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Geomorphometry of the cirques of Shar Mountain

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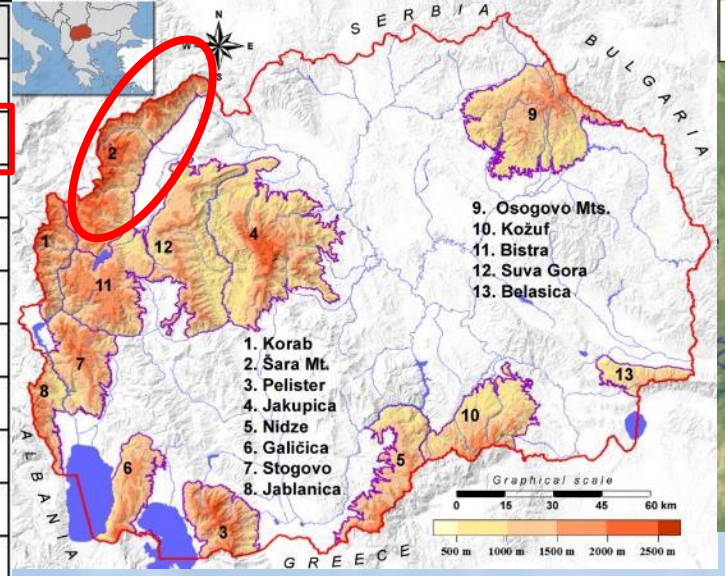
Introduction

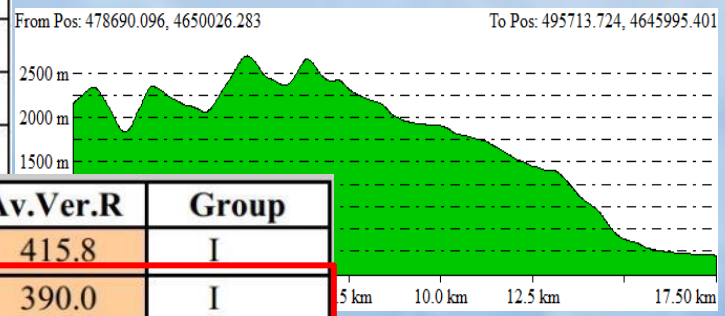
- Considering the importance of glacial cirque landforms, identifying and mapping the distribution of the cirques with an analysis of their quantitative features is a very important.
- Aside from fieldwork, this can be made with analysis of digital elevation/terrain models.
- Despite that most of the attention in the geomorphological studies of Šara Mountain were dedicated to its glacial landscape, a systematic and quantitative analysis of the glacial landforms is still missing.
- Besides, all data for the Macedonian part of the mountain are still based on research performed at the beginning of the 20th century.
- Therefore, additional research was made using the GIS tools with special emphasis on the geomorphometric analysis of the cirques.

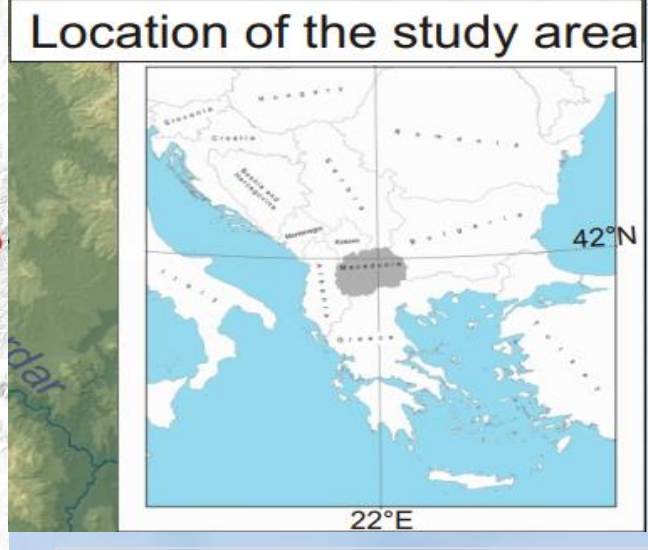
General data about the Šara Mountain

- Šara Mt. is the second highest mountain in North Macedonia (2747 m), after Korab Mt. (2753 m).
- Within the natural borders, it covers an area of 1670 km^2 of which 840 km^2, or nearly half, belongs to North Macedonia.
- This SSW-NNE trending range is about 80 km long, and is part of the Dinaric-Hellenic mountain belt.
- Mean height: 1560 m.
- Mean slope: 24.7°.
- 75 km long in NE-SSW-S direction.
- About 170 peaks higher than 2000 m, of which 41 peaks are higher than 2500 m and 12 peaks are higher than 2600 m.
- Almost all types of landforms/landscapes are present.

	Mountain	Hmax	Hsr m	P km²	Vkm³	iV/P
1.	Korab	2753	1564,9	289,5	282,6	0,98
2.	Shara Mountain	2748	1602,7	828,6	839,1	1,01
3.	Pelister	2601	1480,3	396,6	293,7	0,74
4.	Jakupitsa	2540	1127,2	1272,7	1032,4	0,81
5.	Nidze	2520	1197,3	460,0	425,5	0,93
6.	Galichitsa	2288	1294,3	346,3	208,2	0,60
7.	Stogovo	2268	1345,8	458,0	355,3	0,78
8.	Jablanitsa	2256	1314,2	207,6	153,6	0,74
9.	Osogovo	2252	1074,8	981,0	638,5	0,65
10.	Kozuf	2165	1058,5	543,9	331,6	0,61
11.	Bistra	2163	1384,9	643,7	513,6	0,80
12.	Suva Gora	2061	1070,7	923,4	710,8	0,77
13.	Belasitsa	2029	843,6	167,5	96,3	0,57







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**	

Table 1-2. Comparative morphometry of Šara Mountain and other high mountains in Macedonia.

Starting point: As defined by Evans and Cox (1974), a cirque is a hollow, open downstream but bounded upstream by the crest of a steep slope (headwall) which is arcuate in plan-view around a more gently-sloping floor. It is considered as glacial if its floor has been affected by glacial erosion.

Methodology

- Identification of the cirques on the Macedonian part of Šara Mountain by visual inspection using 5-m DEM of the Agency of Real Estate and Cadaster of North Macedonia (ARECNM) and 0.5 m ortophoto imagery (3D view of the mountain terrain in SAGA GIS, Global Mapper and MicroDEM software).
- Additionally, 3D terrain visualization of Google Earth Pro is used which helps the identification and delineation of cirques and U-shaped valleys.
- The accuracy of the cirques identification was verified on 15 test sites (cirques) in field during 2017-2021.
- After identification, delineation, and vectorization of the cirque borders and elements, SAGA GIS and MicroDEM is used for their detailed geomorphometric analyses, including size, altitude, slope, and aspect.

