

# Doline Morphometric Analysis and Karst Morphology of Biokovo Mt (Croatia) Based on Field Observations and Digital Terrain Analysis\*

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Biokovo Mt is part of the Outer Dinarides, in a coastal position with a NW-SE main tectonic orientation. The highest peak called Sveti [Sv.] Jure (1762 m) towers above a karst plateau of 1300-1400 m mean elevation. Both of the long margins of Biokovo are characterized by steep and high relief energy rockwalls formed along tectonic fault lines. The plateau is intensely karstified with diverse karren forms, large dolines and several shaft caves. Its unique karstmorphological features are the relatively deep dolines with steep walls, so the landscape is characterized mainly by the sharp interdoline ridges and pyramidal peaks instead of negative doline forms. Based on the previous observation, the Biokovo plateau can be considered a „polygonal karst”.

The geomorphological map of a study area from this plateau has been elaborated, based on field observations and topographical maps. After digitizing the contour lines, we have created the digital elevation model (DEM) of the study area and carried out sophisticated doline-morphometrical analysis using the DEM. The most important and unique feature of the landscape, the polygonal structure, has been derived from the DEM using GIS hydrologic modelling tools.

**Key words:** doline, polygonal karst, morphometrical analysis, Biokovo Mt.

## Morfometrijska analiza ponikava i krških reljefnih oblika Biokova (Hrvatska) temeljena na digitalnoj analizi reljefa i terenskom istraživanju

Planina Biokovo nalazi se na obali Jadranskog mora i dio je Vanjskih Dinarida s tipičnim dinarskim smjerom pružanja SZ–JI. Najviši vrh Biokova Sv. Jure (1762 m) izdiže se iznad krške zaravni koja se nalazi na visini od 1300 do 1400 m. Sjeveroistočna i jugozapadna padina Biokova nastale su duž glavnih rasjeda, vrlo su strme i velike su reljefne energije. Krška zaravan građena je od jurskih i krednih vapnenaca i dolomita te je intenzivno okršena. To se očituje u bogatstvu krških reljefnih oblika: škrapa, vrlo velikih ponikava i jama. Posebnost su krškog reljefa Biokova duboke ponikve vrlo strmih padina, tako da je krajobraz istraživanog područja više obilježen ostrim i uskim grebenima i visokim piramidalnim vrhovima koji međusobno odjeljuju ponikve nego udubljenjima. Na temelju dosadašnjih istraživanja biokovsku kršku zaravan možemo smatrati "poligonalnim kršem".

Na osnovi terenskoga kartiranja i različitih analiza topografske karte načinjena je geomorfološka karta istraživanog područja površine od 3 km<sup>2</sup> koje se nalazi jugozapadno od vrha Sv. Jure. Na temelju digitaliziranih izohipsa izrađen je digitalni model reljefa (DEM) istraživanog područja, koji je poslužio sofisticiranoj morfometrijskoj analizi ponikava. Poligonalna struktura dobivena je iz digitalnog modela reljefa uz pomoć GIS hidroloških alata.

**Ključne riječi:** ponikve, poligonalni krš, morfometrijska analiza, Biokovo

\* isti rad je tiskan na mađarskom jeziku 2005. godine u KARSZTFEJLŐDÉS X. Szombathely, 2005. pp. 229-243.

## INTRODUCTION

Biokovo Mt is located in the southern part of Croatia in a coastal position forming a beautiful background to the Makarska Riviera. The main orientation of the mountain is close to the typical Dinaridic NW-SE orientation ( $302^{\circ}/122^{\circ}$ ), but there is a slight S-curve in the planform, the central ranges having a NNW-SSE orientation ( $337^{\circ}/157^{\circ}$ ). It is bounded by the Dubci Pass in the NW and the Mala Vrulja-Dragljani fault line in the SE (Bognar, 2001; Mihljević, 1993; Dragušica, 2003). The total length is 36 km, the widest section is 9.5 km and its highest point is Sv. Jure peak (1762 m). The long SW and NE margins of the mountain are determined by reverse faults (Fig. 1): the Mosor-Biokovo fault next to the Adriatic Sea and the Zagvozd-Vrgorac-Metković fault on the continental side (Dragičević et al, 1999). The major part of the mountain is a karstic plateau with a higher NW section (about 1400 m mean elevation and the massif of Sv. Jure) and a slightly lower southern section (about 1300 m mean elevation).

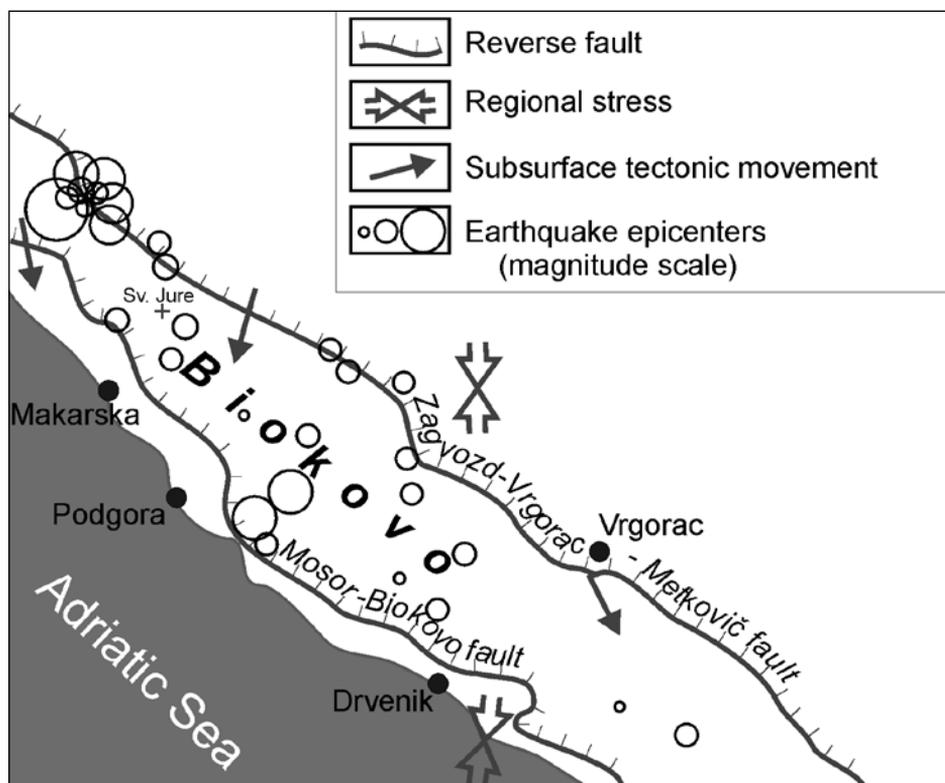


Fig. 1 Tectonic settings of Biokovo Mt (after Dragičević et al., 1999)

Sl. 1. Geološka karta Biokova (Dragičević et al., 1999)

Biokovo Mt is built up of Jurassic and Cretaceous limestones and dolomites. The Tertiary period was characterized by intense tectonic movements and flysch rocks were formed on the then continental slopes (Magaš et al., 1972; Marinčić et al., 1969). The crustal

movements are still active as shown by the large number of recent earthquakes (Herak et al., 1996). Based on data from the GPS-network installed in the area nearby Biokovo the magnitude of present-day tectonic movements may reach 2 cm/year (Cigrovski-Detelić, 1998). The still active talus slopes can be mentioned among other Quaternary formations. Pleistocene glaciation reached the mountain although glacial sediments and large landforms are not typical in the present landscape.

