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GEOMORPHOLOGICAL CHARACTERISTICS OF THE ITALIAN SIDE OF CANIN MASSIF (JULIAN ALPS) USING DIGITAL TERRAIN ANALYSIS AND FIELD OBSERVATIONS

GEOMORFOLOŠKE ZNAČILNOSTI ITALIJANSKE STRANI KANINSKEGA MASIVA (JULIJSKE ALPE), UGOTOVLJENE Z UPORABO DIGITALNEGA MODELA RELIEFA IN TERENSKIM OPAZOVANJEM

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Abstract UDC 911.2:551.432(234.323.6)

Tamás Telbisz, László Mari & Lénárd Szabó: Geomorphological Characteristics of the Italian Side of Canin Massif (Julian Alps) using Digital Terrain Analysis and Field Observations

In this paper, by the example of Canin Massif, it is demonstrated, how GIS-techniques can be used for the study of high mountain karst terrains. In case of Canin, elevation and slope histograms show characteristic differences in plateau levels and landforming processes between the northern, western and southern sectors of the mountains. Ridge and valley map (derived from the digital elevation model) and thalweg analysis are used to recognize drainage reorganizations north of the Italian Canin plateau. Potential snow accumulation locations and nunataks are determined based mainly on the slope map. Geomorphological sketch maps and statistical analysis of closed depressions are also carried out in this study supporting the relatively young age of superficial karstification and the strong structural impact. Finally, it is concluded, that quantitative and visual capabilities of GIS are useful in discriminating the effects of glacial, fluvial, structural and karst processes.

Keywords: Canin, digital elevation model, glaciokarst, GIS, doline, morphometry.

Izvleček UDK 911.2:551.432(234.323.6)

Tamás Telbisz, László Mari & Lénárd Szabó: Geomorfološke značilnosti italijanske strani Kaninskega masiva (Julijske Alpe), ugotovljene z uporabo digitalnega modela reliefa in terenskim opazovanjem

V prispevku je na primeru Kaninskega masiva prikazano, kako z uporabo GIS tehnologij lahko preučujemo visokogorska kraška območja. Histogrami nadmorske višine in naklona na primeru Kanina kažejo na razlike med nivoji planot ter razlike v procesih med severnim, zahodnim in južnim delom pogorja. Na osnovi karte grebenov in dolin, narejene iz digitalnega modela višin ter analize profila dolinskega dna smo potrdili pretekle spremembe smeri odvodnjavanja severnega dela Kaninske planote. Na podlagi podatkov o naklonu smo določili potencialna območja akumulacije snega oz. snežišč in nunatakov. V okviru raziskave so bile narejene tudi skice geomorfoloških kart in statistična analiza zaprtih kotanj, ki nakazujejo na mlado površinsko zakrasevanje in močan vpliv geoloških struktur. Ugotavljamo, da so kvantitativne in vizualne zmogljivosti GIS-ov uporabne pri prepoznavanju vplivov ledeniških, fluvialnih, strukturnih in kraških procesov.

Ključne beside: Kanin, digitalni model relief, glaciokras, GIS, vrtača, morfometrija.

INTRODUCTION

The Canin Massif is located at the western part of the Julian Alps, whereas the main ridge and the highest peak (Canin Alto, 2587 m) form the Italian-Slovenian border. It is a typical high mountain karst terrain most famous for the high density of deep caves. The present landforms of the area are the results of tectonic, karstic, fluvial and glacial processes. Previous geomorphological studies already gave a detailed description of Canin landforms.

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Kunaver (1983) and Audra (2000) studied mainly the Slovenian side, whereas Gasparo (1982) the Italian side. However, recent development in GIS techniques may contribute to a better understanding of karst landform evolution (e.g. Faivre & Pahernik 2007; Orndorff *et al.* 2000; Plan & Decker 2006; Ravbar & Kovačič 2010; Telbisz 2010). Therefore, the aim of this study is not to give a geomorphological overview of Canin massif, but to quantitatively analyze and visualize the effects of different geomorphologic processes based on digital elevation models (DEMs), focusing mainly on the Italian side of the mountains.

GEOLOGIC SETTINGS

The most widespread rock in and around Canin Massif is the Upper Triassic poorly karstifying Main Dolomite („Dolomia Principale") with more than 1000 m thickness. It is overlain by the well karstifying Dachstein Limestone, which is also Upper Triassic and has similar thickness. It builds up the central mass of Canin Massif (Fig. 1). Jurassic limestones are found in a limited extent only at the western and southeastern part of Canin. Quaternary glacial, fluvioglacial and detrital sediments are present mainly in the valleys and at the foot of steep slopes (Buser 1986; Carulli 2006; Jurkovšek 1987; Manca 1999).

The Canin massif is located in a transitional zone between Alpine and Dinaric chains. The South Alpine system consists of south-verging thrusts with W–E striking structures, whereas the dinaric elements are predominantly dextral strike-slip faults with NW-SE orientation (Burrato *et al.* 2008; Kastelic *et al.* 2008). In the western Julian Alps both structures are seismically active as it is indicated by strong earthquakes (e.g. 1998, Bovec). With some simplifications the Canin massif can be thought of as an anticline with W–E axis although WNW–ESE trending dextral strike-slip faults segmented it into several smaller blocks, especially the northern side, where reverse faulting is also observable (Antonini & Squassino 1982).

