.6	23.5
Pelister	27.8	95.7	165.8	100.3	6.5	0.4	396.6	24.1
Jakupica	187.6	403.9	405.3	221.0	45.8	9.1	1272.7	21.6
Nidže	56.6	162.2	163.3	67.8	9.4	0.6	460.0	20.4
Galičica	88.8	138.4	85.7	27.2	5.6	0.6	346.3	17.0
Stogovo	62.3	172.5	154.8	52.5	13.6	2.4	458.0	20.4
Jablanica	36.5	72.6	64.5	26.9	6.1	1.1	207.6	20.0
Osogovo Mt.	136.5	415.1	331.9	89.3	8.0	0.2	981.0	19.1
Kožuf	88.7	215.6	174.6	53.8	9.7	1.5	543.9	19.2
Bistra	119.6	242.8	180.4	69.3	23.8	7.8	643.7	19.7
Suva Gora	125.5	308.3	311.3	154.8	22.1	1.4	923.4	21.1
Belasica	30.7	50.9	49.7	30.2	5.8	0.3	167.5	20.9
Total	**1044.0**	**2617.9**	**2480.2**	**1111.3**	**227.8**	**37.6**	**7518.7**	**20.9**

Tab. 3 Slope angles of the high mountain ranges in the Republic of Macedonia (in degree)

Fig. 3 presents graphs of average slope gradient against altitude, within each range. These gradient curves 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 altitude as a result of steep slopes and deeply incised valley sides, as well as in highest parts on ridge and peak sides. At the mountains base and on top of most peaks and ridges, the slope is lower because of gradual flattening of the terrain. However, mountain ranges highly affected by Pleistocene glaciations (most of them in the western part of the country), show prominent maxima of average slope above 2000 m. That is case with the Korab (2,100 – 2,500 m), the Šara (2,200 – 2,600 m), the Pelister (2,300 – 2,500 m), the Galičica (1,900 – 2,150 m) and the Jablanica (2,050 – 2,200 m). Usually they represent steep slopes of cirques, U-valleys, ridges and sharp peaks. In same time, there are distinctive indentations in higher parts of above and some other mountain ranges related with large karst planation surfaces. Thus, the Galičica have re-