The mountain has a Mediterranean mountain climate. As a result, precipitation falls usually from late autumn to spring (the annual amount is 1845 mm at Vošac station just at the plateau rim); a large proportion of the annual precipitation at the higher parts falls as snow in winter, while summer is almost absolutely dry. The bora wind is extremely strong at Biokovo, similarly to that at Velebit Mt (the wind blasts may exceed 200 km/hour) and this may influence karstmorphological processes as well. The evolution of minor forms such as karren can be directly influenced by the wind (Veress et al., 2006) and the distribution of vegetation also seems to be affected by strong winds: at most parts of the plateau the trees are found largely in the deeper and better protected areas of the dolines, although we do not have data about how the actual pattern of vegetation has been changed by human impact.

## METHODS

The typical landforms of Biokovo have been examined by field observations. As a base map, we used topographic maps with 1:25,000 scale and 10 m contour level intervals. For a detailed study, a 3 km<sup>2</sup> study area SW of Sv. Jure has been examined, where 118 dolines have been found. Within this study area, we mapped typical landforms using the original maps, GPS and laser distance meters. The results of this work are summed up in our geomorphological map.

In recent years, GIS-applications became widespread in karst morphology, especially in doline morphometry (e.g. Angel et al., 2004; Denizman, 2003; Gao et al., 2005a,b; Orndorff et al., 2000; Faivre and Pahernik, 2007; Telbisz et al., 2007). This study is also an attempt to examine karst landforms in a GIS-framework.

The digital elevation model (DEM) of the study area has been created by digitizing contour lines of the original map and interpolation (using Kriging interpolation and Gaussian filtering; grid horizontal resolution: 10 m). Doline morphometrical analysis has been carried out by using the topographic map and the derived DEM.

Based on detailed field measurements, we also created the DEM of a rock slope dissected by rinnenkarren. Depth cross-sections were measured at 10 cm intervals on the rock surface, then field coordinates were transformed to (x,y,z) cartesian coordinates using trigonometric equations, and point data were finally interpolated to get a regular grid. The methodology of this work can be found in detail in Telbisz (2004).

The following GIS softwares have been used for the investigations: ESRI Arcview GIS 3.2 (for most of the analysis), Golden Software Surfer 8 (for the interpolation) and GEOrient (for the rose diagrams).

## GEOMORPHOLOGICAL PROPERTIES

The steep rock walls along the margins of the mountain show strong structural controls. The rockfalls are still active processes on these rock walls. As shown in Fig. 2, the elevation increases from sea level to the 1300-1400 m high level of the plateau within 3.5 km from the coastline. The first part of the slope is a lower angle debris slope (slope angle  $<20^\circ$ ), while the limestone stands up at the second part as very steep wall rock (slope angle  $>40^\circ$ ). The differences between the two slope types and the plateau are even more remarkable on the derived slope curve than on the elevation profile (Fig. 2).

A)

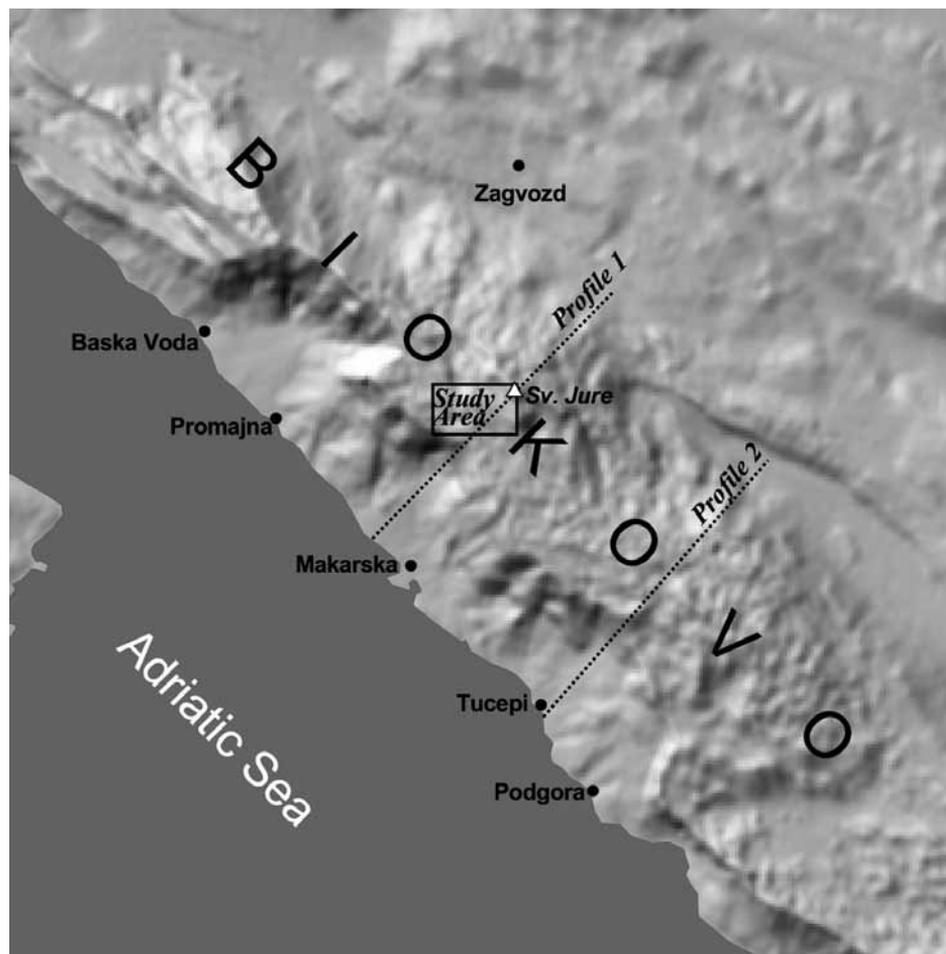


Fig. 2A Location of the study area and profiles in Biokovo Mt  
Sl. 2.A Položaj istraživanog područja s profilima

B)