For both hydrological and speleological reasons the caves and the hydrogeological system of Canin was extensively studied (e.g. Casagrande *et al.* 1999; Manca 1999; Audra 2000; Semeraro 2000; Cucchi *et al.* 2000a, 2000b; Komac 2001; Casagrande & Cucchi 2007; Szabó 2008). Underground drainage was examined by tracer tests and it is concluded that a significant part of the Italian Canin plateau drains southwards (Cucchi *et al.* 2000a and references therein). As for the superficial drainage, Casagrande and Cucchi (2007) described in their evolutionary model that during Late Pleistocene and Holocene, drainage direction was reversed in the Raccolana valley and as a consequence, the Adriatic / Black Sea drainage divide moved to the east.

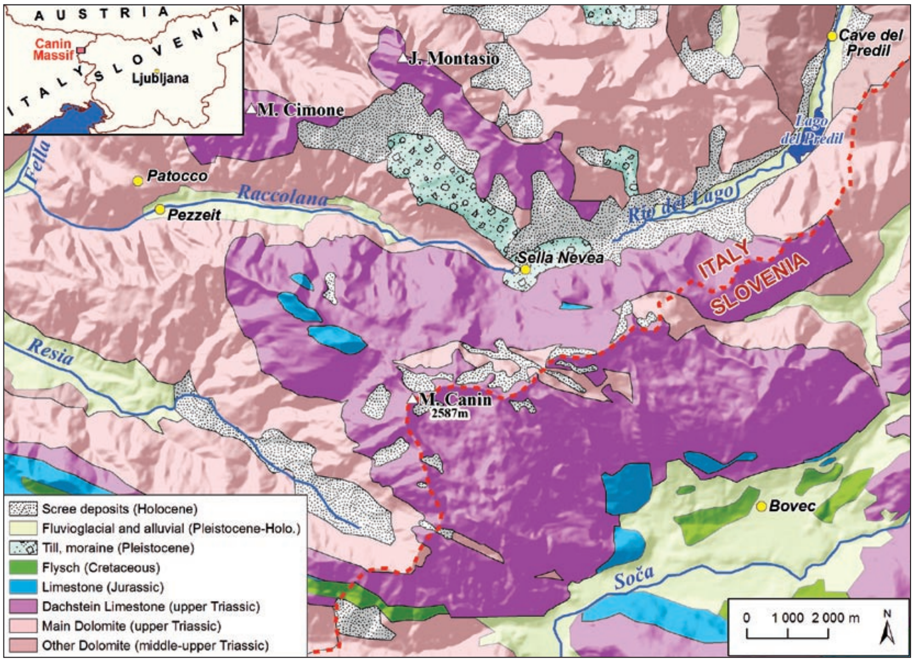

Fig. 1: Map of Canin Massif and its surroundings with simplified geology (after Buser 1986; Jurkovšek 1987; Manca 1999; Carulli 2006)

During Pleistocene cold periods glaciers strongly reshaped Canin Massif. Glacial and glaciokarst features of the Slovenian side were mapped in detail by Kunaver (1983) whereas glaciation extent and its effect on cave development in the Italian side was discussed by Semeraro (2000) and Casagrande & Cucchi (2007). According to Semeraro (2000), Canin-Montasio plateaus were covered by ice and Raccolana glacier had a diffluence step at Patocco. Recent studies focused mainly to maximum glacier extents. To the west, Raccolana valley drains to Fella valley and further to Tagliamento valley, whose giant glacier reached the upper Friuli plain during the last glacial maximum (LGM; Monegato *et al.* 2007; Fontana *et al.* 2008). On the contrary, in the Slovenian side new results suggest that LGM glaciers hardly reached the upper part of Bovec basin (Bavec *et al.* 2004; Bavec & Verbič 2004). At present, only two small, disappearing glaciers exist north of the main Canin ridge (Tintor 1993).

METHODOLOGY

The bases of our study are digital elevation models (DEMs). For mountain-scale analysis a 30 m horizontal resolution DEM (Ferranti 2008) was selected, whereas for smaller-scale landforms (dolines, cirque valleys) a 5 m horizontal resolution DEM (Tarquini *et al.* 2007) was preferred. Both DEMs were created by the digitization of elevation contour lines and interpolation techniques. GIS-analysis was carried out using ArcView GIS (with „Longest Straight Line" extension /Jenness 2003/ for depression axis determination) and ArcMap.

Apart from widely applied standard geomorphometric analysis (e.g. slope maps) we used a DEM filtering method („neighborhood statistics" in ArcView terminology) to emphasize the ridge and valley network of the studied area. The ridge and valley network can be derived from the DEM by the so-called mean difference map, which shows the elevation difference between each pixel and the mean of its circular neighborhood of radius *R*. If this difference is greater than a chosen positive threshold, that pixel can be classified as a ridge; if it is lower than another chosen negative threshold, it can be classified as a valley (Karátson *et al.* 2010) As a result, sharp and high ridges as well as deep and narrow valleys are the more pronounced in this kind of map. The advantage of this method with respect to other curvature-based ridge-enhancing processes, that the radius *R* can be set according to the landform scale (in this study, *R* was set to 450 m on an empirical base).

For the creation of the two geomorphological sketch maps, we used handheld GPS instruments (Magellan MobileMapper, Explorist) to achieve a more accurate determination of smaller closed depressions.