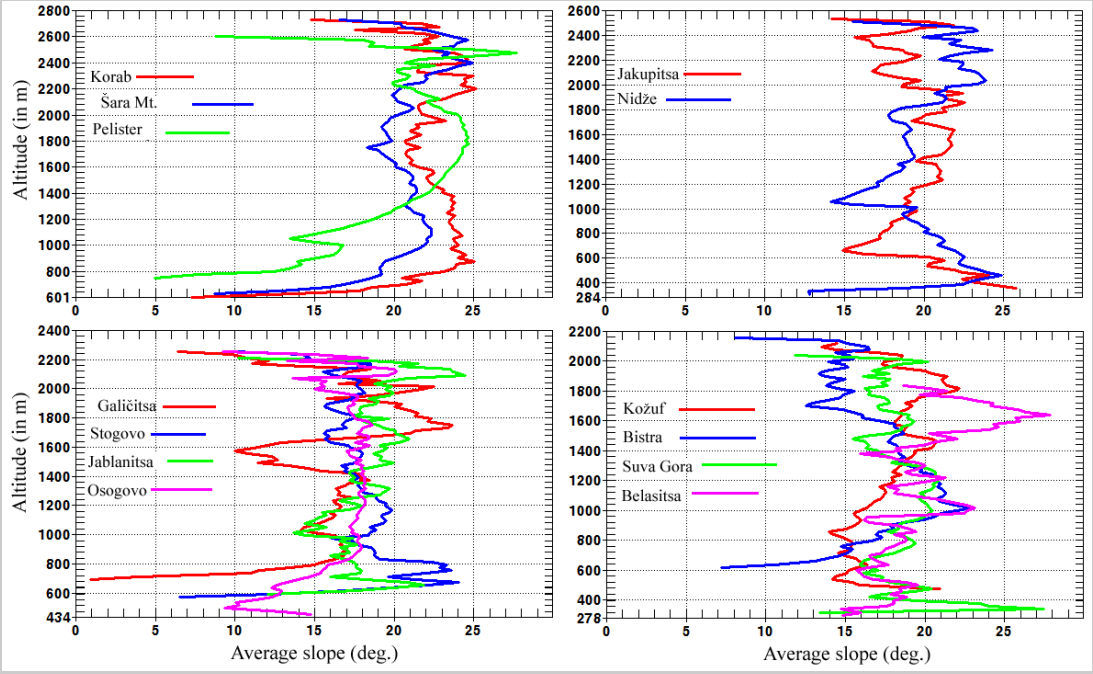

Fig. 3 Graphs of mean slopes against the altitude

Mountain	0-10	10-20.	20-30	30-40	40-50	>50	Pkm^2	Average
Korab	22.9	48.6	64.1	60.8	42.6	50.4	289.5	34.8
Šara Mount.	78.4	167.0	188.5	156.5	105.4	132.8	828.6	33.2
Pelister	28.6	75.0	102.3	88.3	51.8	50.6	396.6	32.0
Jakupica	208.5	309.9	292.9	209.8	120.1	131.6	1272.7	27.4
Nidže	75.5	125.9	118.0	71.9	35.1	33.7	460.0	25.2
Galičica	98.6	93.6	70.0	40.4	19.7	23.9	346.3	21.7
Stogovo	75.8	118.4	112.5	69.2	37.7	44.3	458.0	26.7
Jablanica	41.3	52.9	49.6	31.1	16.5	16.2	207.6	25.1
Osogovo Mt.	184.9	307.7	253.5	133.5	56.4	45.0	981.0	22.6
Kožuf	109.4	162.8	138.7	71.8	32.6	28.6	543.9	22.7
Bistra	144.4	175.6	134.6	83.1	47.4	58.5	643.7	24.7
Suva Gora	155.8	229.1	213.8	153.7	84.5	86.7	923.4	26.7
Belasica	37.3	40.9	33.7	23.8	14.0	17.8	167.5	26.7
Total	**1261.4**	**1907.3**	**1772.2**	**1193.9**	**663.9**	**720.1**	**7518.7**	**26.9**

Tab. 4 Values of the LS factor for the high mountain ranges in the Republic of Macedonia

markable indents (and planation surfaces) on 1,500 – 1,600 m, 1,900 – 1,950 m and 2,150 – 2,250 m, the Bistra Mountains on 1,700 – 2,050 m, and the Jakupica on 2,000 – 2,400 m. There are also indents representing large old surfaces of planation (non-karstic in nature) on the Korab (1,600-2,100 m), the Šara (1,600 – 2,200 m) and the Pelister (2,100 – 2,300 m). These surfaces are partly filled with glacial deposits. Bellow 2,100 m, the Pelister which is typical, almost symmetrical horst, has an regular curve with a broad maximum of gradient at 1,600 – 2,000 m. This contrasts with the Kožuf Mountains which have mean gradients between 14° and 22° from the foothills to the highest parts.

LENGTH-SLOPE FACTOR

Besides the size of the slope, the length of slope is a very important geomorphometric characteristic. Thus, long and steep hillslopes provide greater potential for erosive power in contrast to short hillslopes with the same gradient (ZINGG 1940). Length of slope itself is a consequence of more complex geotectonic and geomorphological processes.

The LS (Length-Slope) factor (**Tab. 4**) is product of the length and magnitude of slope, and is often used in different equations to determine the potential degree of erosion (originally in USLE). LS factor is dimension-less where value 1 correspond to the slope length (L) of 22.1 m and slope steepness (S) of 9 % or 5.1°. The greater the values of this factor, the longer or steeper are the slopes (REMORTEL et al. 2001), showing greater erosion potential. Analysis of the SAGA-calculated LS factor for the high mountain ranges in the Republic of Macedonia shows that values range from 0 to over 100, but are generally between 0 and 50. Values around 0 shows hillslopes of varying length and small slope, while values above 50 indicates long, steep hillslopes. From **Tab. 4** it is clear that highest LS factor values occur in the three highest ranges: the Korab, the Šara Mts.and the Pelister, that also have large average gradients. The lowest values occur in the Galičica Mountains, where the highest parts have relatively flat and short hillslopes. The mean value of the LS factor for the high mountain ranges is 26.9, while for the entire country it is 15.9.

TYPES OF SLOPE

The type of slope or slope curvature is an important morphological and geomorphometric element that indicates what the slopes are by shape: convex, straight or concave. Ridges and peaks have convex slopes, flats or fields and surfaces with uniform slope have straight slopes, while valley bottoms and depressions have concave slopes (HRVATIN and PERKO 2002). In this paper, the types of slope are represented by the SAGA GIS convergence index. By its meaning it is similar to plan or horizontal curvature, but gives much smoother results (OLAYA 2004). 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 (CONRAD 2011). On all ranges, the type of slope changes with elevation from concave (in the lowest parts) to convex (in the highest areas).