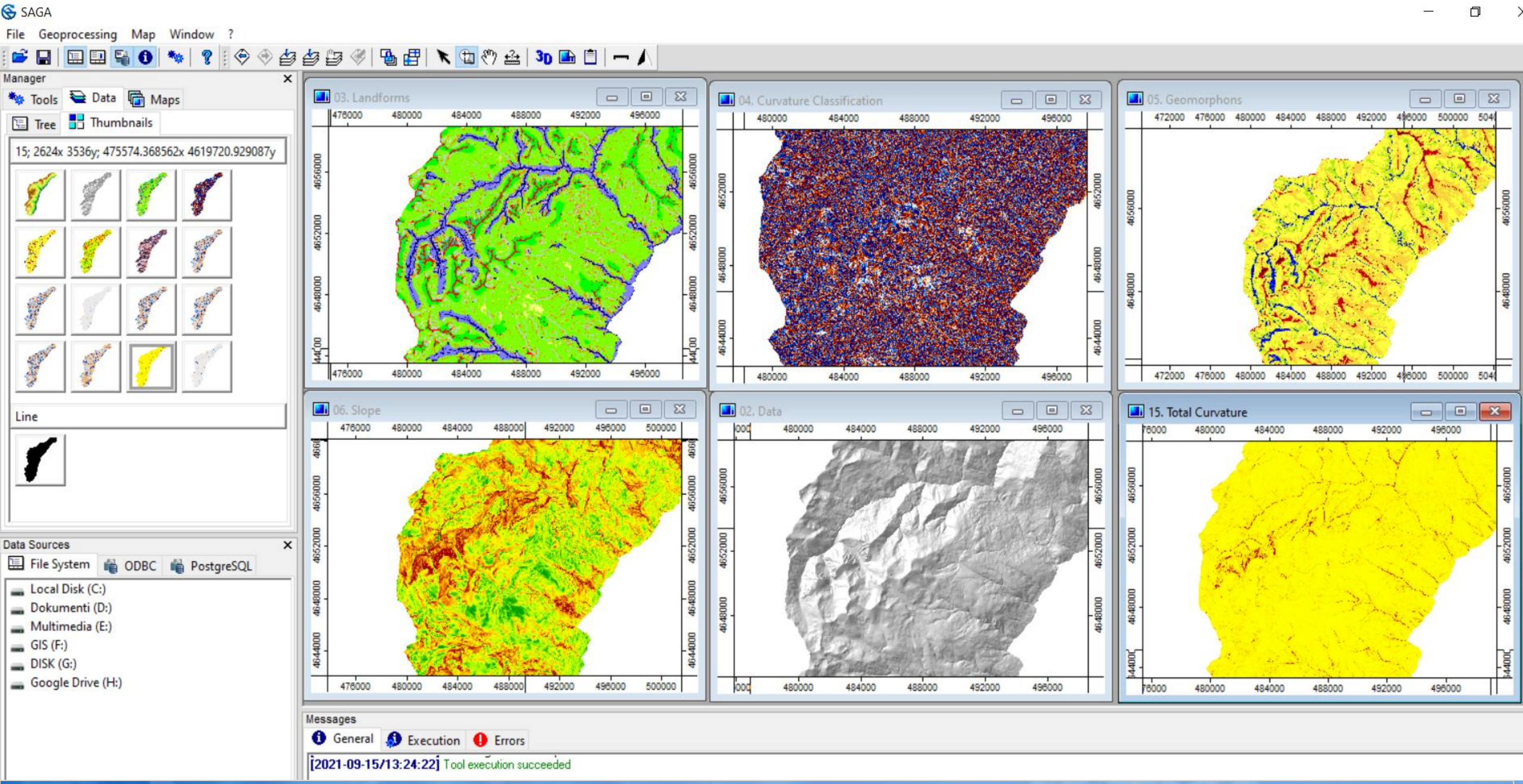
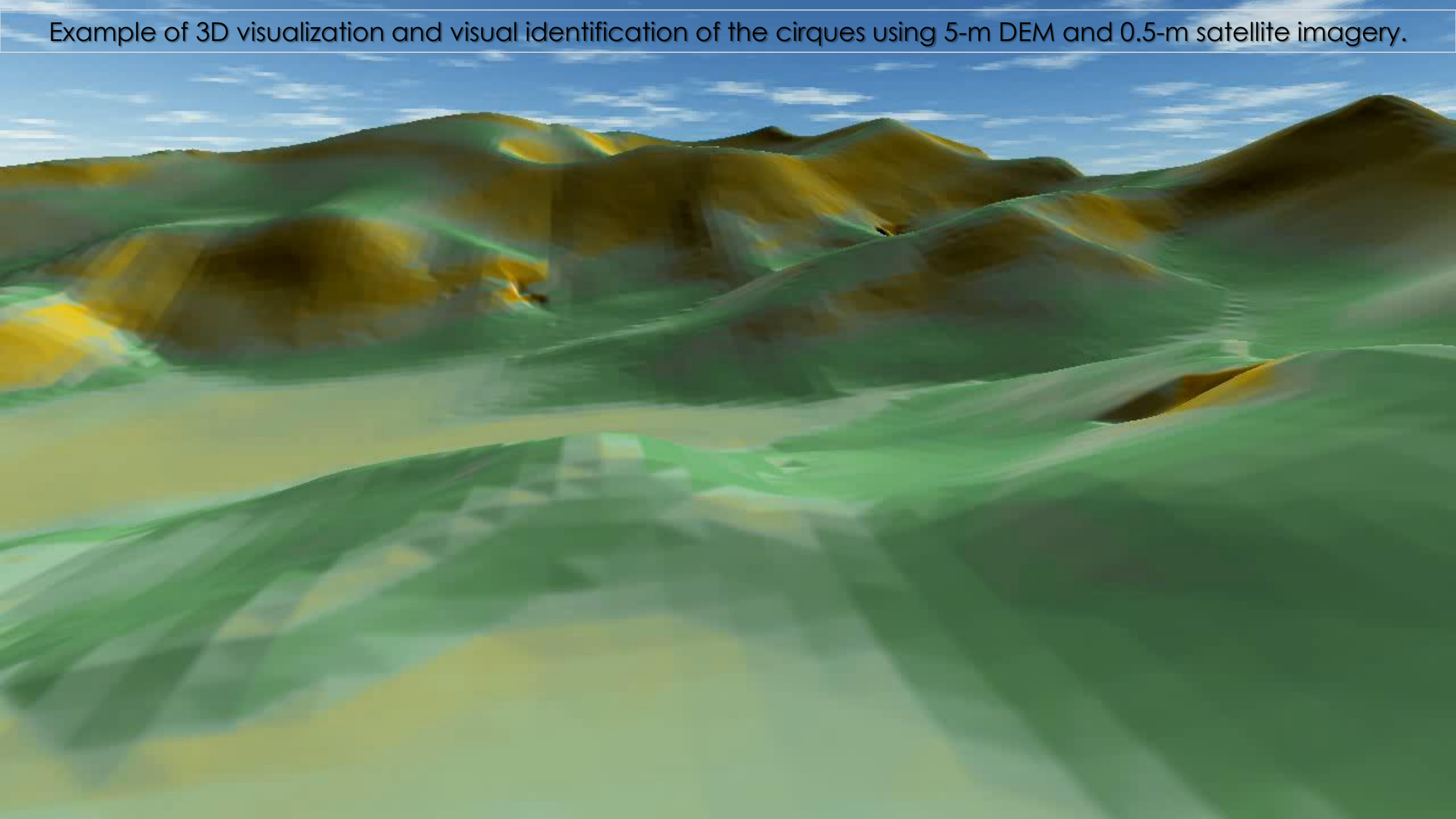
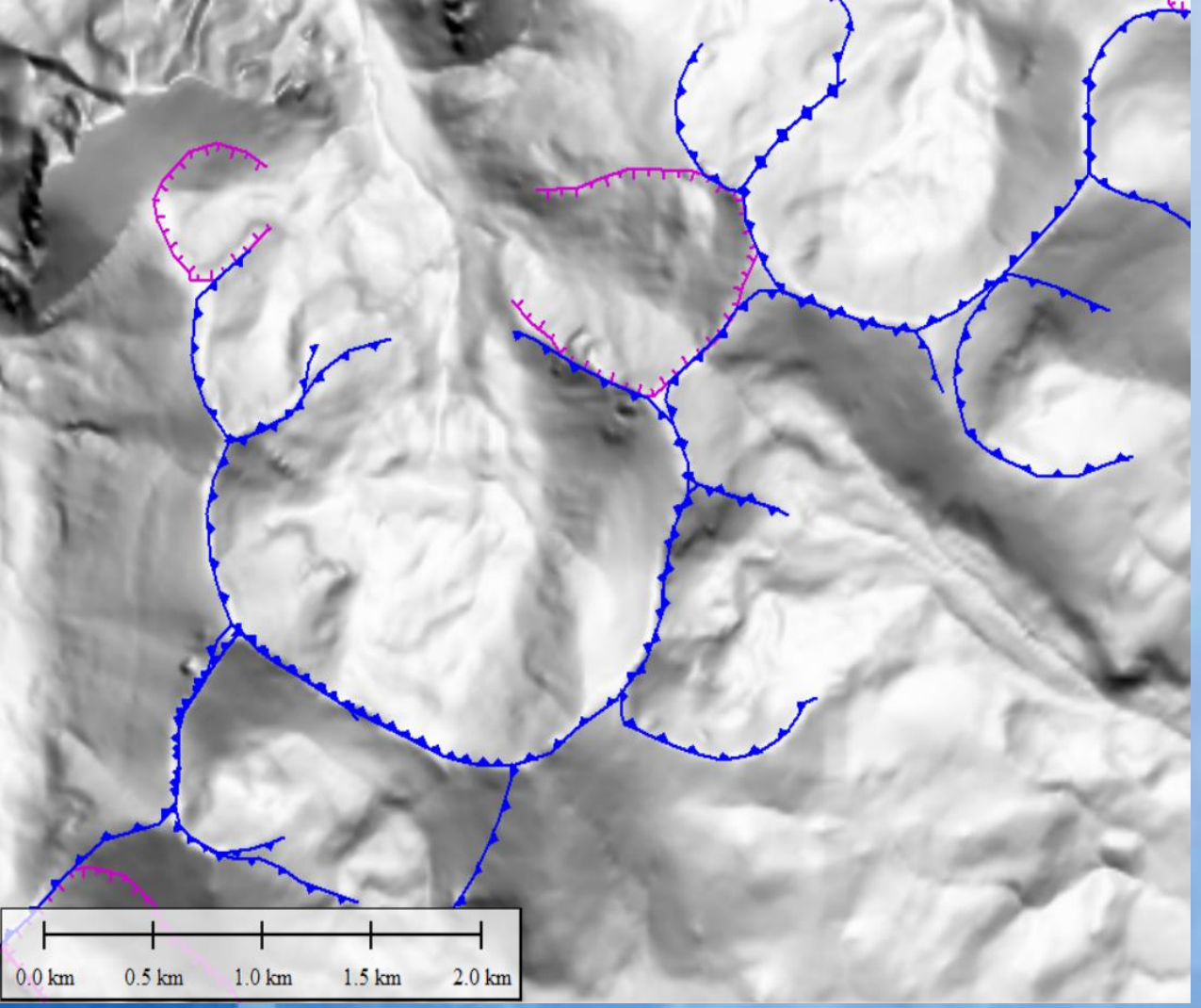