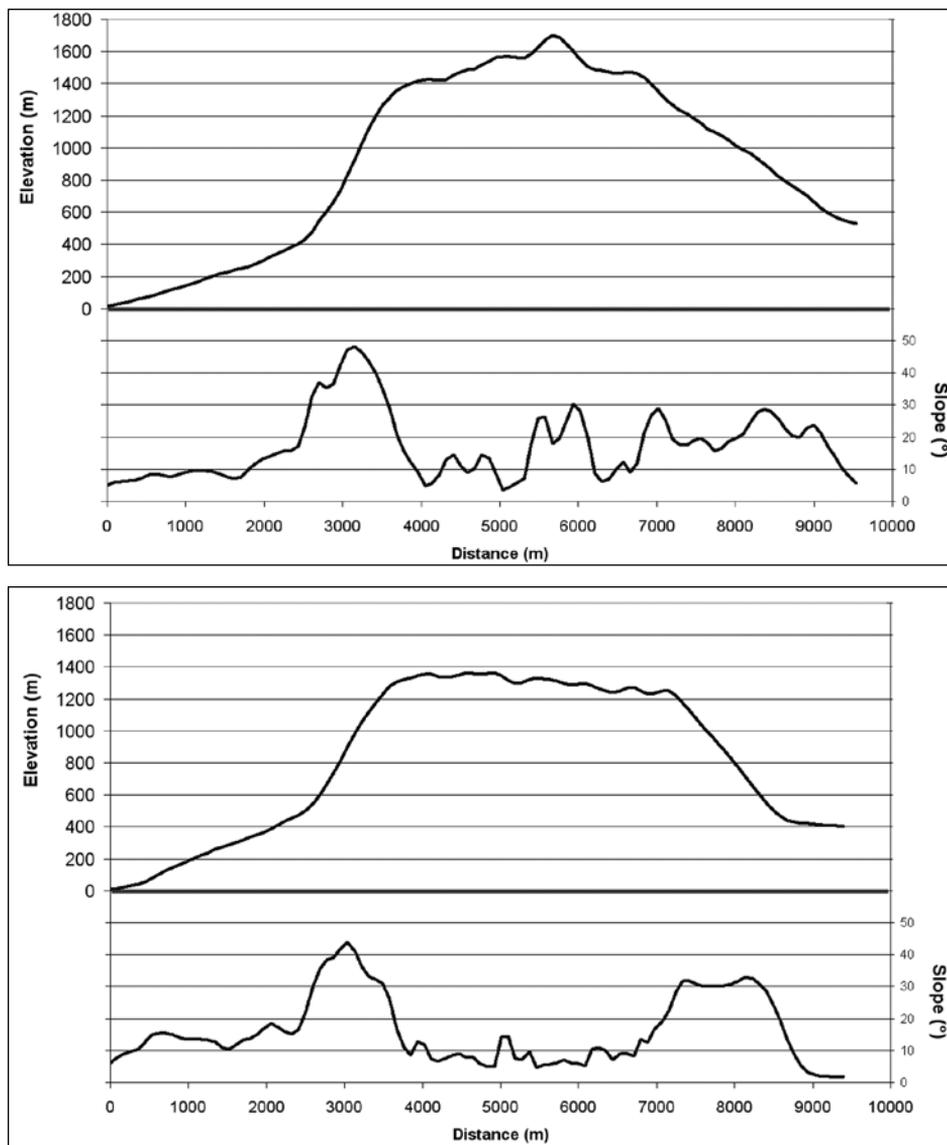


Fig. 2B SW-NE cross sections (elevation & slope) across Biokovo, north of the town of Makarska and south of Tučepi (Vertical distortion is about 2.5-fold . Data from SRTM)

Sl. 2.B Profili JZ-SI (nadmorska visina i nagib padina), sjeverno od Makarske i južno od Tučepa. Vertikalno povećanje 2,5 ×. Podaci iz SRTM-a.

Given the predominance of limestone in the lithology, the main landforms of the plateau are karst landforms. Doline density is 44 dolines/km<sup>2</sup>. This value can be considered as small to medium in a Dinarides context (e.g. Faivre and Reiffsteck, 1999; Faivre and

Pahernik, 2007). Nevertheless, the dolines practically cover the whole surface so there are no wide and rounded interdoline hills and crests such as are found in typical lower elevation karst mountains (e.g. Hungarian karst terrains). The deepening of the dolines is likely to have been a quick process, since the crests and hills between the dolines are sharp, narrow and steep walled with pyramidal peaks at the ridge junction points (Fig. 3).

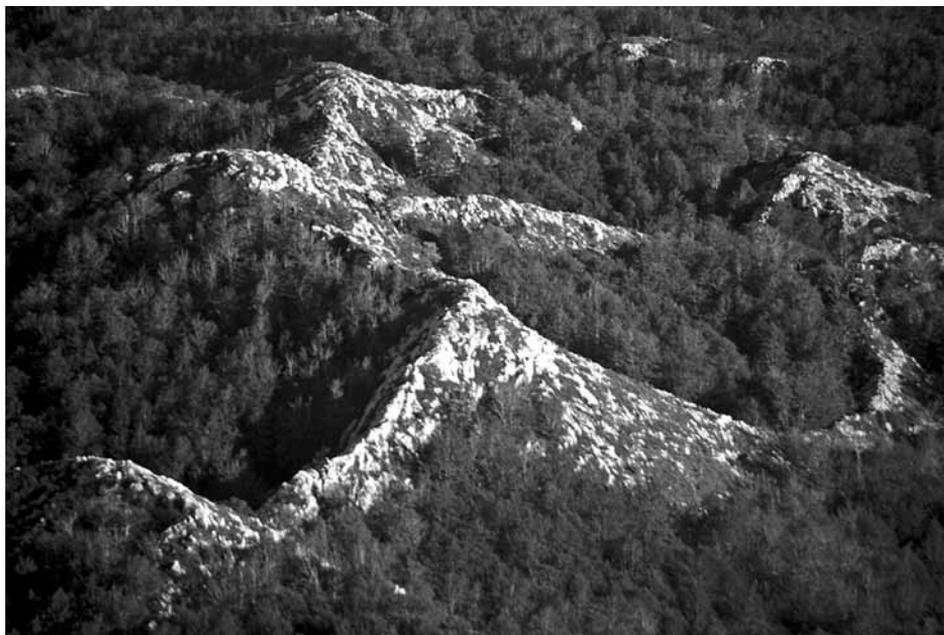


Fig.3 Typical pyramidal interdoline peak.

Sl. 3. *Primjer piramidalnog vrha između ponikava*

As a result, the landscape is characterized by the interdoline ridge network instead of negative doline shapes. In keeping with this statement, the Biokovo plateau can be considered a *polygonal karst*, which is relatively rare in European karst territories, although some other Mediterranean examples from the Dinarides could be mentioned. Collapse dolines (with vertical walls, rock debris at the bottom and cave remnants) are frequent landforms usually found on the slope or at the bottom of larger dolines (uvalas), but some of them are situated at interdoline ridges, too. The above markers (vertical walls, debris) can be found in most of the large and deep depressions, and there are many small and narrow „karst streets” in the case of the uvalas, with high, vertical sides that link the neighbouring dolines. In the formation of these „karst streets” both solutional and collapse origin can be hypothesized.