RESULTS AND DISCUSSIONS

HYPSOMETRIC AND SLOPE ANALYSIS

One of the most striking topographic features of Canin Massif is the triple main ridge with a NW–SE, a N–S and a W–E branch, the two latter being the border between Italy and Slovenia. These ridges divide the mountains into three different morphologic terrains (Fig. 2A). These three connecting sectors were outlined and compared by means of elevation and slope histograms (Fig. 2B). The northern sector is characterized by a well-defined, narrow elevation range between 1720 m and 1940 m a.sl. (30% of the investigated area), that is more pronounced than in case of the southern plateau where a much wider characteristic elevation range between 1500 m and 2100 m a.s.l. (59% of the investigated area) is observable in the diagram. However, a further division reveals that this wide elevation range results from the composition of two subunits, the Kaninski Podi in the west (with characteristic elevation range between 1880 and 2100 m a.s.l.) and Goričica in the east (with characteristic elevation range between 1560 and 1860 m a.s.l.). As some gentler hillslopes next to the Bovec Basin are also part of the outlined area, there is a secondary maximum in the elevation histogram between 400 m and 520 m a.s.l. Meanwhile, the western (Italian) sector has a single and very low elevation modus at about 850 m a.s.l. above which the areal proportions evenly decrease with height.

The above results for the Slovenian parts are in general in agreement with the results of Kunaver (1983), but there are some minor differences and it must be noted that according to our experiences, the 10 m vertical resolution used by Kunaver is too detailed and may reflect random deviations from a more or less continuous elevation distribution.

Slope distributions (Fig. 2C) also discriminate these three sectors: in the steepest slope range (steeper than 48°) the northern sector is the most outstanding. In the medium range (between 28° and 48°), the western sec-

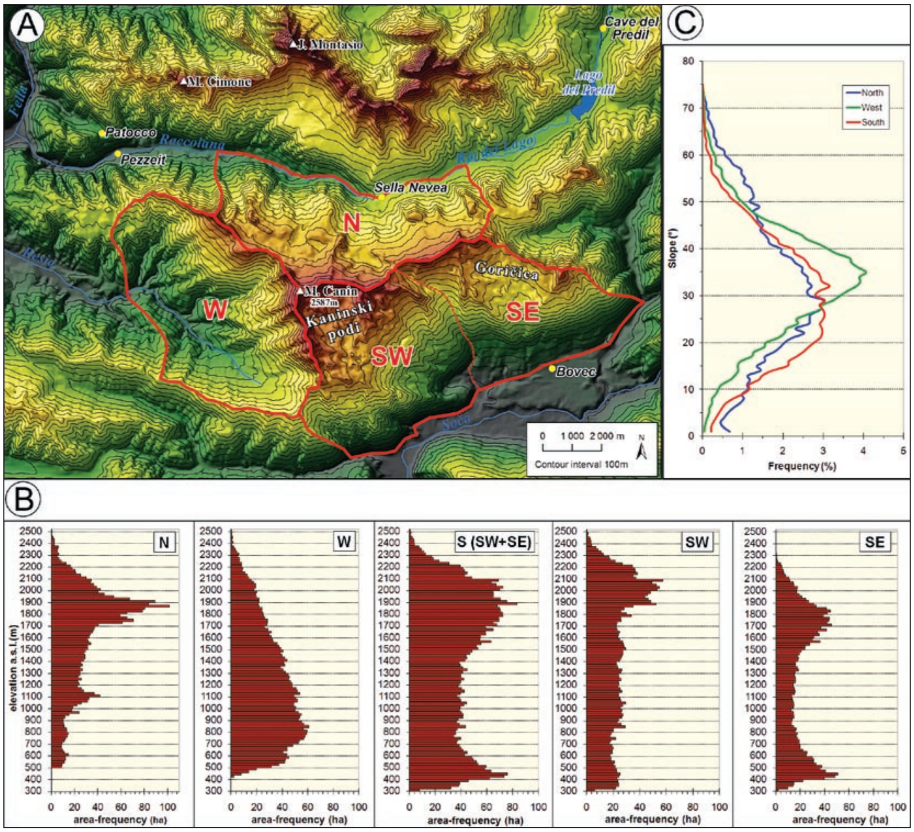

Fig. 2: Hypsometric and slope analysis of Canin Mts. A: Delineation of the three sectors; B: Elevation histograms; C: Slope distributions.

tor is dominant with a distinct peak at 35°, whereas the southern sector has the highest proportion of low angle area and a broad maximum between 21° and 35° is typical of this sector. This slope angle range is characteristic in the northern sector, too.

The above results make it possible to determine the relative importance of different geomorphologic processes in the three sectors of Canin Mts. In general, the low elevation maximum in the histogram, and the even areal decrease with height is typical of fluvially formed landscapes (Telbisz 2004). Slope angle of 35° is characteristic of hillslopes formed by mass movement processes in fluvially dissected terrains. Therefore, both evidences support that the western sector is mainly influenced by fluvial and connecting mass movement processes. These processes are the most active in this sector due to the predominance of Main Dolomite. The northern and southern sectors are more similar to each other (as it is expected since Dachstein Limestone dominates in both sectors). Well-defined elevation ranges usually indicate denudation surfaces. In this case, these surfaces are probably of Tertiary origin and are tectonically uplifted (at different rates) as suggested by Kunaver (1983) and Audra (2000). The lack of significant dissection is due to the fact that during the Quaternary these surfaces were formed principally by karstic and secondary by glacial processes. However, these plateaus are more rugged than many other typical karst plateaus of the world where slope angles below 10° are common. The southern plateaus are more extended and gently inclined (partly due to structural reasons, i.e. southerly dipping strata). The remarkable difference in the steep slope range between the northern and southern sectors (the northern sector having higher proportion of steep slopes) is most probably the result of glacial processes (valley deepening and wall retreat). Thus, according to the slope histogram these processes were more effective in the northern sector as a result of climatic differences between northern and southern faces.

