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# THE VERTICAL ELECTRICAL SOUNDING (VES) OF THE EPIKARST: A CASE STUDY OF THE COVERED KARST OF THE BAKONY REGION (HUNGARY)

# VERTIKALNO ELEKTRIČNO SONDIRANJE EPIKRASA: ŠTUDIJA PRIMERA POKRITEGA KRASA V REGIJI BAKONY (MADŽARSKA)

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**Abstract** UDC 550.837:551.435.88(234.373.1)

***Márton Veress, György Deák & Zoltán Mitre: The vertical electrical sounding (VES) of the epikarst: A case study of the covered karst of the Bakony region (Hungary)***

The epikarsts of five covered karst areas in the Bakony region are compared. The comparison is based on the specific resistances of the bedrock resistance averages measured by vertical electrical sounding (VES). The average largest specific resistance differences (per area) and the mean values (per profile) were calculated to investigate the characteristics of the epikarst. The mean values of specific resistance were compared using analysis of variance (ANOVA) to determine whether the specific resistances of the areas showed significant differences. The studied karst areas can be categorised as high or low specific resistance areas, and the ANOVA method could be applied to three areas based on the available data. It can be concluded that the mean values of their specific resistances are significantly different. The mean values ($\bar{x}$) and standard deviation (S) of the specific resistances of the different areas were analysed. It is described that the karst receives less water in the case of areas with lower specific resistance, while it receives more water in the case of areas with higher specific resistance. Areas with a high specific resistance are less karstified, while areas with a low specific resistance are more karstified. Low specific resistances and small mean values ($\bar{x}$) indicate a higher degree of cavity formation in the epikarst, while the decrease in mean values and standard deviation (S) indicates increasing uniformity of the degree of cavity formation in the epikarst. The different degree of cavity formation is explained by the different karstification rates and the exposure of different time of certain areas.

**Keywords:** Bakony Region, epikarst, VES measurement, specific resistance, karstification, covered karst.

**Izvleček** UDK 550.837:551.435.88(234.373.1)

***Márton Veress, György Deák & Zoltán Mitre: Vertikalno električno sondiranje epikrasa: študija primera pokritega krasa v regiji Bakony (Madžarska)***

Avtorji so primerjali epikraške značilnosti petih območij pokritega krasa v regiji Bakony. Primerjava temelji na specifični upornosti z vidika povprečne upornosti matične podlage, izmerjene z vertikalnim električnim sondiranjem (VES). Za proučevanje značilnosti epikrasa so bile izračunane povprečne največje razlike specifične upornosti (za posamezno območje) in srednje vrednosti (za posamezni profil). Z analizo variance (ANOVA) je bila izvedena primerjava srednjih vrednosti specifične upornosti, da bi ugotovili, ali specifična upornost območij kaže pomembne razlike. Proučevana kraška območja je mogoče razvrstiti v območja z veliko ali majhno specifično upornostjo, metodo ANOVA pa je bilo mogoče na podlagi razpoložljivih podatkov uporabiti za tri območja. Ugotoviti je mogoče, da se srednje vrednosti njihove specifične upornosti pomembno razlikujejo. Avtorji so analizirali srednje vrednosti ($\bar{x}$) in standardni odklon (S) specifične upornosti različnih območij. Iz opisa izhaja, da na območjih z manjšo specifično upornostjo kraško območje prejme manj vode, na območjih z večjo specifično upornostjo pa prejme več vode. Območja z veliko specifično upornostjo so manj zakrasela, območja z majhno specifično upornostjo pa so bolj zakrasela. Majhna specifična upornost in majhne srednje vrednosti ( $\bar{x}$)kažejo na višjo stopnjo prevotljenosti epikrasa, zmanjševanje srednjih vrednosti in standardnega odklona (S) pa kaže na bolj enakomerno prevotljenost epikrasa. Avtorji različne stopnje prevotljenosti posameznih območij razlagajo z različno hitrostjo zakrasevanja in različno časovno izpostavljenostjo zakrasevanju.

**Ključne besede:** regija Bakony, epikras, meritve z vertikalnim električnim sondiranjem (VES), specifična upornost, zakrasevanje, pokriti kras.

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# 1. INTRODUCTION

In this study, the epikarsts of the covered karst areas of the Bakony Mountains with various degree of karstification are compared. These are the following: eastern part of Tés Plateau (Tés 1 which is the area of Tábla Valley, Tés 2 which is the tributary valley of Tábla Valley, Tés 3 which is the area between the two valleys), Homód Valley area (Hárskút Basin), Eleven-Förtés doline group (Kőris Mount), Mester Hajag and the marginal part of Fehérkő Valley. The relationship between the degree of karstification of karst areas and the specific resistance of the karstic bedrock is described. Based on the specific resistance values of karst areas, the different maturity of the epikarst and the different degree of karstification of karst areas can be presented.