Beside the dolines, there is a great number of shaft caves in the area, for example, the Amfora Cave, the deepest one (depth: 788 m). These vertical shafts are mainly opened up to the surface on the doline slopes, but some of them are found near the interdoline ridges. In many cases their location seems to be predetermined by fissures or fault lines.

Summing up the possible reasons for the high rate deepening of the dolines, the following factors can be mentioned: the high altitude of the plateau; the intense uplift of the mountains; the large amount of annual precipitation; the vegetation concentrated in the deepest parts of the dolines (that is very important for the soil effect giving CO<sub>2</sub> and other materials for a higher solution rate); and, the influence of collapse processes (in connection with the large number of shaft caves and collapse dolines).

On the bare rock surfaces, many types of karren can be observed. The most characteristic forms are perhaps Kluftkarren (grikes) showing strong structural control, but Rillenkarrren, Rinnenkarren (grooves) and wall karren are also very frequent and in many cases these are found on dipping rock layer surfaces and bassets. However, since large parts of the plateau (except the block of Sv. Jure) are covered with vegetation (forests, grasslands, cultivated doline fills), the biogenic karren forms are the most widely distributed.

Beside karst processes, diverse mass movement processes also play an important role in the present day landform evolution. The rockfalls are important at the plateau rims (as mentioned above) but are also active in the deep and steep-sided dolines. At the gentler slopes, creep processes are active mainly in areas where soil covers the surface. Snow avalanches may occur in the winter period, principally in the highest area around Sv. Jure.

It is still a question under debate whether or not some morphological landmarks could be in connection with the Quaternary glaciation and especially the Late Pleistocene

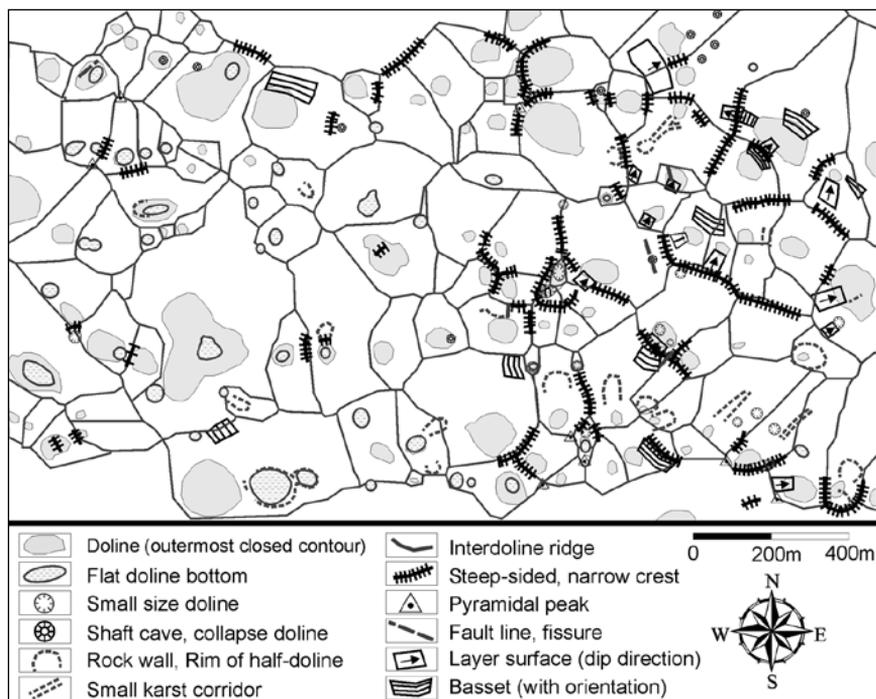


Fig. 4 Geomorphological sketch map of the study area  
 Sl. 4. Geomorfološka skica istraživanog područja

glacial period. And do these landforms imply an ice accumulation in the plateau at this period or not? According to our field experiences (in the Alps and other formerly glaciated karst mountains), the landforms of small-scale glaciations are poorly preserved in karst mountains. This is partly due to the fact that typical glacial landforms such as smaller cirques or nivation hollows are very similar to karst depressions of solutional origin (Ford and Williams, 1989; Hughes et al., 2007). Secondly, the material of the moraines can be dissolved and practically disappear from the area relatively quickly. Taking into consideration all of these uncertainty factors, we could identify some depressions in one of the highest ridges (Troglav peak, Eastern side) as nivation hollows. A smaller cirque may be outlined at the eastern side of the southern part of the plateau, but the most likely glacial landmarks are found in the Prisika Valley of this southern part, where cirque remnants (at 1100 m elevation) and erratic blocks can be found on one side of the wide, bowl-profiled valley at 900 m elevation. This low altitude of Late Pleistocene glaciation may be surprising at first sight; however, several glacial features have been observed at such low altitudes in the Dinarides (e.g. Orjen, Durmitor, etc., see Hughes et al., 2006 and references therein).

The geomorphological map, summing up our field observations of the study area next to Sv. Jure peak, is presented in Fig. 4.

## DIGITAL TERRAIN ANALYSIS

### Rinnenkarren (grooves)

In order better to visualize and examine karren forms, a new tool is applicable: the digital elevation model and terrain analysis. Since it is a new method to investigate small scale forms by DEMs, we do not know of other examples in the literature (except Telbisz, 2004), so comparisons are not yet possible. Fig. 5 presents the DEM of a dipping rock surface dissected by grooves. Dip direction is  $215^\circ$ ; the dip angle is  $30^\circ$  and the planform area is  $5.34 \text{ m}^2$ . The volume of the grooves can be computed from the DEM using standard volumetric calculations that give a value of  $0.231 \text{ m}^3$ . This value can be useful for the estimation of karren age if other karst denudation parameters (i.e. rock density, yearly runoff through this rock surface, mean  $\text{CaCO}_3$  concentration of runoff water) are known. The following formula gives the estimated age:

$$t = \frac{V \cdot \rho}{10^{-6} \cdot R \cdot A \cdot c}$$

where  $t$  is the age of karren (years);  $V$  karren volume ( $\text{m}^3$ );  $\rho$  rock density ( $\text{kg}/\text{m}^3$ );  $R$  runoff ( $\text{mm}/\text{year}$ );  $A$  rock surface ( $\text{m}^2$ ); and,  $c$  mean  $\text{CaCO}_3$ -concentration of runoff water at the bottom of the given rock surface ( $\text{mg}/\text{l}$ ).

In this case, without field measurements of several parameters, only rough estimates can be used ( $\rho=2700 \text{ kg}/\text{m}^3$ ;  $R=1500 \text{ mm}/\text{year}$ ;  $c=50 \text{ mg}/\text{l}$ ) that give an approximate age of 1557 years. However, given the major uncertainties in the parameters, this value is presented only to demonstrate how karren volume can be used to calculate karren age.