Fig. 2. Different efforts for semi-automatic delineation of the cirques on the Šara Mt. in SAGA GIS.

Example of 3D visualization and visual identification of the cirques using 5-m DEM and 0.5-m satellite imagery.





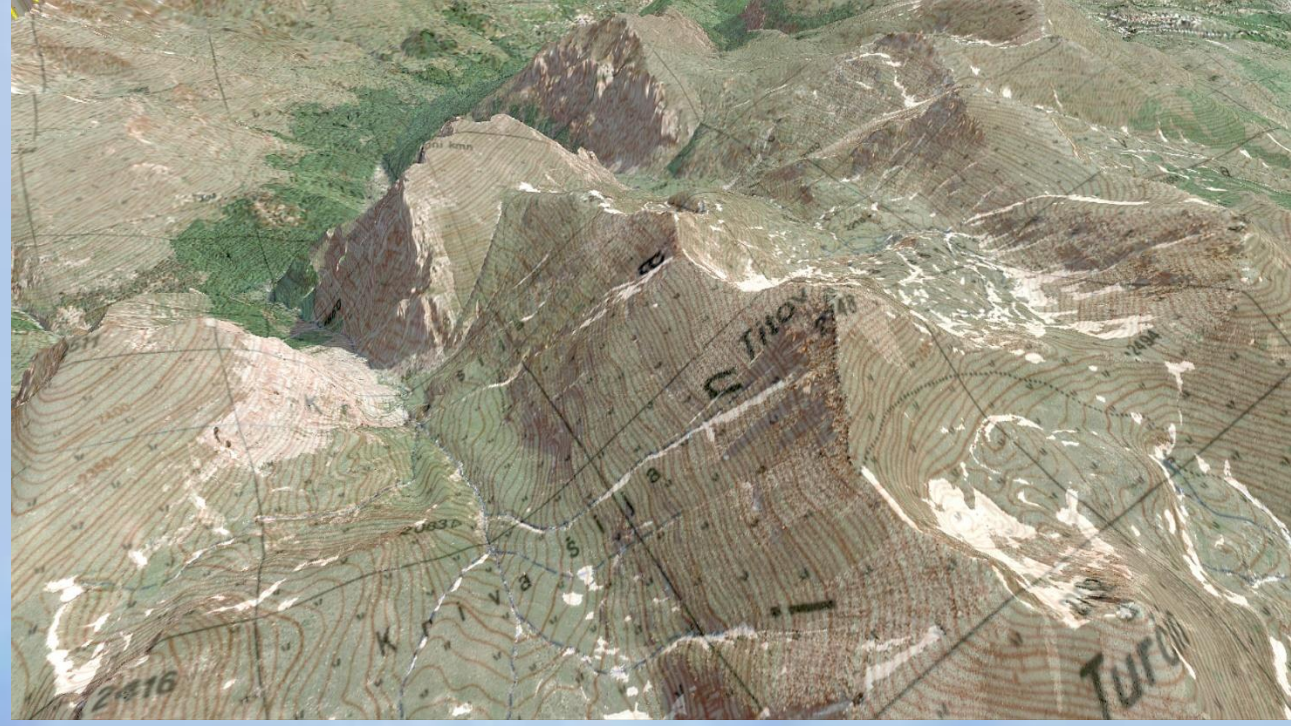


Fig. 2-4. Identification of the cirques and cirque elements on the Macedonian part of Šara Mt. by 2D and 3D visual inspection using 5-m DEM, 25k topo map and ortophoto in Global Mapper v.21 software.