The data in **Tab. 5** show that the high mountain ranges in the Republic of Macedonia are dominated by straight to weakly-convex

	Very concave	**Fairly concave**	**Straight slope**	**Fairly convex**	**Very convex**	**Total area**	**Peaks area**
Mountain	< -40	-40 to -5	-5 to 5	5 to 40	>40	Pkm^2	>60
Korab	7.1	86.4	95.5	93.8	6.6	289.5	1.0
Šara Mount.	18.5	230.0	288.7	277.8	13.6	828.6	2.5
Pelister	7.9	117.6	128.9	135.1	7.0	396.6	0.9
Jakupica	39.3	388.6	357.3	451.5	36.0	1272.7	6.4
Nidže	14.8	148.4	105.6	174.1	17.0	460.0	3.2
Galičica	12.6	96.8	109.7	113.6	13.5	346.3	3.1
Stogovo	14.0	137.8	133.7	159.3	13.0	458.0	2.6
Jablanica	6.7	66.1	54.5	72.8	7.4	207.6	1.6
Osogovo Mt.	43.5	311.4	215.7	372.6	37.8	981.0	6.7
Kožuf	24.6	172.3	123.9	199.7	23.4	543.9	4.2
Bistra	26.4	193.9	169.8	233.6	20.0	643.7	4.6
Suva Gora	29.7	289.9	249.6	326.5	27.7	923.4	5.4
Belasica	5.4	54.1	36.7	64.9	6.4	167.5	1.2
Total	**250.5**	**2293.4**	**2069.6**	**2675.4**	**229.5**	**7518.7**	**43.4**

Tab. 5 Type of slope of the high mountain ranges in the Republic of Macedonia

slopes. Surfaces with extremely convex slopes (>60; characteristic of summits) are found on the Galičica (0.9 %), the Kožuf (0.8 %), the Jablanica (0.75 %), the Bistra (0.7 %), the Belasica (0.7 %), the Nidže with the Kozjak (0.69 %), and the Osogovo Mountain (0.68 %). On these ranges, in relation to their total areas, numerous weakly expressed peaks or more rounded and flattened summits occur. On the other hand are the Pelister (0.2 %), the Šara Mts. (0.3 %) and the Korab (0.36 %), which compared to their total areas have smaller numbers of peaks, but usually sharper (and thus with small areas). Mountain ranges with the greatest relative share of concave slopes are the Kožuf (4.5 %), the Osogovo Mountain (4.4 %) and the Bistra (4.1 %).

SLOPE ASPECT

Slope aspect is another important morphometric element which is a result of geotectonic-structural and geomorphologic-evolutionary processes. In addition, aspect is important for the intensity of erosion processes, for climate-vegetation features and for soil characteristics. The paper presents the slope aspects of high mountain ranges in the Republic of Macedonia in terms of the 8 standard directions (4 main and 4 auxiliary). From **Tab. 6** great diversity is apparent in aspect distributions. There are several reasons for that: geotectonic-morphological features of the ranges, dominant ridge trend, extension of the larger river valleys, and extension of the mountain ranges in relation to

Mountain	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**N**	**Total**
Korab	52.1	64.3	50.0	38.5	26.7	15.0	11.7	31.1	289.5
Šara Moun.	109.4	153.7	177.8	140.9	90.0	48.6	46.4	61.9	828.6
Pelister	50.7	54.3	50.0	32.1	40.8	54.9	51.5	62.3	396.6
Jakupica*	171.5	181.8	143.0	131.4	160.7	191.9	154.2	138.2	1272.7
Nidže	66.6	42.8	33.0	35.2	54.9	75.4	76.5	75.5	460.0
Galičica	42.8	55.1	35.2	25.9	34.3	74.1	49.5	29.5	346.3
Stogovo*	58.9	61.8	52.2	53.7	75.6	63.4	46.3	46.3	458.0
Jablanica	48.9	55.8	33.4	20.8	10.1	6.5	10.8	21.1	207.6
Osogovo Mt.	102.7	121.4	112.5	126.2	163.2	147.8	109.6	97.6	981.0
Kožuf	87.1	75.1	43.7	31.9	47.9	89.3	88.2	80.5	543.9
Bistra*	93.6	93.2	75.0	67.4	72.0	81.5	79.9	81.1	643.7
Suva Gora*	118.4	125.4	131.0	118.1	92.8	93.7	111.4	132.4	923.4
Belasica	27.5	14.9	7.4	11.6	19.1	22.3	26.4	38.4	167.5
Total	**1030.3**	**1099.6**	**944.1**	**833.7**	**888.2**	**964.4**	**862.3**	**895.9**	**7518.8**

Tab. 6 Terrain aspects of the high mountain ranges in the Republic of Macedonia (*mountain ranges entirely located in Macedonia)