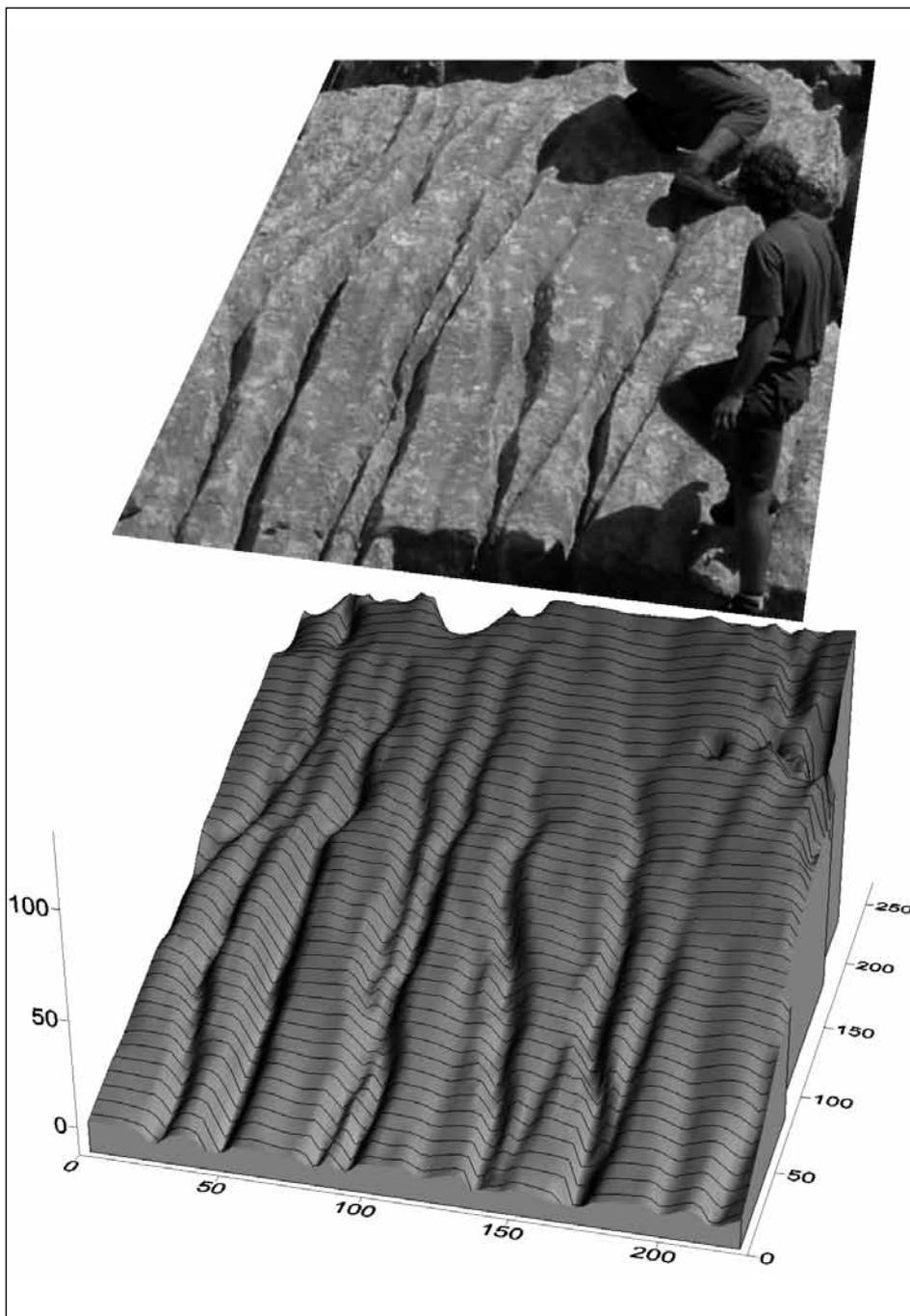


Fig. 5 Rillenkaren photo and digital elevation model (DEM) of the rocky surface (distances are in cm.)

Sl. 5. Fotografija i 3D digitalni model žliba u blizini doma na Lokvi (udaljenosti u cm)

## Dolines

### *Different ways to define doline boundaries*

The aim of our work was to define doline boundaries using the map and the DEM and calculating the morphometric parameters based on these boundaries, in order to give a correct comparison between this area and other doline karst landscapes. There are three possible algorithms with differing theoretical backgrounds to define doline boundaries.

1) The most often used, traditional method is to define the doline border by the *outermost closed contour line* around the doline. The main advantage of this method is the clear, unequivocal definition (if the same map is used) and the fact that this task can be carried out easily by manual processing, even if the DEM is not available. The precise definition and the use of standardized criteria are especially important in the case in which a larger area is processed by a team and not by a single person. This method may result in an elevation error range equal to the contour interval. The error of the doline area data can not be determined so easily, because it is also influenced by the angle of the doline slope.

2) According to the second method, the boundary of the doline can be defined by theoretically *filling up the doline* to the level at which the water overflows from the depression, i.e. the height of the doline boundary is defined by the *lowermost point of the rim around the doline*. This definition corresponds best to the „theoretical doline shape”; however, it is not always possible to use this definition consistently based solely on topographic maps. Nevertheless, the DEM may help to resolve the problem of consistency. In hydrologic modelling there are a number of widely used algorithms to remove „pits” from the DEM (e.g. Martz and Garbrecht, 1998). In a „normal case” (meaning no karst terrain) the pits are usually DEM errors (resulting mainly from the interpolation), but in the case of karst areas these small depressions are just the objects we are interested in. Thus, the doline boundaries and doline volumes can be derived by calculating the difference of the „filled DEM” and the original DEM. (As a software solution for the pit removal we used the *DEMFill* extension of *ArcView 3.2*).

3) However, the characteristic „polygonal dolines” of the Biokovo plateau are not perfectly represented by the aforementioned methods because it is obvious from field observations that the real doline boundaries are the interdoline ridges. This ridge network (the skeleton of the landscape) can be drawn manually from topographic maps but, by using the DEM, this step can be performed automatically, too. Taking the doline centres as sinks (as they really are) the watersheds belonging to these points can be identified again with the help of hydrologic modelling (we used the *Watershed* extension of *ArcView 3.2*).

The doline boundaries derived by the three above mentioned methods can be studied in Fig. 6. It is concluded that the „*outermost closed contour line*” and the „*filling doline*” definitions give the same boundaries in most cases, although in several cases the second definition results in much larger doline shape. Nevertheless, the real image of the landscape is represented by the polygonal watershed-boundaries.