No.	Name	Exc.	L1 km	L2 km	L3 km	P km²	Hmin m	Hmax m	Hsr m	A-sr
1	Бистрички-1	NE	1.6	1.2	4.8	2.0	2038	2515	2302	24.5
2	Боговински-1	N	1.4	1.2	4.1	1.5	2143	2562	2302	21.4
3	Боговински-2	NE	0.7	0.6	2.1	0.4	2207	2468	2300	19.9
4	Боговински-3	SE	0.7	0.7	1.9	0.4	2284	2554	2402	24.5
5	Боговински-4	SE	0.6	0.8	2.2	0.5	2227	2592	2387	24.5
6	Боговински-Езерски	NW	1.5	1.0	3.5	1.5	2095	2661	2232	23.1
7	Боговински-Езерски-1	N	0.6	0.6	1.7	0.3	2255	2575	2386	30.1
8	Боговински-Езерски-2	NW	0.8	0.8	2.2	0.5	2228	2658	2427	34.7
9	Бриставец-1	NE	0.6	0.6	2.1	0.4	2293	2675	2490	28.0
10	Бриставец-2	E	0.6	0.6	1.9	0.3	2144	2545	2300	34.5
11	Вакафски	E	1.1	0.9	2.3	0.6	1953	2185	2075	19.7
12	Врачански	E	1.7	1.3	5.8	2.9	1839	2576	2158	29.6
13	Врачански-1	N	0.5	0.7	2.1	0.5	2197	2512	2345	33.3
14	Деделбег-1	E	2.0	1.1	5.0	2.6	1752	2220	2018	17.8
15	Деделбег-2	NE	1.1	0.9	3.7	1.4	1757	2128	1930	19.6
16	Деделбешки	E	3.7	1.6	7.5	6.0	1613	2216	1885	18.5
17	Доброшки	E	0.9	1.1	3.9	1.0	2180	2572	2350	22.1
18	Зендел-бег	NE	1.5	1.2	4.3	2.2	1736	2192	1958	20.4
19	Казани	E	1.1	1.0	3.3	0.9	2243	2633	2378	23.7
20	Казанишки	N	1.5	1.1	3.3	1.3	2203	2559	2372	24.1
21	Казанишки-1	N	0.7	0.7	1.9	0.4	2129	2532	2283	27.2
22	Карабунар	E	2.0	1.5	5.9	2.7	1986	2530	2182	22.6
23	Карабунар-1	S	0.7	0.7	2.3	0.5	2185	2496	2335	24.9
24	Карариколички-1	NE	1.7	1.3	4.7	2.4	1931	2469	2178	23.5
25	Карариколички-2	NE	1.0	1.0	2.7	0.8	2150	2471	2295	23.0
26	Кржелински	E	1.1	1.4	3.9	1.2	2045	2658	2368	30.8
27	Кривошиски	N	2.0	1.2	4.4	2.3	2105	2718	2324	24.3
28	Кривошијски-1	E	0.6	0.6	2.4	0.6	2103	2505	2286	27.7
29	Лешнички	N	2.2	1.2	5.8	3.0	2071	2747	2379	26.9
30	Лешнички-2	N	0.5	0.5	1.6	0.3	2222	2564	2363	30.5
31	Маздрача-1	SE	1.6	1.0	4.3	1.7	2020	2401	2221	20.8
32	Маздрача-2	N	1.5	0.8	3.6	1.2	1995	2380	2213	22.5
33	Маздрача-3	N	0.6	0.7	1.6	0.3	2123	2335	2214	25.0
34	Маздрача-4	NE	0.6	0.7	1.6	0.3	2032	2224	2112	17.6
35	Маздрача-5	E	1.1	1.1	3.4	1.1	1975	2331	2149	17.9
36	Мала Смрека-1	S	1.2	1.2	3.5	1.0	2272	2605	2418	21.2
37	Мала Смрека-2	SE	1.0	0.9	3.8	1.2	2026	2550	2280	24.8
38	Моравски	NE	1.5	0.8	3.4	1.5	1868	2146	2011	15.2
39	Садере	SE	1.5	1.1	3.0	1.0	1975	2405	2160	27.9
40	Садере-1	SE	0.5	0.4	1.2	0.2	2234	2411	2317	26.4
41	Скакалски-1	NE	0.9	1.2	3.4	1.0	2113	2504	2302	23.5
42	Скакалски-2	E	0.5	0.6	1.3	0.2	2240	2514	2373	34.0
43	Скакалски-2	E	1.0	1.0	2.8	1.0	2040	2514	2153	26.8
44	Смрека-1	N	1.0	0.8	2.4	0.7	2195	2545	2334	24.2
45	Смрека-2	NE	0.5	0.7	2.2	0.4	2050	2406	2190	26.1
46	Сорупа	E	0.8	0.9	2.5	0.7	2072	2450	2199	28.6
47	Стрга	S	1.3	1.4	3.9	1.1	2014	2477	2263	23.7
48	Турчин-1	S	0.7	1.2	3.9	1.1	2298	2745	2441	21.5
49	Турчин-2	E	0.7	0.7	2.1	0.5	2475	2747	2564	26.7
50	Церипашина-Бобинов	E	0.8	1.1	3.3	1.0	2052	2527	2315	22.9
51	Церипашина-Орловски	E	0.8	0.7	2.1	0.5	2181	2516	2333	26.8
52	Црно Езеро	E	1.5	2.7	6.3	3.3	2145	2675	2400	24.4
53	Црно Езеро 1	NE	0.8	1.0	2.7	0.6	2208	2636	2356	29.2
54	Чаушица-1	SE	0.8	1.0	2.8	0.6	2119	2600	2373	31.5
55	Цинибег	N	1.0	1.0	2.7	0.9	2291	2610	2409	22.1
	Average		1.1	1.0	3.2	1.2	2096.9	2500.7	2274	24.8

Table 3. Morphometric data for the identified cirques on the Šara Mountain.

Fig. 5-7. Photos of some of the cirques on the Šara Mountain.

Results

- Out of 100 potential cirques, 55 were identified as typical glacial cirques, and the rest (40) were classified as nivation hollows.
- Most of the identified glacial cirques occur in the upper parts of the Pena catchment and its tributaries (a total of 16 cirques), as well as in the upper parts of Bogovinska River (15 cirques).
- With careful inspection, additional 40 nivation hollows (cirques) are identified so far, as well as 28 U-shaped valleys.
- After identification, delineation, and vectorization of the cirques, SAGA GIS software is used for their detailed geomorphometric analyses, including size, altitude, slope, and aspect.

Cirque aspect is given as median axis aspect, cirque length (L) as the length of the median axis, cirque width (W) as the longest line perpendicular to the median axis, cirque height (H) as the vertical distance between the lowest and highest point within the cirque boundaries, cirque size as the cube root of volume ($3\sqrt{L \times W \times H}$), and cirque floor altitude as the modal floor altitude.

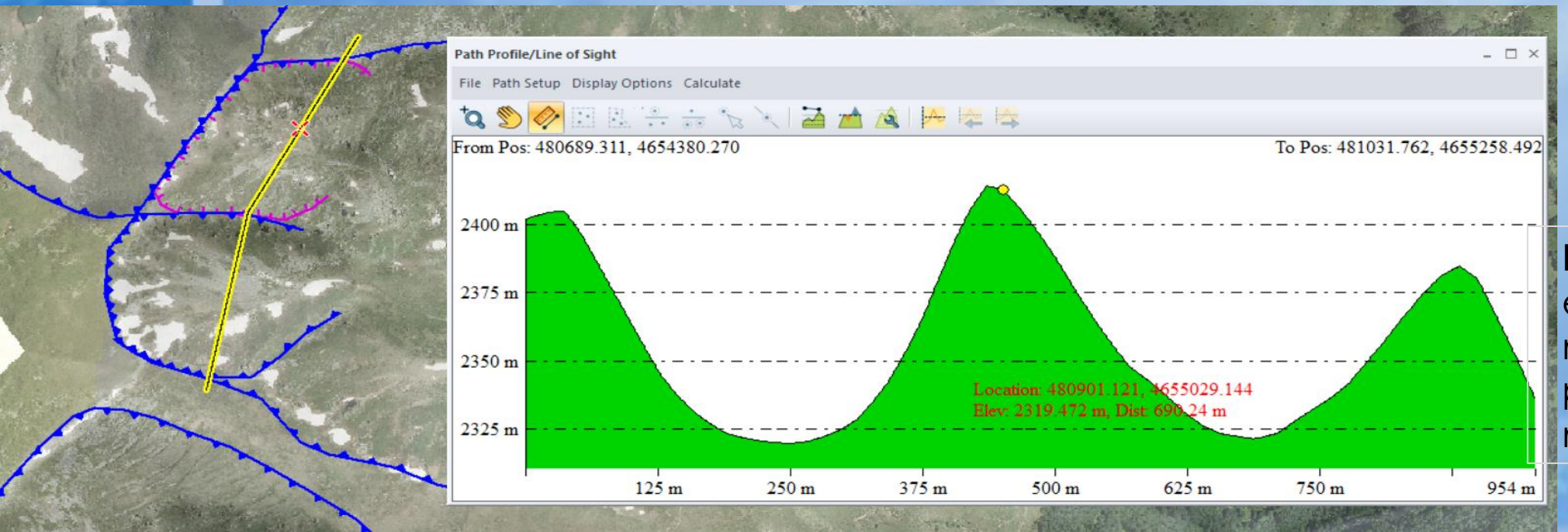


Fig. 8-9. For every cirque, number of profiles are made.