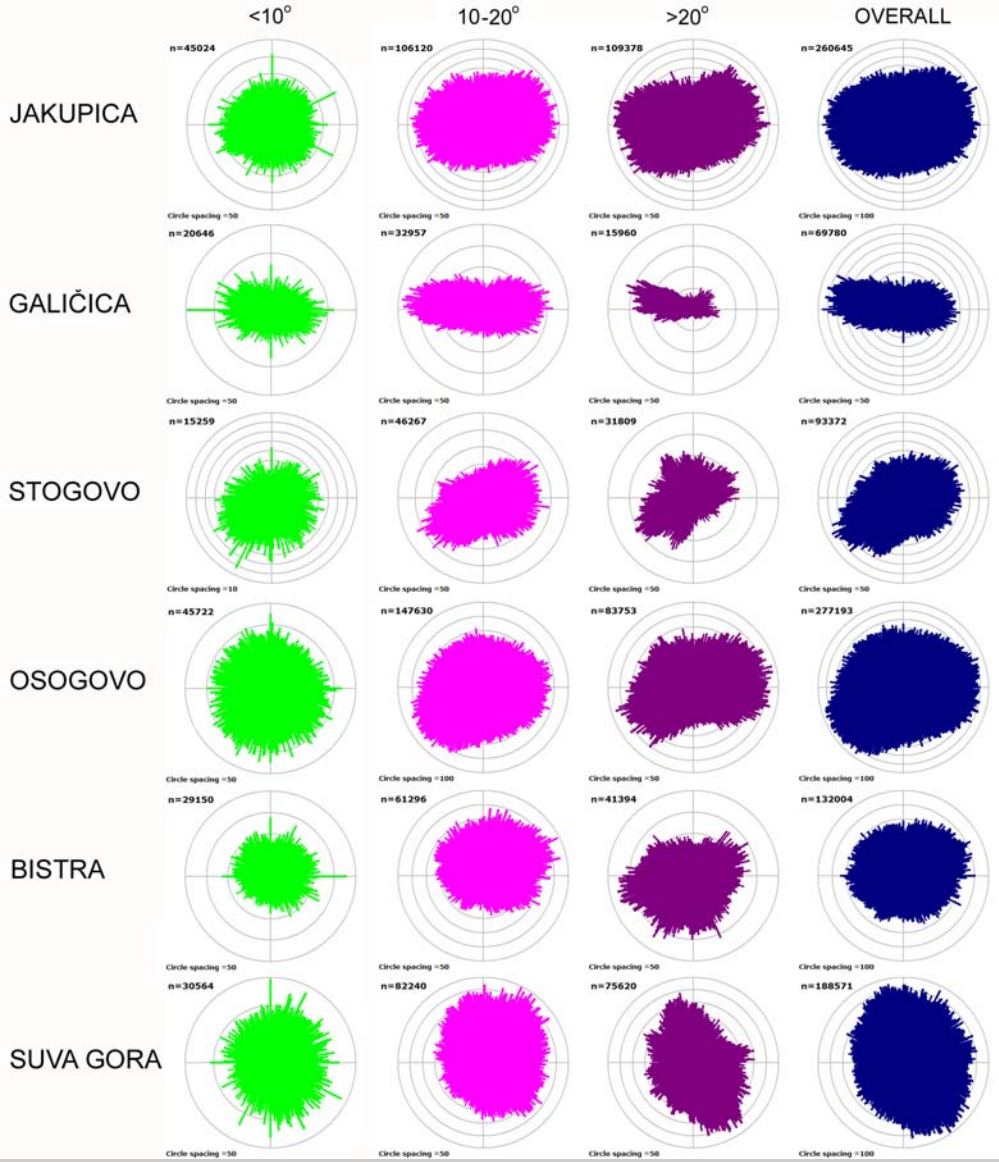

Fig. 4 Graph of aspects against the slope classes of 6 mountain ranges which are entirely or almost entirely located in the Republic of Macedonia (the Osogovo is represented within its natural borders)

state borders. Because of the borders, a realistic view of aspect distributions is given only for the ranges which are wholly located in the Republic of Macedonia: the Jakupica, the Stogovo, the Bistra, the Suva Gora and mostly the 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**. It is interesting that only the Galičica and the Stogovo Mountains shows very bi-directional aspect distributions (W-E and SW-NE) exactly in opposite to their elongations. The reasons for that is geotectonically predisposed poor lateral relief dissection. In contrary is the Osogovo Mountains, where aspects distribution is the same as its elongation (ENE-WSW) mostly because of very high perpendicular valley dissections. Relatively similar situation is with the Jakupica and the Suva Gora Mountains, while the Bistra Mountains which is without clear elongation have uneven distribution of aspects. However, on all 6 mountains except on the Suva Gora, west and east aspects are dominant. Actually, that is the same for all 13 mountains, where the western aspects are dominant (by number of ranges), followed by the eastern ones (by area). This is consistent with the dominant Dinaric-Hellenidic (N-S and NW-SE) direction of most ranges in of Macedonia. Exceptions are the Nidže, the Kožuf, the Osogovo and the Be-