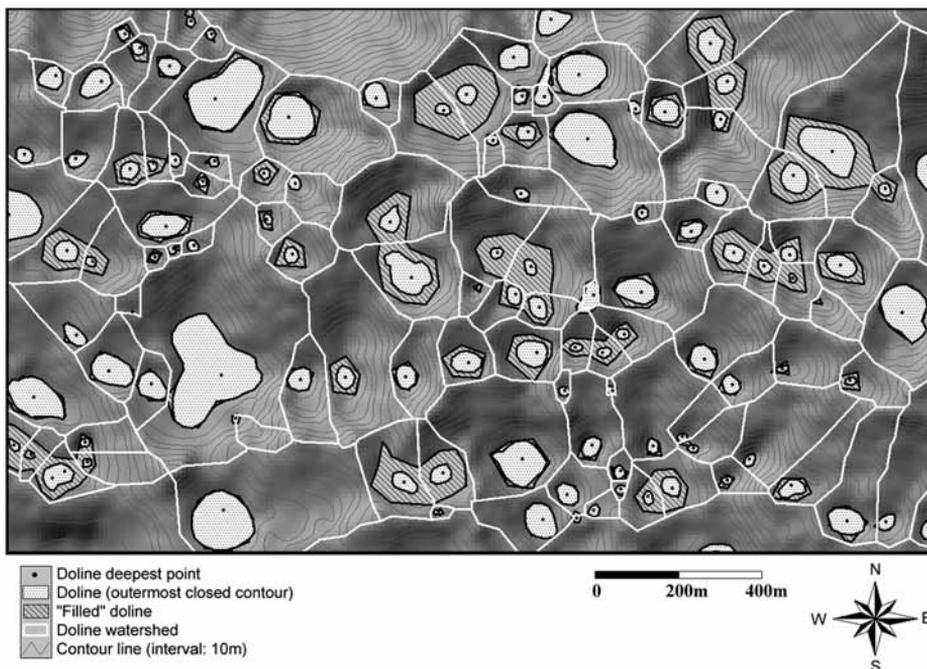


Fig. 6 Three possibilities to define doline boundaries  
 Sl. 6. Tri metode određivanja ruba pojedine ponikve

Furthermore, we examined the morphometric parameters of dolines derived by these methods and compared the data with other karst areas.

### Size parameters

In the present paper we focus on three morphometrical variables: area, depth and surface/area ratio and for comparison purpose, we give three statistical parameters of the above variables: minimum, median and maximum. From *Table 1* one can calculate that *the ratio of the doline area median* for the three different definitions is *1 : 2.2 : 11.2* and also that *the ratio of the doline depth median* is *1 : 2.3 : 9.4*.

Tab. 1 Morphometric characteristics of the dolines found in the sample area  
 Tab. 1. Morfometrijske karakteristike ponikava na istraživanom području

|  | Area (m <sup>2</sup> )                               | Depth (m)   | Surface/Area   |
|--|--|---|--|
| <b>Dolines defined by the outermost closed contour</b> | Median = 1330<br>Minimum = 220<br>Maximum = 36815    | Median = 6.7<br>Minimum = 1.7<br>Maximum = 45.0   | Median = 1.066<br>Minimum = 1.003<br>Maximum = 1.259 |
| <b>Dolines defined by filling-up to the rim</b>        | Median = 2870<br>Minimum = 68.5<br>Maximum = 35757   | Median = 15.2<br>Minimum = 0.2<br>Maximum = 46.0  | Median = 1.090<br>Minimum = 1.002<br>Maximum = 1.251 |
| <b>Doline watersheds</b>                               | Median = 14876<br>Minimum = 1166<br>Maximum = 176317 | Median = 62.9<br>Minimum = 2.5<br>Maximum = 276.1 | Median = 1.115<br>Minimum = 1.003<br>Maximum = 1.454 |

In order to compare Biokovo with other typical temperate karst terrains, we used data about dolines in the Aggtelek Karst (Hungary) based on Telbisz (1999, 2003). Doline data from Aggtelek were calculated using the „outermost closed contour line” method and 1:10,000 scale topographic maps. There, the median of doline area equals 2455 m<sup>2</sup> and the median of doline depth is 6m. That suggests that dolines from the Biokovo study area are smaller in extent but somewhat deeper. The intense vertical doline development of Biokovo can be better expressed by the *vertical doline ratio* (=length/depth). The higher this parameter, the flatter the doline. The mean value of this parameter for all dolines (N=1100) of the Aggtelek Karst is 16.3, it is only 6.6. for the Biokovo sample area. However, the „deep character” of Biokovo dolines is best expressed if the 2nd or 3rd doline border definitions are used, although no comparison data is available in the case of Aggtelek Karst.

The surface/area ratio can easily be calculated from the DEM (e.g. *ArcView 3.2. Surface Tools* extension, Jenness, 2006). It is stated based on the results that the real surface of a doline is on average 7-12% larger than the area measured directly from the map. In our opinion, this difference is not very high; however, the real solution surface is supposed to be manifold this value because the rock debris and fissures increase very effectively the possible surface of karst corrosion. Nevertheless, the quantification of this real surface is not yet resolved.

The total volume of the dolines based on the DEM using the „fill-in definition” is  $5.63 \cdot 10^6$  m<sup>3</sup>. This value is slightly lower than the volume calculated by the „simplified calotte-formula” ( $V = \text{area} \times \text{depth} / 2$ ) that is  $7.12 \cdot 10^6$  m<sup>3</sup>. This result suggests that the shapes of the dolines in the sample area are closer to the „negative cone form” than to the

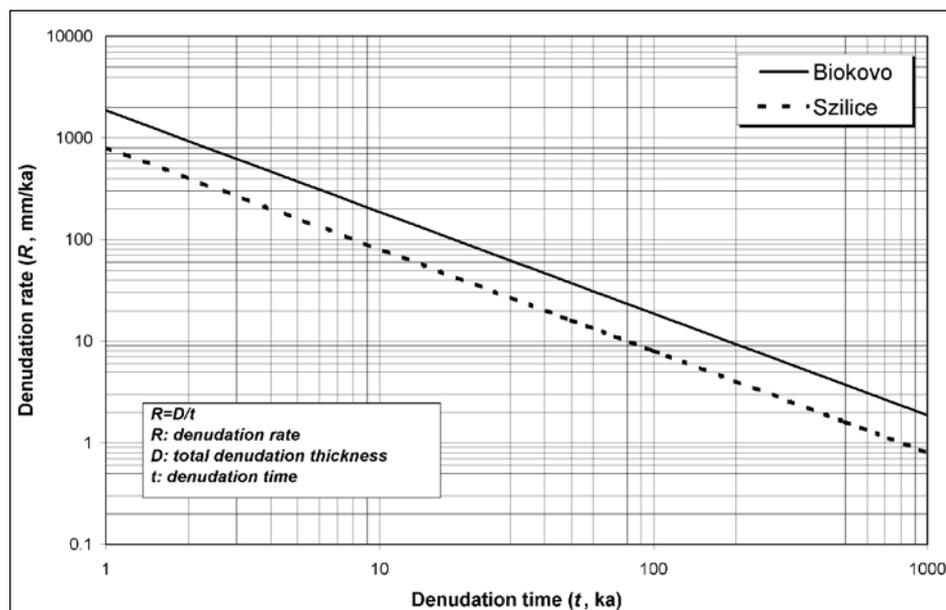


Fig. 7 Denudation rate vs. duration of denudation in the case of a given total denudation. Based on doline morphometric data from sample area in Biokovo and Silicka Planina (Slovakia, data from Telbisz and M6ga, 2005)