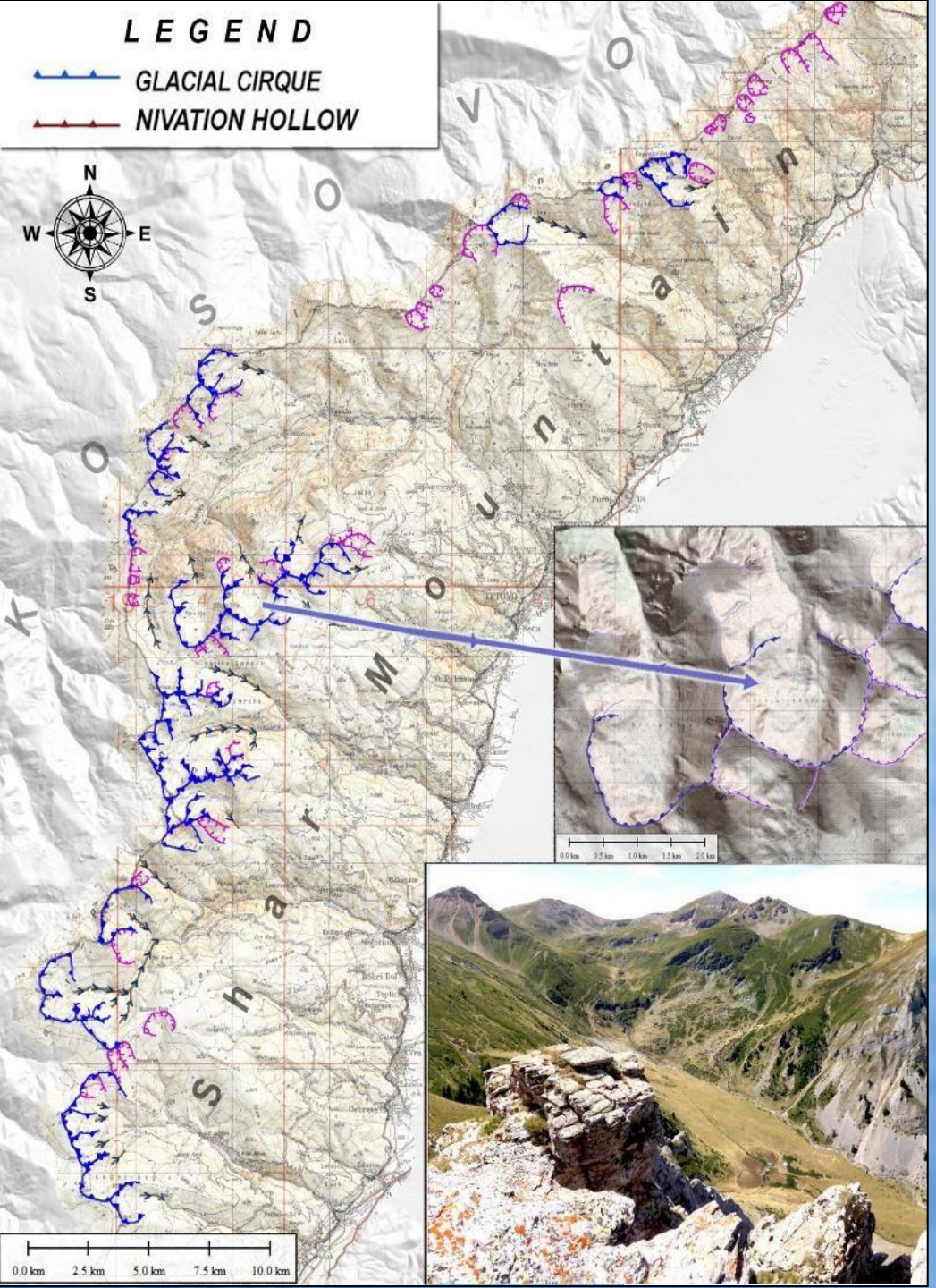


Fig. 10. Map of the glacial cirques and nivation hollows on the Macedonian side of Šara Mountain with the highest cirques around Titov Vrv (2747 m).

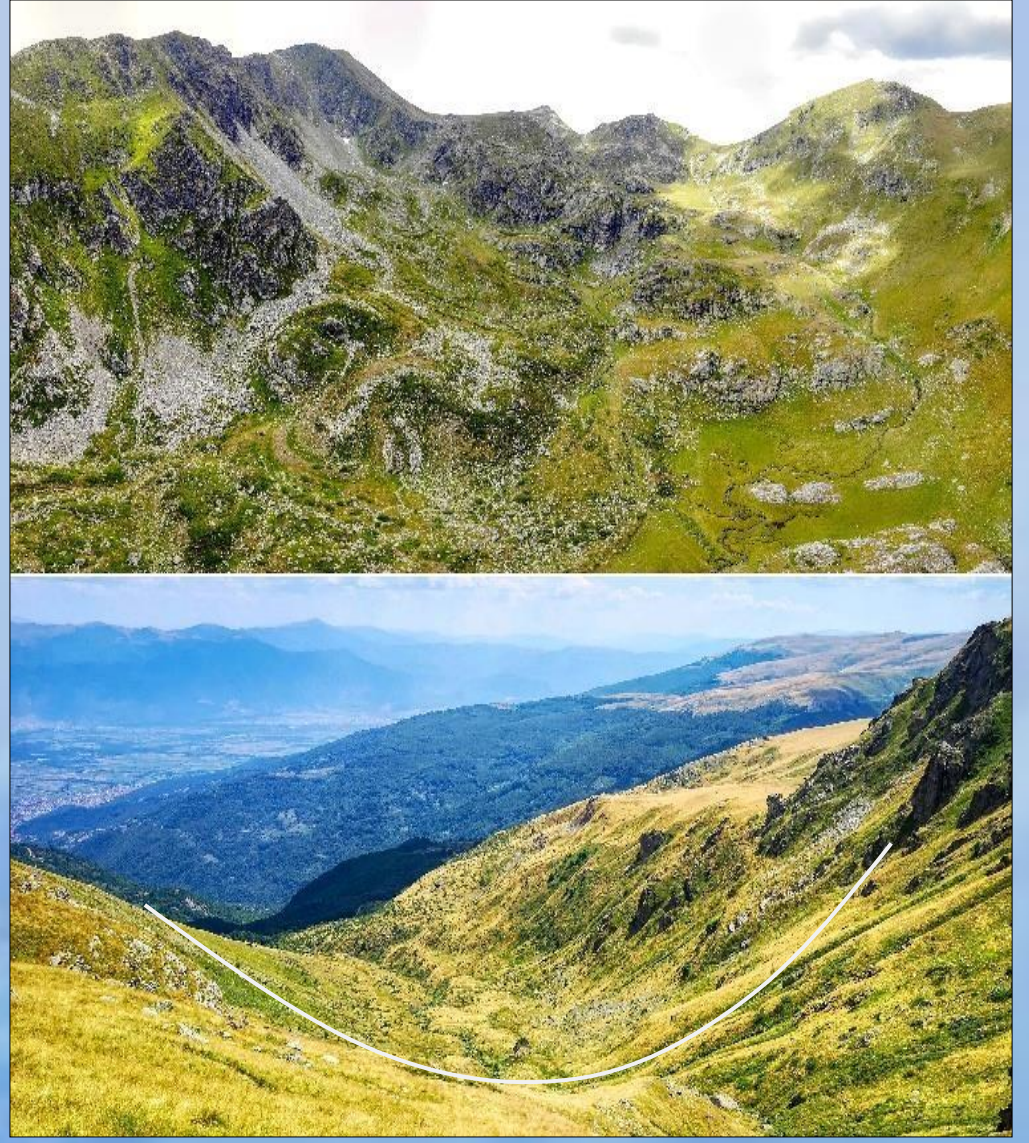


Fig. 11. Cirques (up) and trough (bottom) of Crno Ezero Lake in the upper part of Mazdrača Valley on Shar Mountain.