Mountain	NE	E	SE	S	SW	W	NW	N
Korab	24.5	25.3	27.2	27.9	26.8	24.0	24.5	24.4
Šara Mountain	22.8	22.1	22.4	24.1	25.9	25.2	24.5	23.7
Pelister	22.6	24.4	25.6	24.6	24.1	23.7	24.7	23.5
Jakupica*	21.5	21.7	20.8	21.1	22.2	22.3	21.9	21.0
Nidže	22.7	21.9	19.7	18.7	20.0	20.4	21.2	21.5
Galičica	17.3	15.9	14.6	14.1	15.5	19.8	18.3	16.4
Stogovo*	20.6	19.7	17.9	19.2	21.1	20.8	22.0	22.1
Jablanica	21.3	20.1	18.8	20.1	20.2	15.2	19.9	20.5
Osogovo Mt.	20.5	20.2	18.7	18.0	18.9	19.2	18.5	18.7
Kožuf	19.6	20.5	20.5	19.9	19.5	19.4	17.6	18.0
Bistra*	18.2	18.5	18.9	21.2	22.5	22.4	19.2	17.7
Suva Gora*	19.3	20.8	21.5	21.9	21.6	21.4	21.5	21.0
Belasica	23.3	20.8	14.5	14.0	15.4	20.5	22.7	24.1
Total	**21.1**	**20.9**	**20.1**	**20.4**	**21.1**	**21.1**	**21.3**	**21.0**

Tab. 7 Average slopes against the aspects of the high mountain ranges in the Republic of Macedonia (in degree; *mountain ranges entirely located in Macedonia)

lasica Mountains, which are W-E oriented because of Aegean extensional neotectonic regime (BURCHFIEL et al. 2008).

With further analyses, the average gradients for each aspect were calculated (**Tab. 7**) with remark that truncations of the border mountains slightly affect the results. The data shows that the most common aspects do not have the greatest slopes, but usually the opposite. This is fairly logical because a smaller slope increases the area with a given aspect. Thus, the Korab Range extends in a north-south direction, and eastern (22.2%) and northeastern aspects (18%) are most frequent. On the other hand, south - and southeast - facing slopes have the highest average gradients, due to the steep valley sides of the southern Ribnička River, the Žirovnička River, the Lopušnik River and others. In the Šara Mts., southeast (22.5%), eastern (18.5%) and southern aspects (17%) dominate. The opposite south, west and north-west aspects have the greatest slope gradients, however, due to the steep valley sides of the upper courses of the Radika River, the Pena River and other rivers. In fact, the most common aspects represent long, extensive mountain slopes that are perpendicular to the trend of the ranges. 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. In addition, from **Fig. 4** it is clear that aspect distributions significantly change with slope from more uneven to more directional on steeper slopes.

DRAINAGE DENSITY

Landscape drainage density is a morphometric indicator that indicates horizontal dissection by the density of linear fluvial-denudation forms: valleys and gullies. Usually it is expressed as the total length of drainage channel network in km, per km^2 area. Horizontal dissection on the high mountain ranges in the Republic of Macedonia was obtained by a complex procedure in SAGA GIS in which the drainage network was extracted from the digital terrain model, and its density was then calculated. The results show that dissection in the high mountain ranges is generally uniform and ranges from about 2.48 km/km^2 on the Nidže Mts. to 3.13 km/km^2 on the Korab. High densities are found in the Šara Mts. (3.11), the Stogovo (2.93), the Galičica (2.90), the Jakupica (2.89) and the Pelister (2.89). The Suva Gora (2.85), the Jablanica (2.81) and the Bistra (2.75), which are mostly karstified, have lower values: as do the Kožuf (2.53), the Belasica (2.53), the Osogovo (2.51), and the Nidže (2.48) which are in the eastern, less humid area of the country.