STRUCTURAL EFFECTS IN THE MORPHOLOGY

The northern Canin plateau is densely dissected by fault lines (Fig. 3), and at most places these lines are clearly observable on the bare rock surface (Fig. 4) and in the DEM, too. The most striking structural element in the mesoscale morphology of the Italian Canin plateau is the fault line from Sella Prevala through Sella Bila Pec to Sella Blasic (in fact, this line continues more to the east and more to the west). It is a WNW–ESE oriented dextral strike-slip fault with vertical component, too. Elongated depressions or troughs are often created along strike-slip faults and it is exactly the case for the northern Canin as well. The plateau can be divided into two large, elongated depressions separated by Sella Bila Pec (Fig. 3). Depression bottoms are relatively flat (as seen in the cross-sections of Fig. 5), that is due to glacial carving. These large depressions are not perfectly closed, the western depression is cut by a small cirque valley west from Col delle Erbe, whereas the eastern one is separated from the steep northern slopes facing Sella Nevea by a small threshold only, east from Bila Pec. Profiles 4 and 6 (Fig. 5) demonstrate that ridge lines

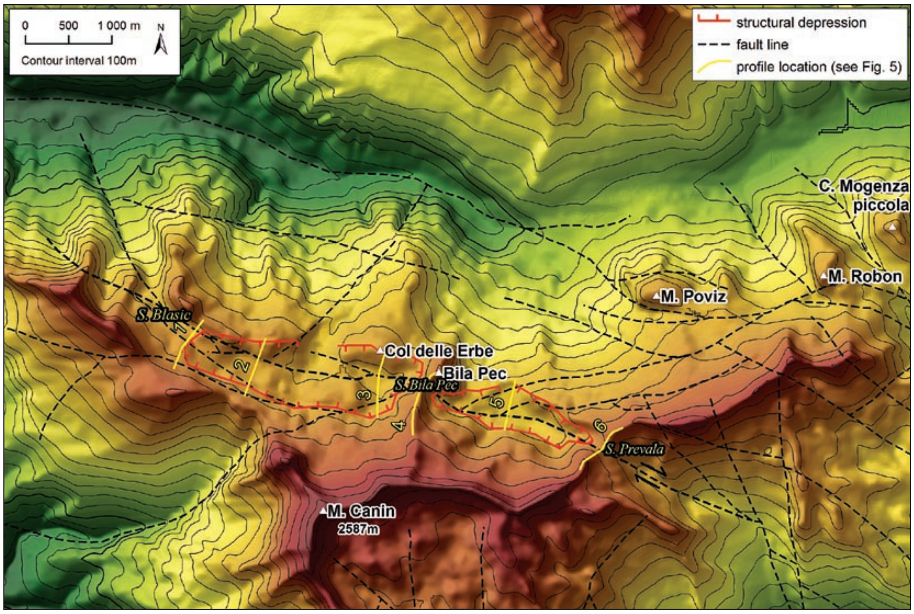

Fig. 3: The northern Canin plateau with fault lines and structurally controlled depressions. (Fault lines are after Manca 1999).

are significantly lowered (by about 150 m) where crossing this fault line (at Sella Prevala and at Sella Bila Pec) also supporting a structural origin. Surface lowering along this line is favoured by the outcropping dolomitic rocks, too.

DRAINAGE REORGANIZATIONS

In this study, we deal only with superficial drainage directions in the northern foreground of Canin Massif. By a quantitative DEM-based analysis we attempt to support and complete the scheme of Casagrande and Cucchi (2007) about drainage reversal in Raccolana valley.

Fig. 4: Pits along a solutionally enlarged fault line west of Bila Pec (person for scale).

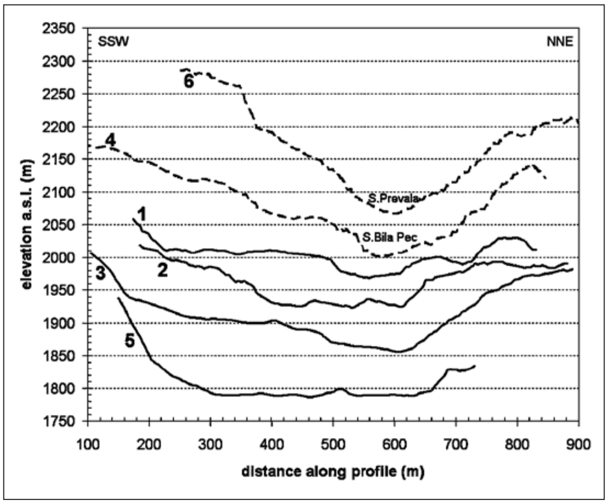

Fig. 5: Elevation profiles across the WNW–ESE oriented Sella Prevala fault line (for profile locations see Fig. 3).