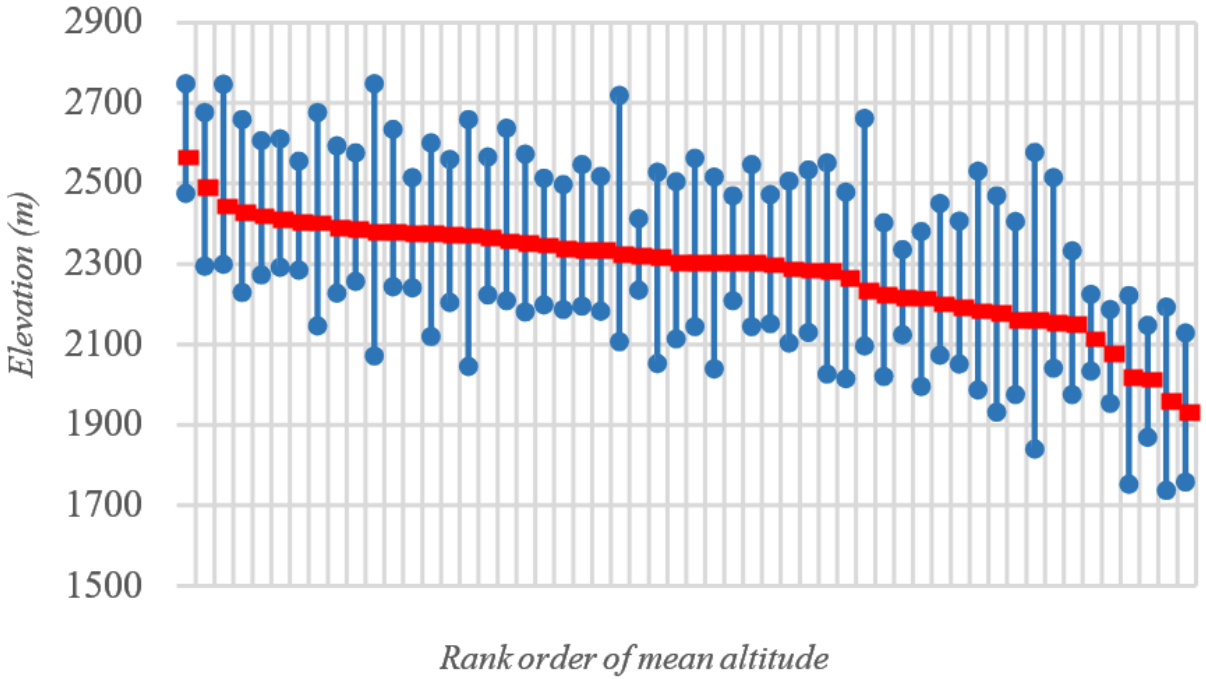
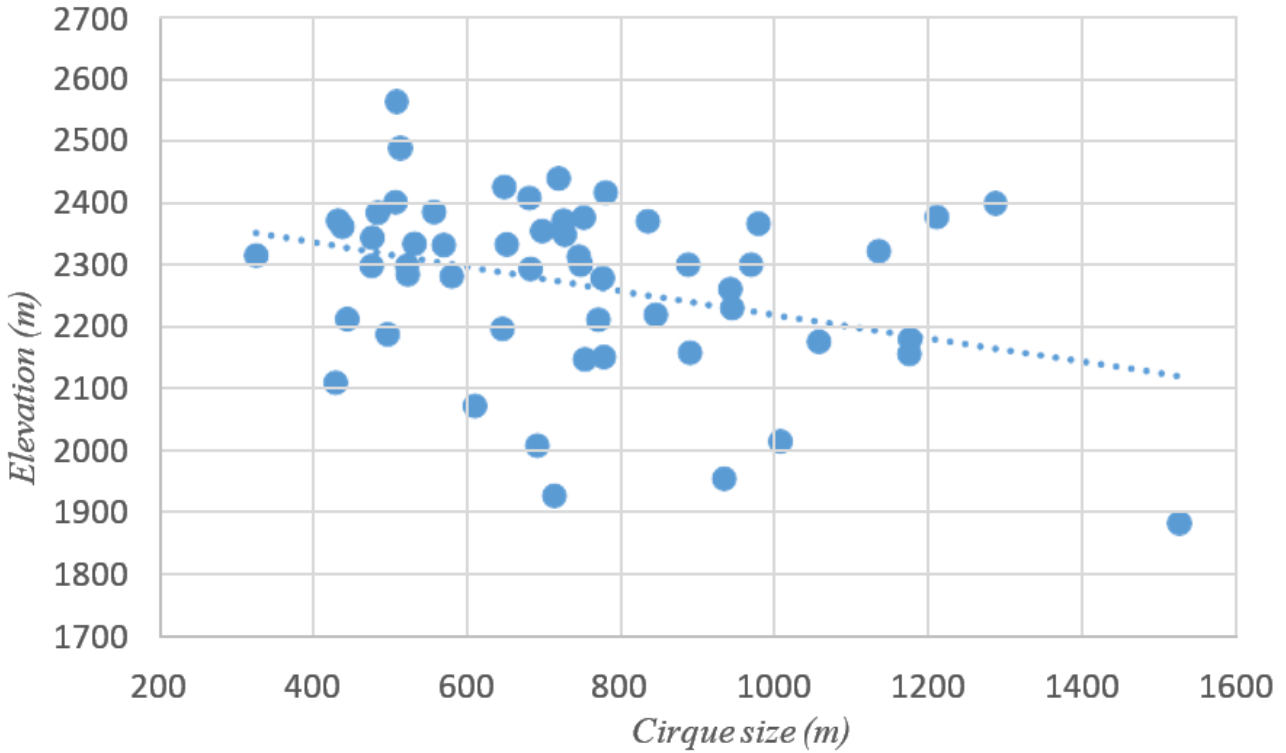


Fig. 11. Elevation (m a.s.l.) of the lowest and highest point of the cirques as well as the mean altitude (red dot) of the 55 glacial cirques in the Šara Mt. in North Macedonia, from the highest to the lowest one.

Fig. 12. Cirque size (as a $\sqrt[3]{(L \times W \times H)}$) vs mean elevation of the 55 glacial cirques in the Šara Mountain in North Macedonia with the trend line.

Elevation	W	L	L_1	A	Min	Max	H	Avg
1885-2300 m	1.32	1.01	3.56	1.48	1968.2	2387.7	419.5	2151.9
2300-2564 m	0.95	0.96	2.95	0.93	2192.3	2584.9	392.6	2365.1

Table 4. The average size of glacial cirques of Šara Mountain, by elevation: W cirques width (km), L cirques length (km), L1 cirque ridge (crest) length (km), A area of the cirque (km^2), Min - the lowest point of the cirque floor (m), Max - the highest point of the cirques (m), H height of the cirque (m), Avg – Mean elevation of the cirques (m).



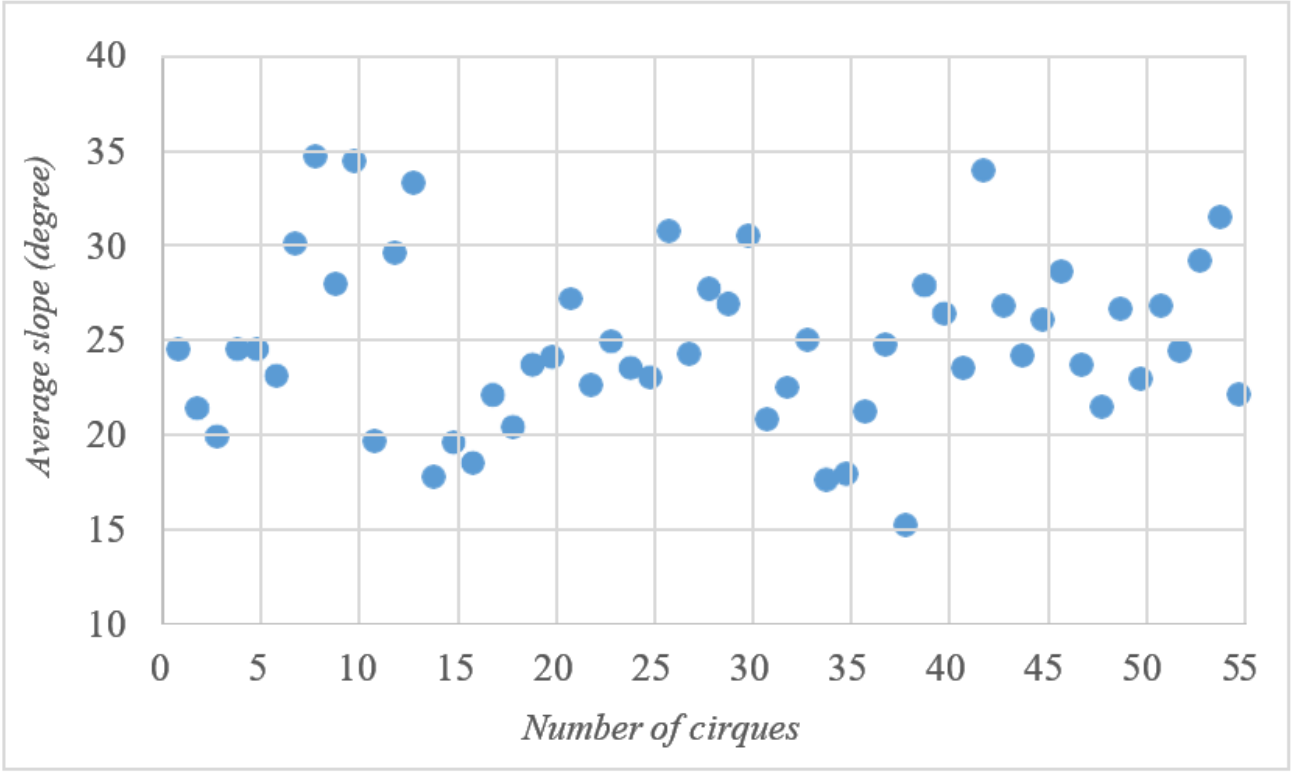


Fig. 13. Average slope of the 55 glacial cirques in the Šara Mt.