RELIEF

Relief is very important morphometric element that indicates the maximum height differences of a particular area – usually within a square with sides of 1 km (1 km^2). This variable is closely correlated with the intensity of neotectonic processes and the dynamics of geomorphologic processes (especially fluvial erosion), and indicates the potential erosion energy of the landscape (MARKOVIC 1983). Relief of the high mountain ranges in the Republic of Macedonia was computed with MicroDEM software, showing values from 0 (flats) to 1,130 m/km^2 (extremely dissected relief). High values are indications of strongly differentiated neotectonic movements, and the associated intense Quaternary river valley incision

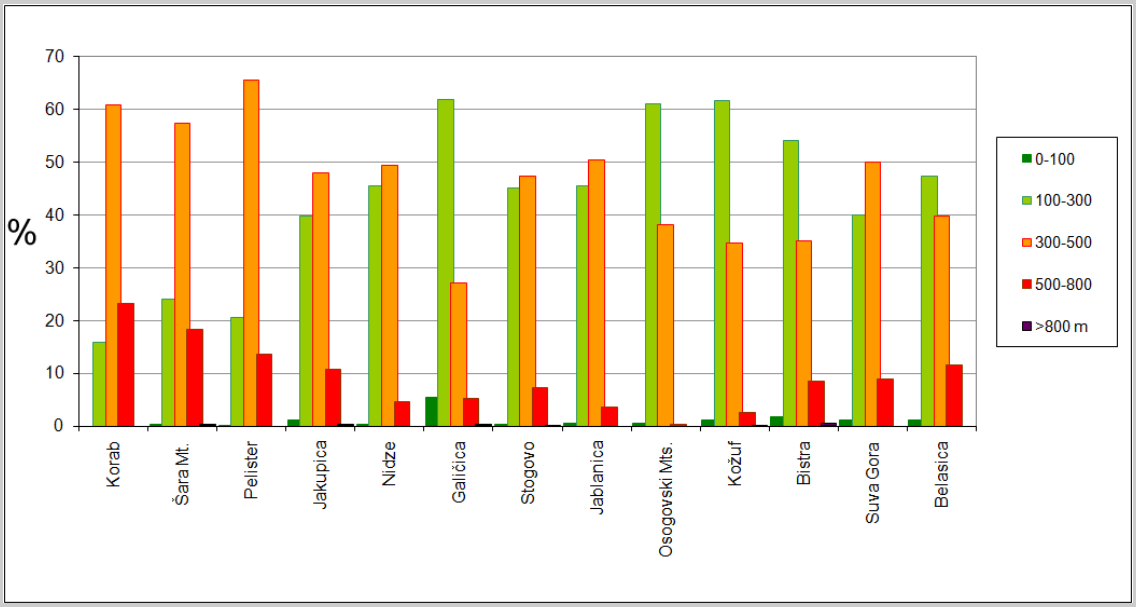

Fig. 5 Graph of terrain relief of the high mountain ranges in the Republic of Macedonia with modal classes according to the General geomorphological map of the Republic of Macedonia (MANAKOVIK et al., 1998)

in the mountain ranges. In that sense, the maximal value (above 1000 m/km^2) are find on the south slope of the Jakupica Mountains in the area of the Nezilovo Rocks – an impressive 1200 m deep tectonic escarpment composed of marbles.

The data in **Tab. 8** shows high average values of relief which range from 416 m/km^2 for the Korab to 270 m/km^2 for the Galičica. The Osogovo and the Kožuf Mountains have small vertical relief (278 and 282 m/km^2), while besides the Korab, the Šara Mts. and the Pelister also have high relief with large portion of area in the modal class of 500-800 m/km^2 (**Fig. 5**). The average relief of all high mountain ranges in the Republic of Macedonia is 329 m/km^2. That is significantly above the 207 m/km^2 average relief in the country, which is already a high value.

MORPHOMETRIC CLASSIFICATION

The morphometric variables analyzed above indicate some similarities as well as differences between high mountain ranges in the Republic of Macedonia. But it will be even more valuable to use these in constructing a complex characterization and classification of the ranges. For that purpose six variables were used: maximal altitude, average altitude, volume index, mean slope gradient, average length-slope (LS) value and average relief. First of all, mountains are ordered in regard to the overall mean value of each variable (above or below

Mountain	**0-100**	**100-300**	**300-500**	**500-800**	**>800**	**Pkm^2**	**Average**
Korab	0.0	45.8	176.3	67.4	0.0	289.5	415.8
Šara Mountain	1.4	199.7	474.9	151.4	1.2	828.6	390.0
Pelister	0.1	82.0	260.2	54.4	0.0	396.6	386.8
Jakupica	13.2	506.2	611.5	138.8	2.9	1272.7	340.9
Nidže	1.4	209.7	227.2	21.7	0.0	460.0	316.4
Galičica	18.3	214.4	94.3	18.6	0.7	346.3	269.7
Stogovo	0.9	206.1	216.4	34.0	0.5	458.0	327.2
Jablanica	0.9	94.6	104.5	7.5	0.0	207.6	315.4
Osogovo Mt.	3.7	599.1	373.7	4.5	0.0	981.0	278.5
Kožuf	5.6	334.7	188.9	14.6	0.0	543.9	282.4
Bistra	11.0	347.9	226.6	55.6	2.6	643.7	306.8
Suva Gora	9.5	369.1	462.6	82.1	0.0	923.4	333.0
Belasica	1.8	79.3	66.7	19.7	0.0	167.5	322.0
Total	**67.9**	**3288.9**	**3483.8**	**670.1**	**8.0**	**7518.7**	**328.6**