Raccolana and Rio del Lago streams are parts of the same, continuous valley with a relatively low elevation watershed pass at Sella Nevea (1180 m a.s.l.). Valley orientation is structurally determined, especially the WNW–ESE Raccolana segment. Both valleys are incised in Pleistocene and Holocene fluvioglacial sediments underlain by Main Dolomite, and their U-shaped glacial profile is well preserved. Yet, differences are also significant. From the ridge and valley map (Fig. 6) it is evident, that Raccolana valley is narrower and more deeply incised than Rio del Lago valley (dark blue colour indicates that mean differences are more negative in case of Raccolana). Thalweg profile from Fella river through Sella Nevea to Cave del Predil (Fig. 7) unambiguously demonstrates that headward erosion is more intensive in the Raccolana segment. To the west, the base of erosion (Fella river) is 14 km from Sella Nevea and 805 m lower than the pass. To the east (at Cave del Predil) 10 km from Sella Nevea the elevation is only 280 m lower than at the watershed. With more details, the valley can be divided into several subsegments based on the mean valley gradient. Raccolana segments have 29, 94, 212 m/km; Rio del Lago segments have 103 and 16 m/km gradients, respectively. Higher gradients in Raccolana valley suggest faster erosion. Turning it back in time means that the watershed had to be more to the west. Moreover, considering the high ridges of M. Cimone and western Canin as well as the NNW-SSE and SSW-NNE subsequent valley and ridge directions (marked with arrows in Fig. 6) it seems possible that the watershed was in a westerly position as far as Patocco.

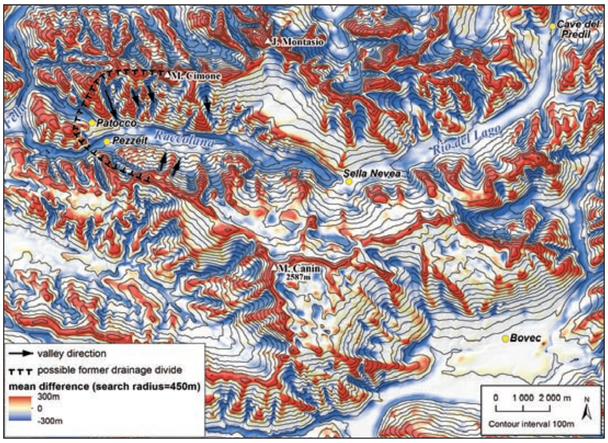

Fig. 6: Ridge and valley (i.e. mean difference) map of Canin Massif and its surroundings.

This eastern motion of the superficial Adriatic / Black Sea divide is likely due to the indirect effect of the intense fluvioglacial deepening of Tagliamento valley whose giant glacier reached the southern pre-Alpian foreland.

Further drainage reorganization is very likely just at Patocco. First, the valley WNW from Patocco is collinear with the upper part of the Raccolana valley and predetermined by the same fault line. Second, this valley misses its head. Third, Raccolana valley downstream of Pezzeit is the narrowest and the most deeply incised part (Fig. 6). Consequently, it seems probable that the lower Raccolana captured the upper Raccolana river at Pezzeit. This capture apparently predates the formation of the 300 m high glacial diffluence step (mentioned by Semeraro 2000) at Pezzeit.

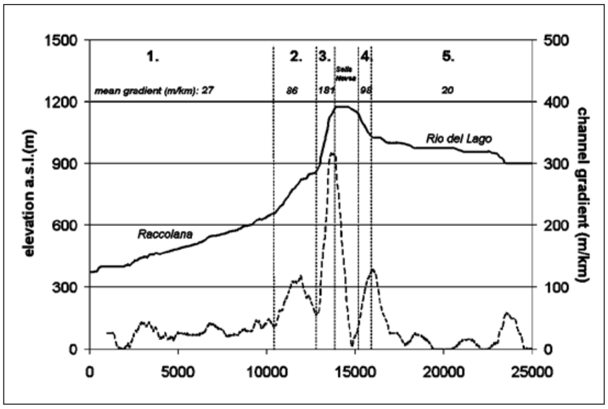

Fig. 7: Thalweg elevation and gradient profile from Fella river through Sella Nevea to Cave del Predil.

GLACIAL FORMS

As already mentioned, the Raccolana and Rio del Lago valleys have a characteristic U-shaped profile. The two large depressions of the plateau also show signs of glacial carving. In the western depression, glacial till is preserved (in the western part).

In addition to this, there are several bastion-like peaks at the northern edge of the plateau (Bila Pec, M. Poviz, M. Robon, C. Mogenza piccola). These features are almost completely surrounded by steep (>50°) slopes, not parts of the main ridge, but 80-170 m higher than the saddles connecting them to the main ridge (Fig. 8). Therefore, during intense glaciation, these peaks could have been nunataks, i.e. unglaciated summits surrounded by glacier ice.