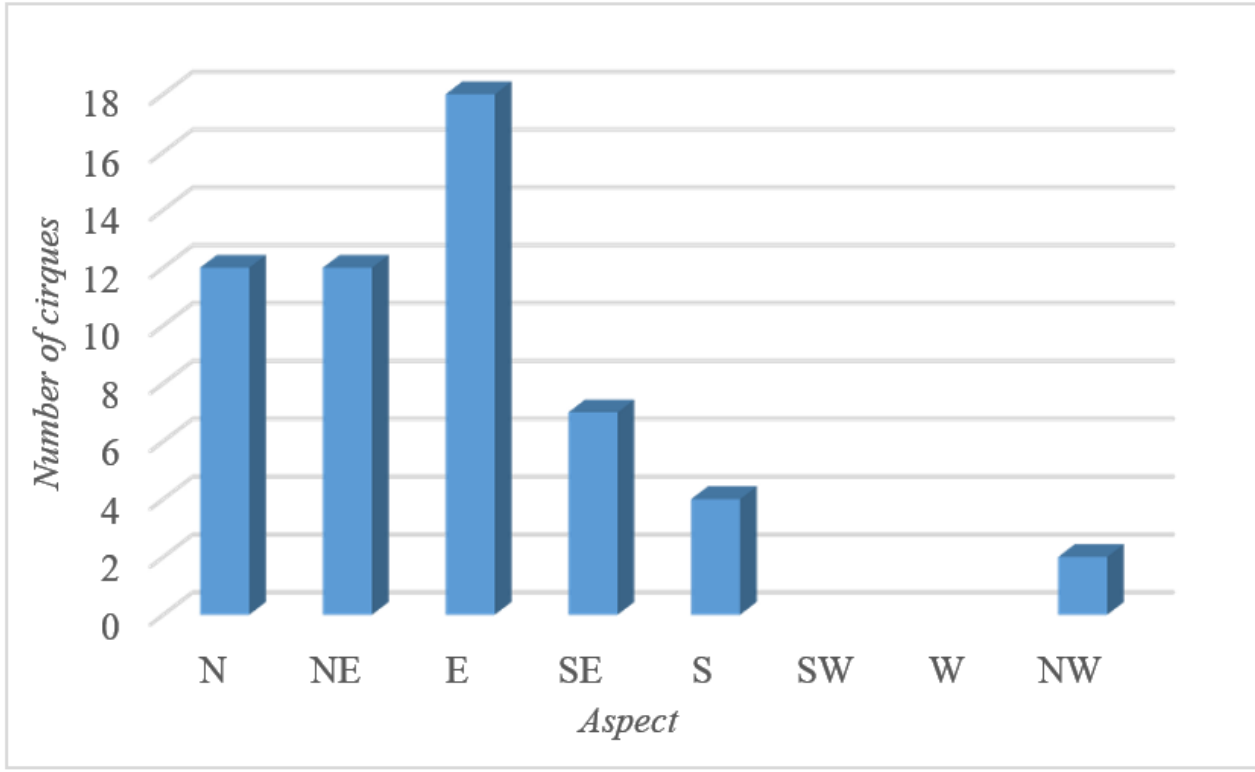


Fig. 14. The number of cirques on Šara Mt. in regard to the dominant aspects.

Asp.	W	L	L_1	A	Min	Max	H	Avg
N, NE	1.08	0.9	3.03	1.08	2096.3	2478.0	381.7	2264.4
S, SE	0.96	0.95	2.98	0.84	2150.4	2530.2	379.8	2327.0

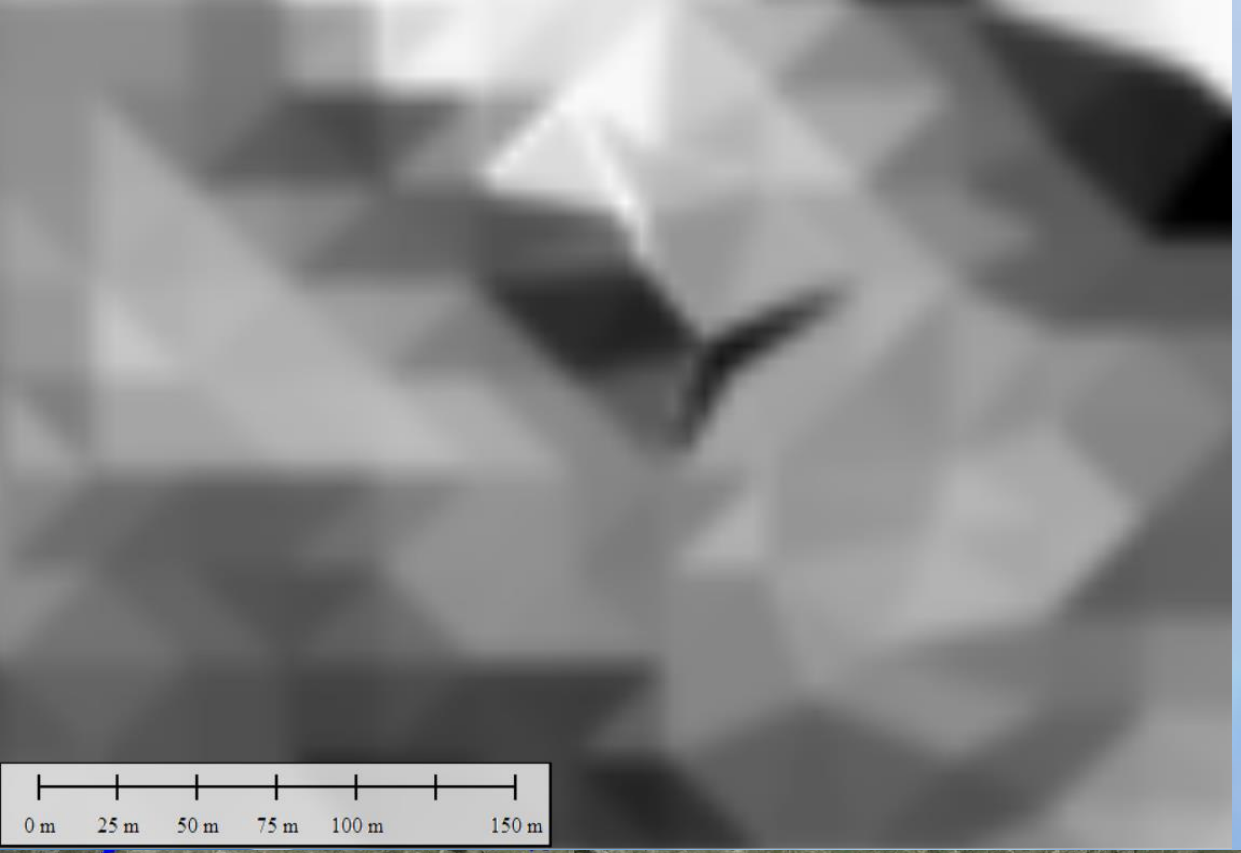
Table 5. The average size of glacial cirques of Šara Mt. in relation to aspects: W cirques width (km), L cirques length (km), L1 cirque ridge (crest) length (km), A area of the cirque (km^2), Min - the lowest point of the cirque floor (m, a.s.l.), Max - the highest point of the cirque (m, a.s.l.), H height of the cirque (m), Avg – Mean elevation of the cirques (m, a.s.l.).