Tab. 8 Terrain relief of the high mountain ranges in the Republic of Macedonia (in m/km^2)

Mountain	Hmax	Hsr m	iV/P	Av.slope	Av.L-S	Av.Ver.R	Group
Korab	2753	1564.9	0.98	25.8	34.8	415.8	I
Šara Mountain	2748	1602.7	1.01	23.5	33.2	390.0	I
Pelister	2601	1480.3	0.74	24.1	32.0	386.8	I
Jakupica	2540	1127.2	0.81	21.6	27.4	340.9	I-II
Nidže	2520	1197.3	0.93	20.4	25.2	316.4	II
Galičica	2288	1294.3	0.60	17.0	21.7	269.7	III
Stogovo	2268	1345.8	0.78	20.4	26.7	327.2	II
Jablanica	2256	1314.2	0.74	20.0	25.1	315.4	II
Osogovo Mt.	2252	1074.8	0.65	19.1	22.6	278.5	III
Kožuf	2165	1058.5	0.61	19.2	22.7	282.4	III
Bistra	2163	1384.9	0.80	19.7	24.7	306.8	II
Suva Gora	2061	1070.7	0.77	21.1	26.7	333.0	III
Belasica	2029	843.6	0.57	20.9	26.7	322.0	III
Average	**2357**	**1248.3**	**0.77**	**20.9**	**26.9**	**328.6**	

Tab. 9 Morphometric classification of the high mountain ranges in the Republic of Macedonia

that mean value). After that, according to the principle of supervised classification, they are classified into three groups (**Tab. 9**).

In the first group are the three highest ranges (above 2600 m) the Korab, the Šara and the Pelister Mountains, which have an average elevation of 1480 to 1602 m, high average slope gradients (over 24°), high length-slope factor (LS>32) and high relief (>380 m/km^2). These ranges are characterized by large volume indices (Vkm^3/Pkm^2) that range from 1.0 for the Korab to 0.75 for the Pelister.

According to the morphometric features, the Jakupica lies between the first group and the second. It belongs to the group of ranges reaching higher than 2500 m: it has a high volume index (0.81), but lower average altitude (1127 m) and lower average slope (21.6°) than the above group. It has also a smaller length-slope factor (LS=27.4) but relatively large horizontal dissection and vertical relief (340.9 m/km^2). Its hillslopes are substantially convex in form.

In a second group are the Nidže, the Stogovo, the Jablanica, the Suva Gora and the Bistra Ranges. Although according to the highest peak the Nidže is higher than 2500 m, in terms of the other morphometric elements it has similarities with other ranges in this (second) group. Namely, all have only average values for mean slope gradient (20-21°) and for length-slope factor (LS=25-27). They also have average values of relief (315-333 m/km^2) and lower horizontal dissection. Mean altitudes of these mountain ranges are somewhat smaller than in the first group, ranging from 1,200 m to 1,350 m.

In the third group are the Galičica, the Osogovo Mountain, the Kožuf and the Belasica Ranges. They are characterized by smaller average slope (17°-20°), extremely convex forms (Icon> 60), low average length-slope factors (LS=21.7-24.7), low relief (<310 m/km^2) and small average altitudes, below 1,400 m. The Belasica Range in the Republic of Macedonia has a much lower average altitude and average index of volume, because its highest parts are in the territory of Bulgaria (the Radomir Peak, 2,029 m). In **Fig. 6** characteristic cross-sections from each group are presented, with the morphological and morphometric differences mentioned above clearly visible.

CONCLUSION

Because of variable structural and geomorphic evolution, high mountains (reaching higher than 2000 m) in the Republic of Macedonia have significant morphometric differences, clearly evident in their hypsometry, volume index, slope gradient, aspect and convergence, length-slope factor, horizontal dissection and relief. According to averaged values of six of these variables, a supervised morphometric classification of the mountain ranges is made and they are classified into three groups. The first is a group of very high (for Macedonian or even Balkan conditions), ranges with steep slopes: the Korab, the Šara Mts. and the Pelister. The large Jakupica (Mokra) Range lies between the first and second groups. The second group contains mountain ranges with moderate altitude, slope and relief: the Nidže, the Stogovo, the Jablanica, the Suva Gora and the Bistra. The third group includes the lower ranges, with gentle slopes and large planation surfaces: the Galičica, the Osogovo, the Kožuf and the Belasica. This morphometric classification is strongly correlated with geotectonic po-