To evaluate the role of glaciers in Canin plateau, we can identify snow accumulation centers. In order to find locations most suitable for snow accumulation we determined places that are relatively flat and not part of a positive landform (ridge or summit). In terms of GIS, we performed a map query with the following conditions: slope angle is smaller than 15° and mean difference value is smaller than 20 m. Threshold values are somewhat arbitrary but their change does not significantly influence the result. Nevertheless, this simple model neglects some other controlling factors whose effects are difficult to quantify. Namely, aspect and shadows obviously influence the heat budget. However, these factors may change the timing (duration) of snow accumulation at a given location, but the location itself is only slightly modified. Another factor is wind direction. The leeward side of ridges is favoured by snow accumulation but we do

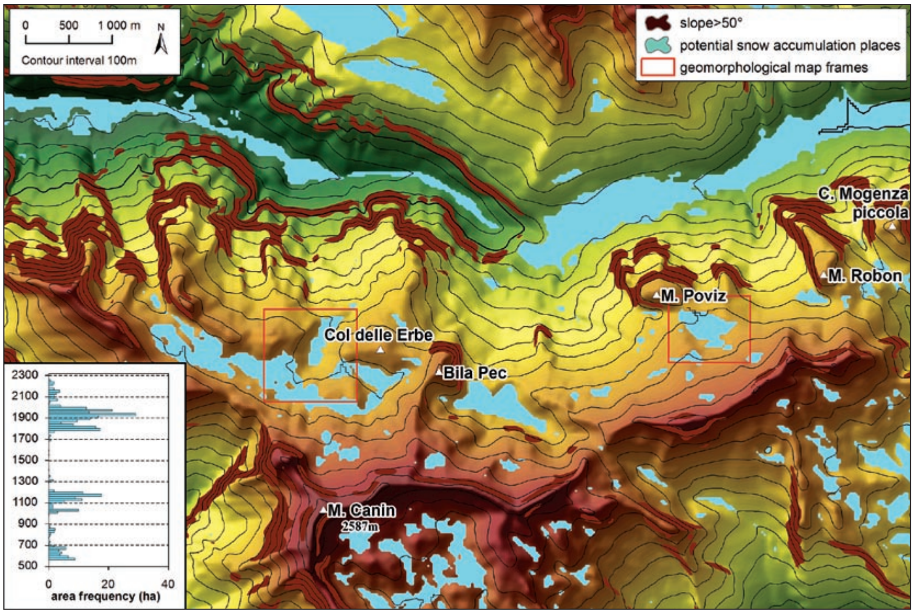

Fig. 8: Selected slope categories representing possible nunatak and snow accumulation locations. Inset graph shows the elevation histogram of snow accumulation locations.

not have data about prevailing wind directions during glacial periods. Basically, hypothesizing westerly wind direction (due to relief control), it is supposed that the eastern side of ridges are preferred for snow accumulation.

The resulting map (Fig. 8) clearly shows three type localities for snow accumulation. First, there is a possibility for small cirques just north of the main ridge at about 2060–2240 m a.s.l. (A remainder of this type of glaciers can be the small perennial snow patch found north of Canin Alto peak.) Second, there are suitable places for glaciers in the two structural depressions of the plateau and at a smaller, relatively flat area SE of M. Poviz with elevations between 1780 and 2000 m a.s.l. Third, glaciers could be formed in the Rio del Lago and Raccolana valleys. But between the second and third elevation ranges, there is no „place" for snow accumulation. Taking the nunatak locations also into consideration, at most extensive glaciation all of these different glacier types could coalesce and form a large glacier from which only the aforementioned nunataks and the main ridge stood out (Fig. 9). Therefore, preceding superficial karst landforms were mostly destroyed. However, there is no evidence that this was also the situation during the Last Glacial Maximum.

In a glacier withdrawal period, glaciers were gradually reduced to upper elevations (Fig. 9) and later, glacially carved depressions of the plateau became suitable for karstification.

KARST DEPRESSIONS

Closed depressions are present in diverse forms and dimensions. However, as it was previously discussed, the formation of large depressions is related to geological

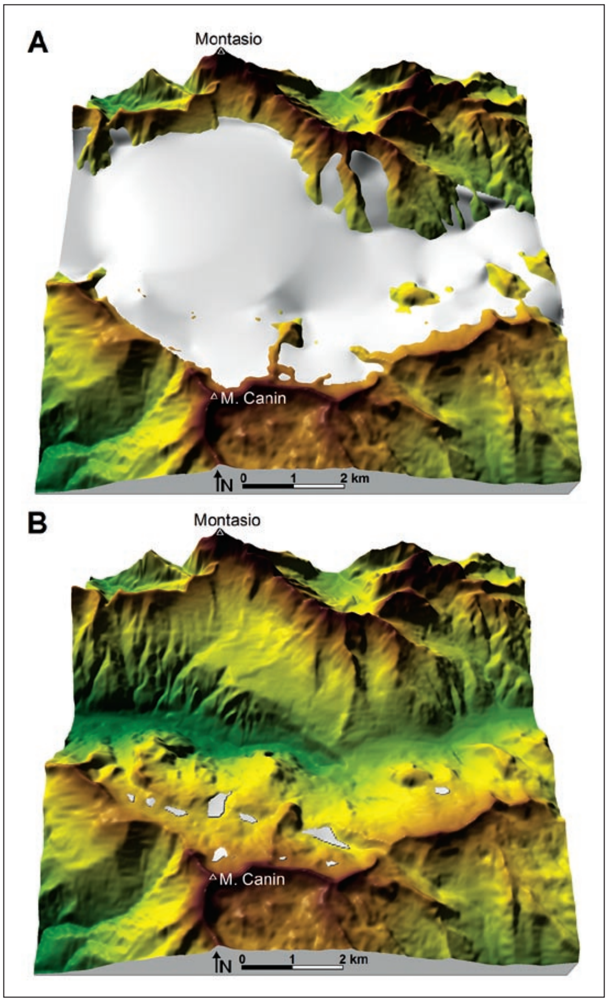

Fig. 9: Hypothesized 3D view of glacier cover in the Northern side of Canin and Southern side of Montasio at most extensive glaciation (A) and during a glacier withdrawal period (B) (Glaciation of other parts of the mountains are not considered in this figure.).

structures and glacial processes. Most depressions of solutional origin are small with diameters in the order of 1–10 m. Their shapes are often influenced by the dipping of the strata and the faults. For the lack of soil these depressions are not rounded and in most cases it is difficult to define their borders. Nevertheless, water infiltration is not always diffuse as it could be expected from the high secondary porosity of Dachstein Limestone, but during a significant part of the year (under the present climate) the snow cover works as an impermeable layer and concentrates the melt water runoff into the sinking points found in the centers of closed depressions (Fig. 10). This way, closed depressions may increase their size and become similar to classical dolines (Fig. 11).