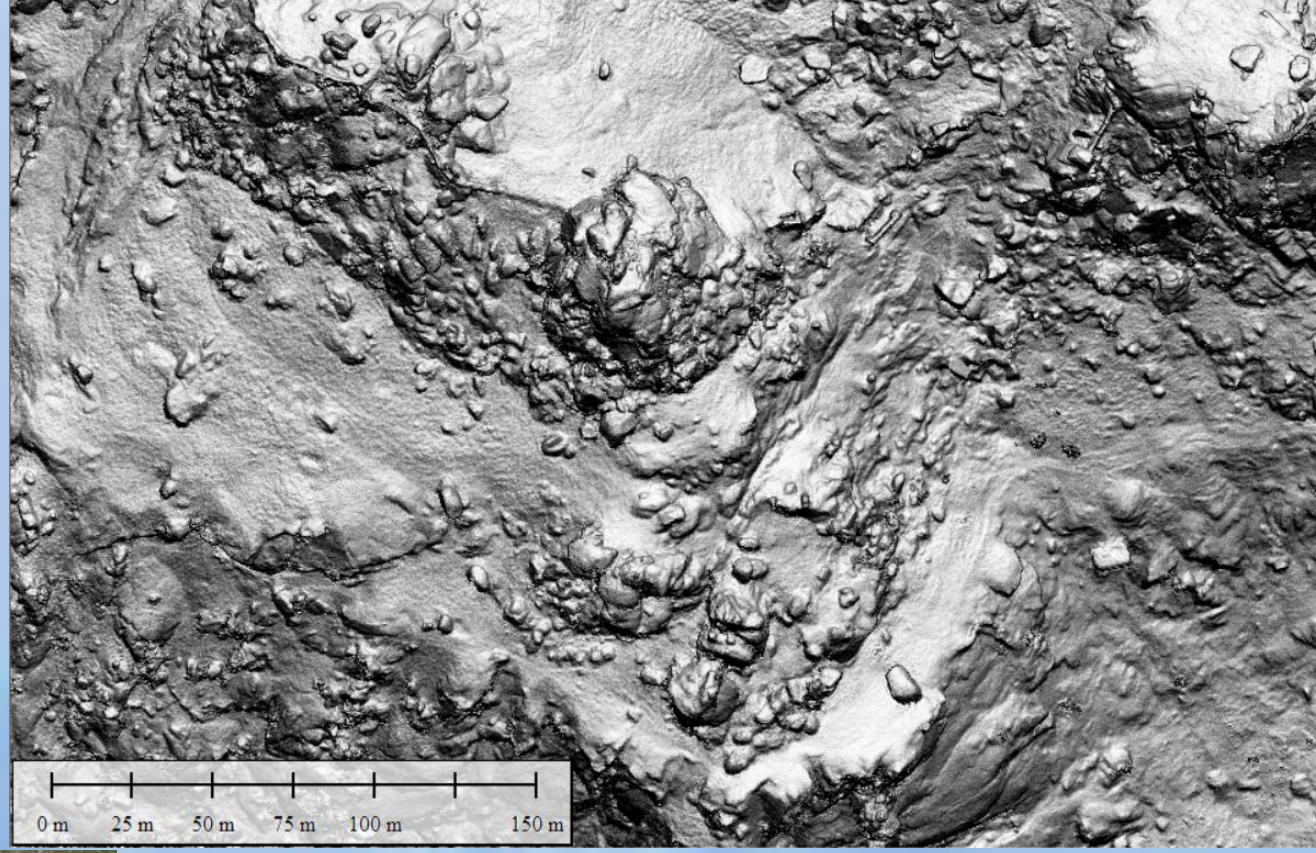
Conclusions

- In terms of glacial landscape, Šara Mountain has the most spectacular glacial landscape in North Macedonia.
- In this study 55 glacial cirques, 40 nivation hollows and 28 glacial valleys have been identified primarily by careful visual inspection of the 5-m DEM and 0.5-m ortophoto imagery.
- For the identification and general geomorphometric analyses of the cirques, 5-30 m DEM is sufficient.
- However, for the more detailed feature identification and analysis (cirque floor, moraines etc.), 1-m DEM is more suitable (especially LiDAR or UAV based).
- For now, the most reliable way for cirque identification is with manual inspection of the digital elevation models, ortophoto and fine-scale topo maps (we try number of attempts with geomorphometrical tools without acceptable accuracy).

Conclusions

- Geomorphometrical analyses of the cirques can significantly help in explaining of the formation and evolution of the glacial landscape.
- Most of the cirques are located between 2100 m and 2500 m a.s.l., with E, N, and NE aspect, steep headwalls and almost flat floors.
- Generally, cirque elevations rise southward.
- The morphometric analysis of the cirques showed that most of the cirques are well developed. The wide and open cirques together with deep and stepped glacial valleys with several thresholds might suggest that glacial erosion during the most extended glacial phases was displaced from the cirques down valley.
- The development stage of the cirques may refer to more dynamic cirque glaciers in the deeper, better developed cirques and less dynamic and/or shorter- lived glaciers in the poorly developed ones. However, the lithology, as well as the pre-glacial topography are important determinants also.





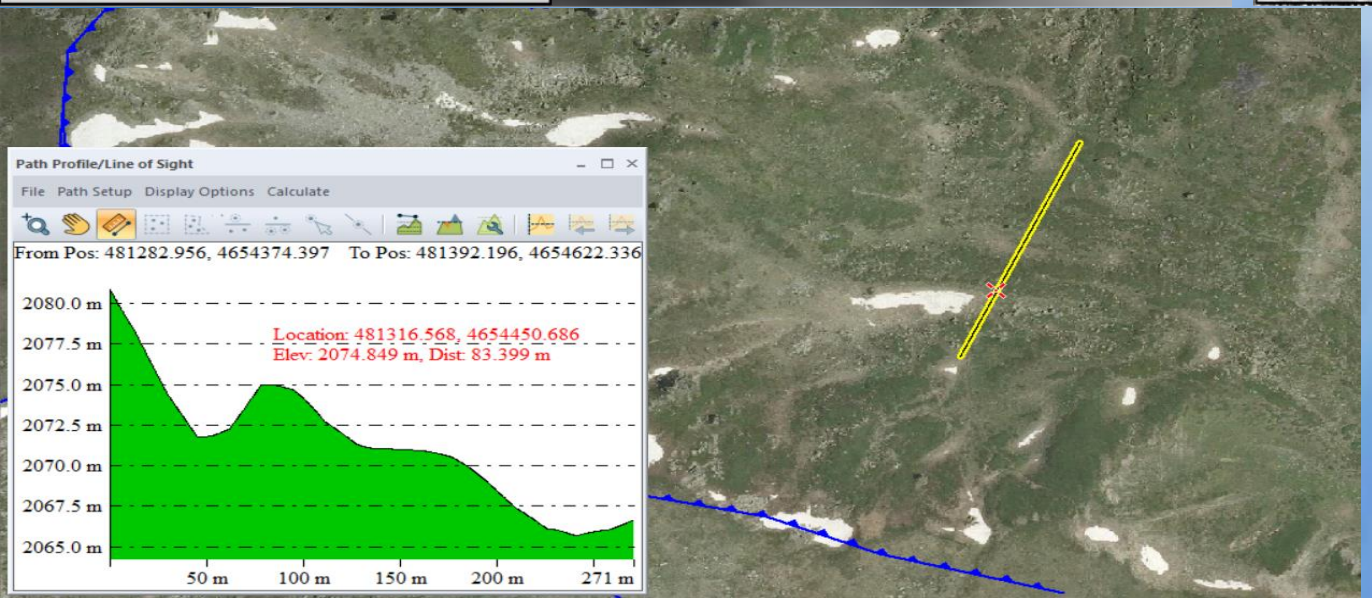


Fig. 16. 5-m DEM of the ARECNM (left) vs. 0.1-m UAV DEM (right) of the part of Skakalo cirque. On the UAV-DEM very small details of the moraines in the bottom of the cirque can be identified and analyzed.


Bogovinje glacial Lake in trough and complex polycyclic mega cirque


Cirques, moraines and rock glacier east of Bakardan

U – shaped valley of Slapska River

Thank you for your attention!

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