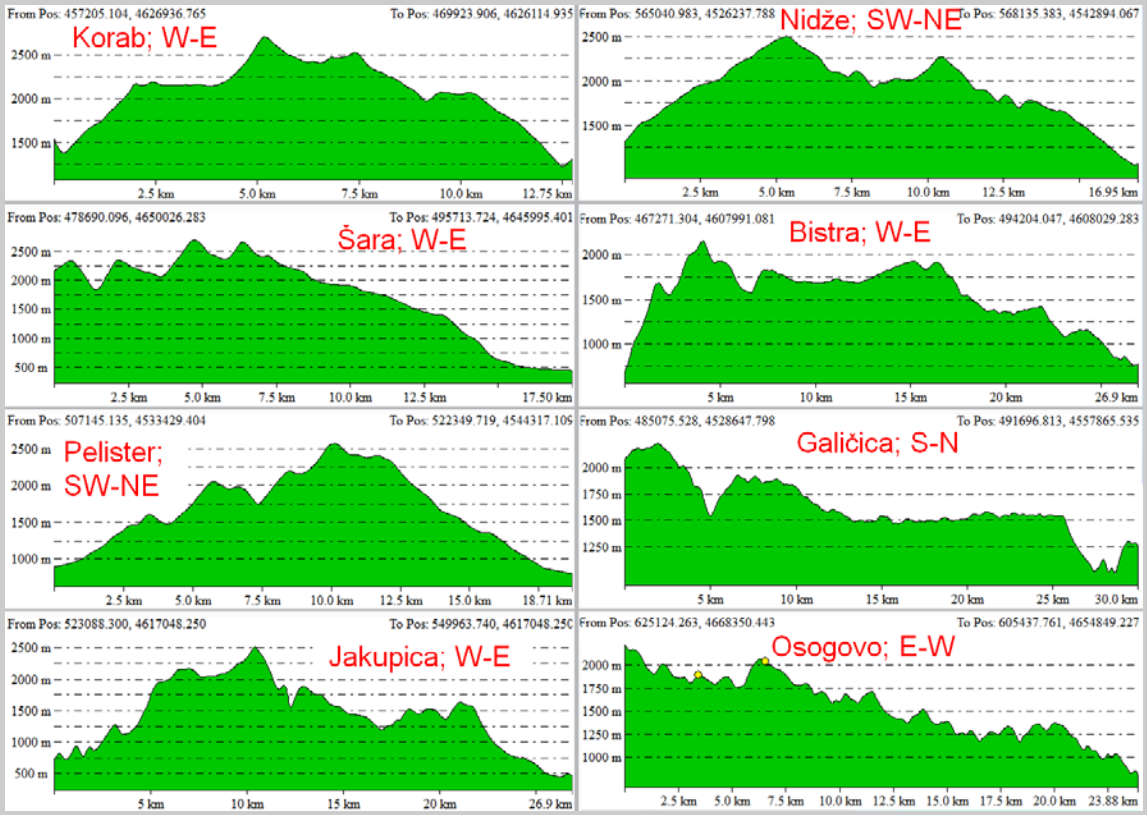

Fig. 6 Characteristic cross-sections of the high mountain ranges in Macedonia through the highest peaks

sition and mountain evolution. Thus, the first and second groups of mountain ranges belong to the inner Dinarides and Hellenides geotectonic belt characterized by intensive E-W tectonic compression especially during the Tertiary (DUMURDZANOV et al. 2004). Numerous remnants from Wurmian glacial phase with cirques, narrow ridges and sharp peaks extending above the karst planation surfaces (on 1,600 – 2,000 m), make distinctive morphology of these ranges. Unlike them, except for the Galičica the third group is closer to the Balkanides geotectonic belt, with a highly expressed N-S extensional regime of development.

Our morphometric classification is relative in nature, based only on the mean morphometric characteristics of 13 analyzed mountain ranges in the Republic of Macedonia. However, it satisfactorily well reflects the morphological similarities and differences of them on ge-neral scale. The next step will be an attempt of semi-automated classification of mountain ranges, but for that task probably somewhat different approach is needed. In broader research, with further improvements of variables and setting of correct limiting values, such kind of classification can be used at least for the high mountain ranges on the Balkan Peninsula which are similar in morphometry. Beyond purely theoretical research approaches, detailed and localized morphometric correlations may have practical significance for better structural and morphological interpretations, as well as for some erosion potential modeling and geohazards indicators.

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