Fig. 10: Melt water runoff in a closed depression close to Col delle Erbe.

Fig. 11: Partly snow-filled doline close to M. Poviz.

Small size (less than 10 m diameter), relatively deep depressions with almost vertical walls are called „Schachtdolinen" or „kotliči" (e.g. Kunaver 1983 and references therein) and their formation is supposed to be favoured by snow accumulation. Others (e.g. Plan & Decker 2006) suggest that pit shaped dolines can be former shaft caves truncated by glacial erosion. Although kotliči are present in the northern side of Canin as well, these forms are not as predominant as in the Slovenian side.

We have created geomorphological sketch maps of two sample areas where doline-like closed depressions were relatively well definable (Fig. 12). GPS-aided field observation and detailed contour maps were used for the creation of these maps. Statistical distributions of closed depression area and rose diagrams of depression axes were also produced from these datasets (Figs. 13–14). The first map presents the small cirque valley cutting the western structural depression west of Col delle Erbe, whereas the second map is about the area SE from M. Poviz.

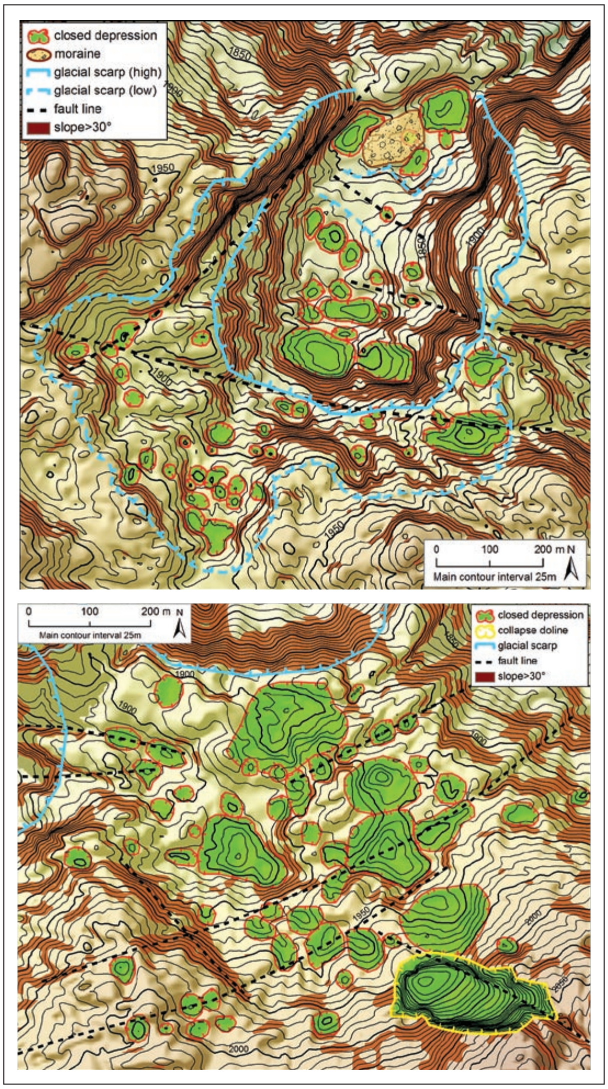

Fig. 12: Geomorphological sketch maps of two sample areas. A: near Col delle Erbe; B: near M. Poviz. Location of the sample areas are marked with red boxes in Fig. 8.

Both study areas have similar characteristics (~0,5 km^2; ~55 depressions; ~110 km^{-2} depression density; Fig. 13) but mean depression area is double in case of the Poviz sample territory (2649 m^2 compared to 1328 m^2 at Col delle Erbe). However, the mean value does not characterize well the depression population, since in many doline karst terrains, doline area distributions are lognormal (e.g. Gao, Y. *et al.* 2005; Plan & Decker 2006; Telbisz *et al.* 2007, 2009). It means that while the original distribution is strongly right-skewed, when plotting the distribution in a semi-logarithmic coordinate system (taking the logarithm of area on the horizontal axis) it looks like the normal Gaussian bell-curve. Deviations from the lognormal distribution may indicate the existence of multiple doline-subpopulations (Plan & Decker 2006) or the limited duration of doline development. In case of the Canin sample territories (Fig. 13), the frequency of large depressions is lower than expected from the lognormal distribution. Moreover, taking into consideration that these relatively large depressions are partly of glacial origin, it is concluded, that most karst depressions of the study areas are relatively young (probably of post-glacial origin).