Sl. 7. Intenzitet denudacije u odnosu na trajanje denudacije, određeni prema morfolometrijskim obilježjima ponikava na istraživanom području Biokova i Silicka planine (Slovačka) (Telbisz i M6ga, 2005)

calotte (cf. Telbisz, 2004). The total volume can be used for calculating the total denudation thickness ( $D = \text{total volume} / \text{area}$ ) of the whole sample area that gives 1866 mm. From the total denudation thickness, the denudation rate ( $R$ ) can be expressed as an inverse function of the denudation time ( $t$ ), i.e.  $R = D/t$  (Fig. 7).

### *Directional analysis*

Directional analysis can be used to present structural constraints on doline development. It is usually assumed that the long axes of dolines are elongated in tectonically preformed orientation along fissures and fault lines. In order to perform this analysis we determined both the orientation and length of the long axes of the dolines defined by the outermost closed contour line, and of the doline watersheds (using *ArcView 3.2. Longest Line* extension, Jenness, 2003, Fig 8).

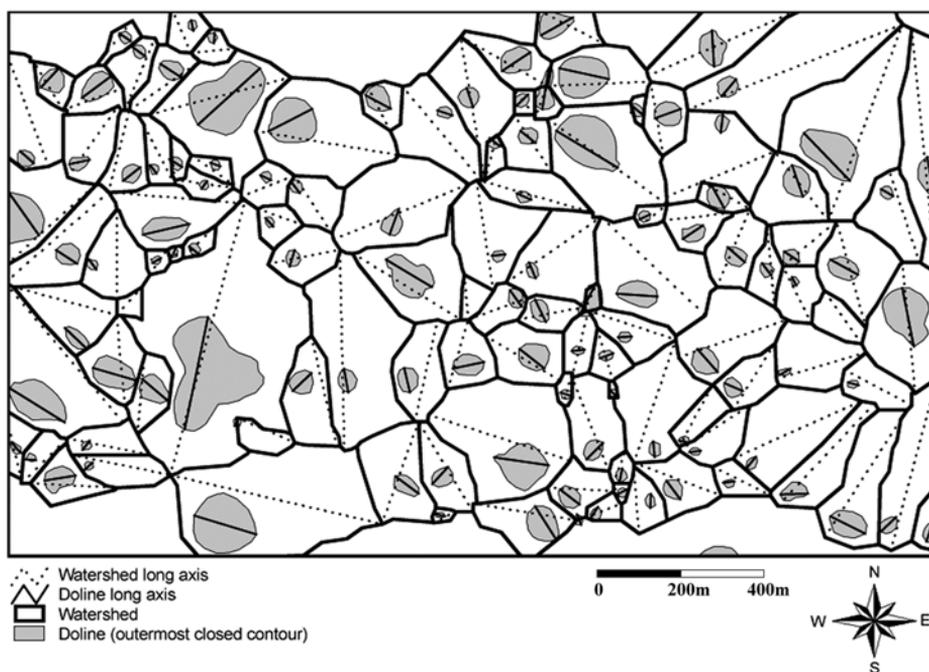


Fig. 8 Doline long axes  
Sl. 8. Osi pružanja ponikava

Surveying the polygonal ridge-network of the sample area (Fig. 9), there is an apparent asymmetry of the doline watersheds relative to the more traditionally defined dolines, in the sense that the geometric centre and the deepest point of a given object are usually much further from each other in the case of watersheds. The reason for this fact is that several watersheds contain larger hillslopes as well. The question arises as to which factors determine the „shift” of doline centres (i.e. the vector from the geometric centre to the deepest point).

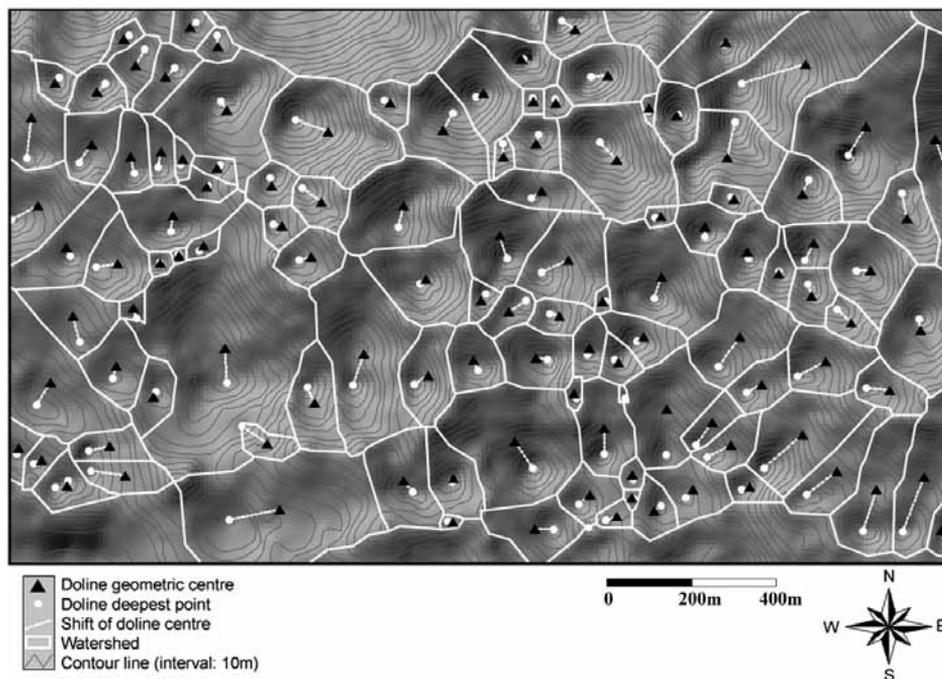


Fig. 9 Doline geometric centres (centroids) and deepest points

Sl. 9 Geometrijska središta ponikava (centroidi) i najdublje točke ponikava

To answer the above questions, rose diagrams (Fig. 10) have been created. In Rose A) a well-defined orientation is observable, whereas in Rose B) a circular sector can be observed instead, while Rose C) seems to be a mixture of several directions. These results can be