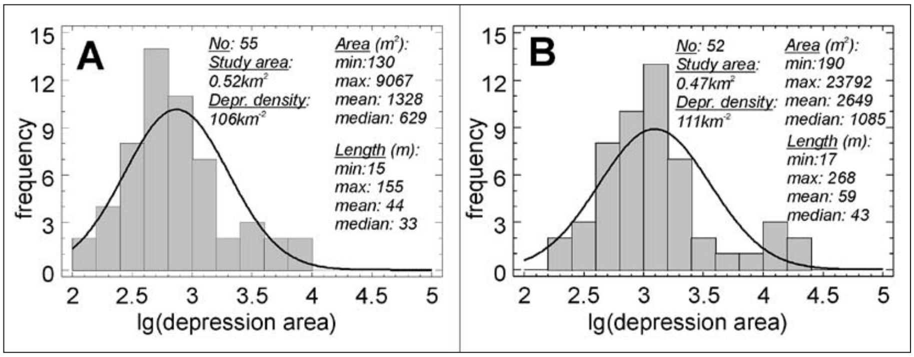

Fig. 13: Frequency distributions of closed depression area. A: near Col delle Erbe; B: near M. Poviz.

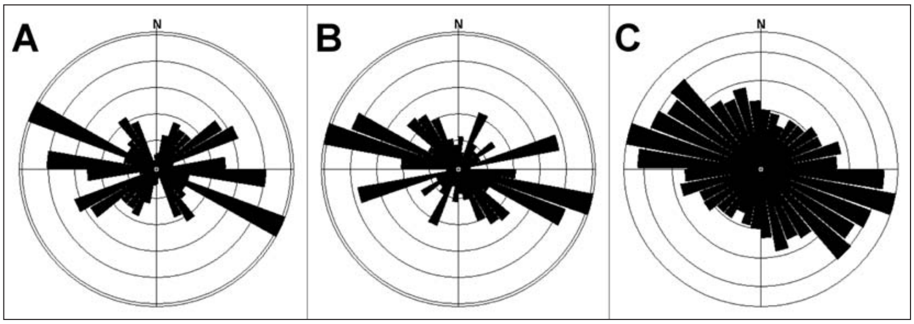

Fig. 14: Rose diagrams of closed depression long axes (with length-weighting)). A: near Col delle Erbe; B: near M. Poviz; C: rose diagram of Gortani cave passages (from Szabó 2008).

In both rose diagrams (Fig. 14A, B), the most outstanding direction is WNW–ESE. This is parallel with the main fault line of Canin plateau, suggesting that in the development of closed depressions this structural effect is also a highly influential factor. It is observed that the same direction is dominant in cave passage orientations, which are structurally determined, too (Fig. 14C; Szabó 2008).

It is noted that the large and deep doline (area: 23,792 m^2; min. depth: 40 m) at the SE corner of Poviz sample area (Fig. 12B) is a collapse doline, which is a unique feature of this size in the northern Canin plateau (Fig. 15).

Fig. 15: Large collapse doline SE from M. Poviz (person for scale).

CONCLUSIONS

It is concluded that DEM-based hypsometric analysis is suitable for exactly identifying plateau levels in Canin Mts: 1720–1940 m a.s.l. for the northern side, 1880–2100 m a.s.l. for Kaninski Podi in the southwest and 1560–1860 m a.s.l. for Goričica in the southeast. The western, fluvially formed side lacks a dominant elevation range and the elevation modus is found as low as 850 m a.s.l.

Slope histograms are also useful in discriminating the three sides of Canin. The majority of relatively low slope angles (20–35°) mean that denudation surfaces were preserved in the southern and northern sector due to karstification. The dominance of medium slope angles (~35°) indicate the significance of mass movement processes in the fluvially dissected western sector. The primacy of the northern sector in the high (>48°) slope angle range suggests that glacial processes were the most influential at this side.

The northern Canin plateau has two large WNW-ESE elongated depressions, which are structurally controlled as these are formed along a dextral strike-slip fault.

Using DEM-derived ridge and valley map and thalweg profiles of Raccolana and Rio del Lago valleys, faster erosion of Raccolana stream was demonstrated and as a consequence, the easterly movement of the watershed during Quaternary times was supported. Evidences for a stream capture at Pezzeit were also presented. The basic reason for these drainage reorganizations is most probably the intense fluvio-glacial deepening of Tagliamento valley.

Potential glacier source locations were identified based on slope map and ridge and valley map. Considering some peaks (Bila Pec, M. Poviz, M. Robon, C. Mogenza piccola) as nunataks, a large glacier covering the whole area except nunataks and the main ridge is hypothesized during the most extensive glaciations.

Closed depressions of two sample locations were mapped and analyzed in terms of statistics. High depression density (~110 km^{-2}) and small size (area range between 130 and 23,792 m^2; median: 769 m^2) is typical. Similarly high doline density values (~120 km^{-2}) are reported by Plan & Decker (2006) for the Hochschwab Massif (Northern Calcareous Alps) and by Faivre & Reiffsteck (2002) for the Velebit mountain range. Frequency distributions of depression area approach lognormal but with a shortage in larger depressions supporting the immature state of superficial karstification. Closed depressions are of glaciokarstic origin with a considerable collapse doline SE of M. Poviz. According to the rose diagrams the elongation of closed depressions is strongly influenced by structural factors.

Finally, digital terrain analysis proved to be an easy and effective tool in the quantitative geomorphological characterization of Canin Massif. Since these mountains were exhaustively studied by previous researchers, GIS-analysis mainly resulted in new evidences to earlier ideas. Nevertheless, the above methods are undoubtedly suitable for the analysis of less-known karst mountains to achieve new results.

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