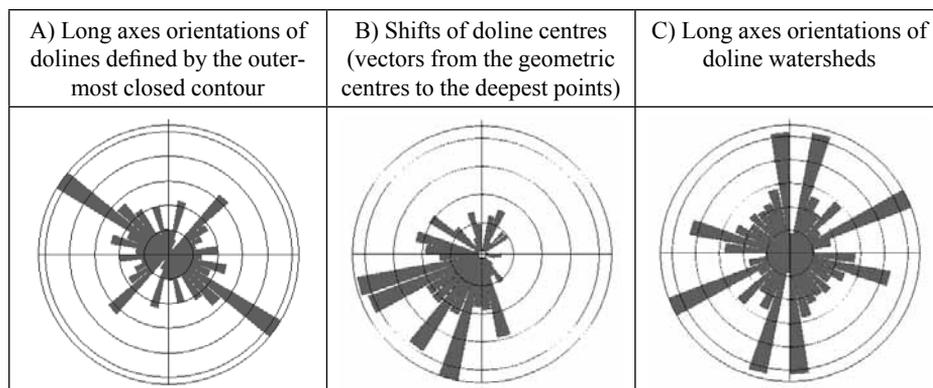


Fig. 10 Rose diagrams from doline data of the sample area (with length weighted frequency values)

Sl. 10 Dijagrami prostornog rasporeda morfolometrijskih obilježja ponikava na istraživanom području

interpreted as follows. The structural constraints mainly affect the closely defined doline shape. In the case of the sample area, this main orientation is about NW-SE, being in good agreement with the general orientation of the mountain. The ridges have parallel orientation to this NW-SE direction that results in a large proportion of hillslopes facing to the SW, thus dolines formed on these hillslopes show a centre shift towards the slope direction as is suggested by Rose B). In the multimodal circular distribution of the doline-watershed long axes (Rose C), three orientations can be recognized: the main tectonic orientation with some distortion (WNW-ESE), the main hillslope aspect (SW-NE) and an N-S orientation. (In *Fig. 8* one can identify where the doline and watershed long axes coincide or differ significantly from each other.) This directional analysis suggests that the formation of doline-watersheds is a highly compound process showing the influence of several factors.

## CONCLUSIONS

Biokovo is a typical Mediterranean high karst area. Its plateau is uplifted along tectonic lines and it is a medium doline density polygonal karst terrain where a great number of collapse dolines and shaft caves are also found. Beside tectonic and karst processes, the mass movements play an important role in the present formation of the landscape. Based on some characteristic glacial landforms, it seems likely that there was a small extent of glaciation in the area during the Pleistocene

Using the DEM of an arbitrarily chosen 3 km<sup>2</sup> study area in the vicinity of the main peak, Sv. Jure, doline morphometric properties have been investigated. Three different „definitions” of dolines have been examined and applied to determine doline boundaries. These definitions were based, respectively, on the outermost closed contour line, on the lowermost point of the doline rim and on the doline-watershed. These three definitions can be used for different purposes and may give insights to different aspects of doline development. The most closely defined doline definition seems to be the most convenient in implying structural orientations. The calculation of doline volume and the estimation of total denudation is the most reliable, based on the „fill-in doline” definition. And finally, the real image of the landscape as it is observed in the field can best be presented by the watershed method.

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## SAŽETAK

# Morfometrijska analiza ponikava i krških reljefnih oblika Biokova (Hrvatska) temeljena na digitalnoj analizi reljefa i terenskom istraživanju

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Planina Biokovo nalazi se na obali Jadranskog mora i dio je Vanjskih Dinarida s tipičnim dinarskim smjerom pružanja SZ–JI. Najviši vrh Biokova Sv. Jure (1762 m) izdiže se iznad krške zaravni koja se nalazi na visini od 1300 do 1400 m. Sjeveroistočna i jugozapadna padina Biokova nastale su duž glavnih rasjeda, vrlo su strme i velike su reljefne energije. Krška zaravan građena je od jurskih i krednih vapnenaca i dolomita te je intenzivno okršena. To se očituje u bogatstvu krških reljefnih oblika: škrapa, vrlo velikih ponikava i jama. Posebnost su krškog reljefa Biokova duboke ponikve vrlo strmih padina, tako da je krajobraz istraživanog područja više obilježen ostrim i uskim grebenima i visokim piramidalnim vrhovima koji međusobno odjeljuju ponikve nego udubljenjima. Na temelju dosadašnjih istraživanja biokovsku kršku zaravan možemo smatrati "poligonalnim kršem". Mogući preduvjeti za nastanak "poligonalnoga krša" na istraživanom području jesu: velika nadmorska visina krške zaravni, intenzivno tektonsko izdizanje, velika godišnja količina padalina te vegetacija koja je uglavnom koncentrirana u dubljim dijelovima ponikava, čime se povećava koncentracija CO<sub>2</sub> i tako pospješuje proces urušavanja.

Prilikom istraživanja obuhvaćeno je područje od 3 km<sup>2</sup> jugozapadno od vrha Sv. Jure te je na temelju terenskoga kartiranja i topografske karte izrađena geomorfološka karta. Interpolacijom digitaliziranih izohipsa izrađen je digitalni model reljefa (DEM), a primijenjen je i za novi pristup istraživanju mikrokrških reljefnih oblika (škrapa). Načinjen je dakle DEM škrapa istraživanog područja, koji je osim za vizualizaciju upotrijebljen i za izračunavanje denudacije.

U morfometrijskoj analizi ponikava primijenjene su tri različite metode za određivanje ruba svake pojedine ponikve: najviša zatvorena izohipsa, ispunjavanje ponikve do najniže točke njezina ruba te na temelju određivanja sljevnog područja. Za dvije posljednje metode upotrijebljeni su GIS hidrološki alati za modeliranje. Rezultati morfometrijske analize uvelike se razlikuju ovisno o primijenjenoj metodi. Gustoća ponikava na istraživanom području iznosi 44 ponikve/km<sup>2</sup>.

Orijentacija dužih osi ponikava (dobivena metodom najviše položene zatvorene izohipse) poklapa se s orijentacijom orografske osi cijele planine (SZ–JI). Ako npr. primijenimo treću metodu determinacije (s pomoću određivanja sljevnog područja svake ponikve), rezultati postaju multimodalni, što upućuje na to da je na nastanak sljevnog područja svake pojedine ponikve utjecalo više čimbenika. Najdublje točke ponikava na istraživanom području uobičajeno se nalaze na jugozapadnom dijelu ponikve zbog opće orijentacije i nagiba terena.

Možemo zaključiti da prikazane metode određivanja granica ponikava mogu biti upotrijebljene u različite svrhe te stoga mogu dati različite uvide u pojedine aspekte razvoja ponikava. Prva metoda najuže definira ponikvu te je zato pogodna za određivanje strukturne orijentacije. Za izračunavanje volumena ponikve i ukupne denudacije najpogodnija je metoda ispune (*fill-in*), dok je za pravu sliku ponikve kako je promatramo na terenu najprikladnija metoda determinacije sljevnog područja.

Received (Primljeno): 2007 – 05 – 09

Accepted (Prihvaćeno): 2009 – 03 – 03

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