The epikarst is the upper, subsurface part of the vadose zone with cavities (Williams, 1972, 1983, 1985; Mangin, 1975; Klimchouk, 1987, 2004; Bakalowicz et al., 1974; Bakalowicz, 2005, 2019; Palmer, 2004; Jones, 2013; Tobin et al., 2021; De Waele & Gutierrez, 2022), (Figure 1), where secondary porosity may even be 20% (Williams, 2008). Since porosity decreases in the vadose zone below the epikarst (about to 2%), the infiltrating waters accumulate temporarily at the lower part of the epikarst and flow laterally (Klimchouk, 2004; Williams, 2008; Bakalowicz, 2019). The surface of the water of the epikarst, the piezometric surface, fluctuates depending on water supply. Its elevation and fluctuation depends on the degree of local cavity formation of the epikarst, on the degree and distribution of water supply, and on the drainage intensity out of the epikarst. Therefore, the piezometric surface is uneven, non-horizontal, and dissected by depressions (Williams, 2008). Its lower surface is the saturation level which also constitutes an uneven surface. It penetrates deeper and creates a depression at a site where water with higher dissolution capacity arrives at the epikarst. On covered karst the thickness and calcareous content of the cover affect the upper and lower surfaces of the epikarst. The thicker the cover, to the higher degree the water is stored in it, and the higher its calcareous content, the more saturated water arrives at the epikarst. A lot of infiltrating water (at water catchment feature and in case of thin cover) rises the piezometric surface. If the cover is calcareous-free, the water has a higher dissolution capacity, the epikarst has more cavities, and the saturation level is deeper and thus, forms a depression.

The epikarst plays an important role in the karstic development of the surface, but it itself develops too and becomes more and more dissected by shafts and the motion of its water becomes more and more vertical (Klimchouk, 2004). Klimchouk (2004) differentiated young epikarst, mature epikarst, and old epikarst development phases. Figure 2 presents epikarst with various maturity degree and environment.

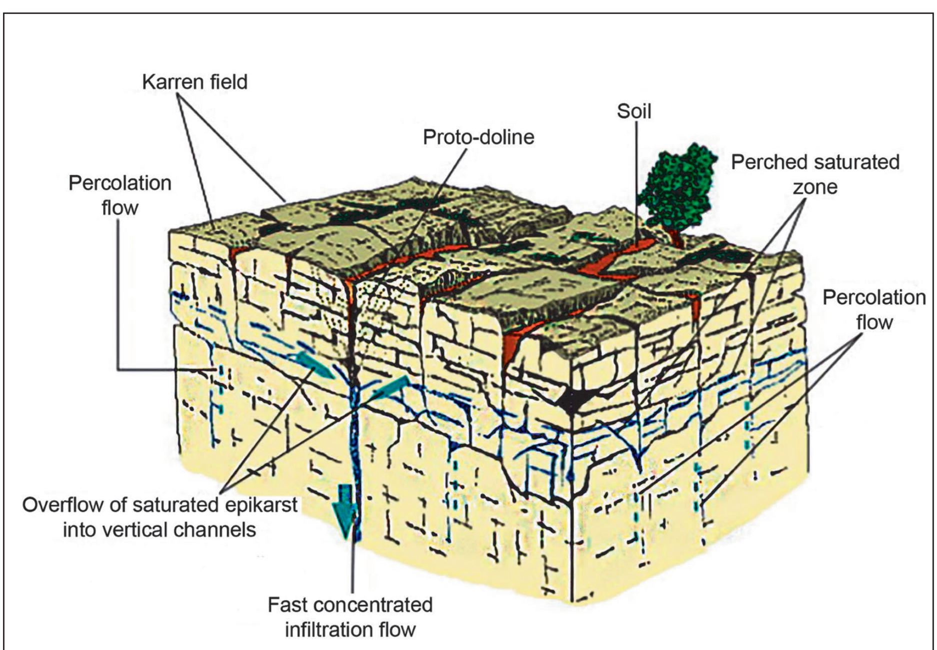


*Figure 1: The epikarst (Bakalowicz, 2019).*

## 2. THE BAKONY REGION AND RESEARCH AREAS

Our studies were made in the karstic terrain sections of the Bakony Region (Transdanubian Mountains, Hungary). The Bakony Region (4900 $km^2$) is separated to the Bakony Mountains (2200 $km^2$) and the surrounding micro region groups. It is enclosed by the Little Hungarian Plain, the Great Hungarian Plain, the Vértes Mountains, and the Transdanubian Hills. The Bakony Mountains with an elevation of 200-700 m, is separated into the Northern Bakony and Southern Bakony, its eastern part is the Eastern Bakony, the most expanded part of which is the Tés Plateau.

The main constituting rock of the Bakony Mountains is Triassic Main Dolomite (Main Dolomite Formation) which is overlain by Triassic Dachstein Limestone (Dachstein Limestone Formation) in patchy development and mainly in small thickness (from some tens of metres to some hundreds of meters) and by Jurassic, Cretaceous and Eocene Limestones (Kercsmár et al., 2022).

The Late Cretaceous tropical karstic peneplain of the mountains (Szabó, 1968; Bulla, 1968) had become tectonically dissected since the Eocene (Pécsi, 1980) therefore the Late Oligocene-Early Miocene delta gravel (Korpás 1981) (Csatka Gravel Formation) covered a dissected surface. Younger limestones mainly developed at the marginal parts of the mountains (Lajta Limestone Formation, Tinnye Limestone Formation), and also Pliocene freshwater limestones were formed (Császár et al., 1981). Pannonian clay also occurs in small expansion (Jaskó, 1961) and loess in wide expansion developed too.

The Bakony Mountains is separated into blocks (horsts) and block groups with different elevation and landscape evolution (Pécsi, 1980, 1991). On lower

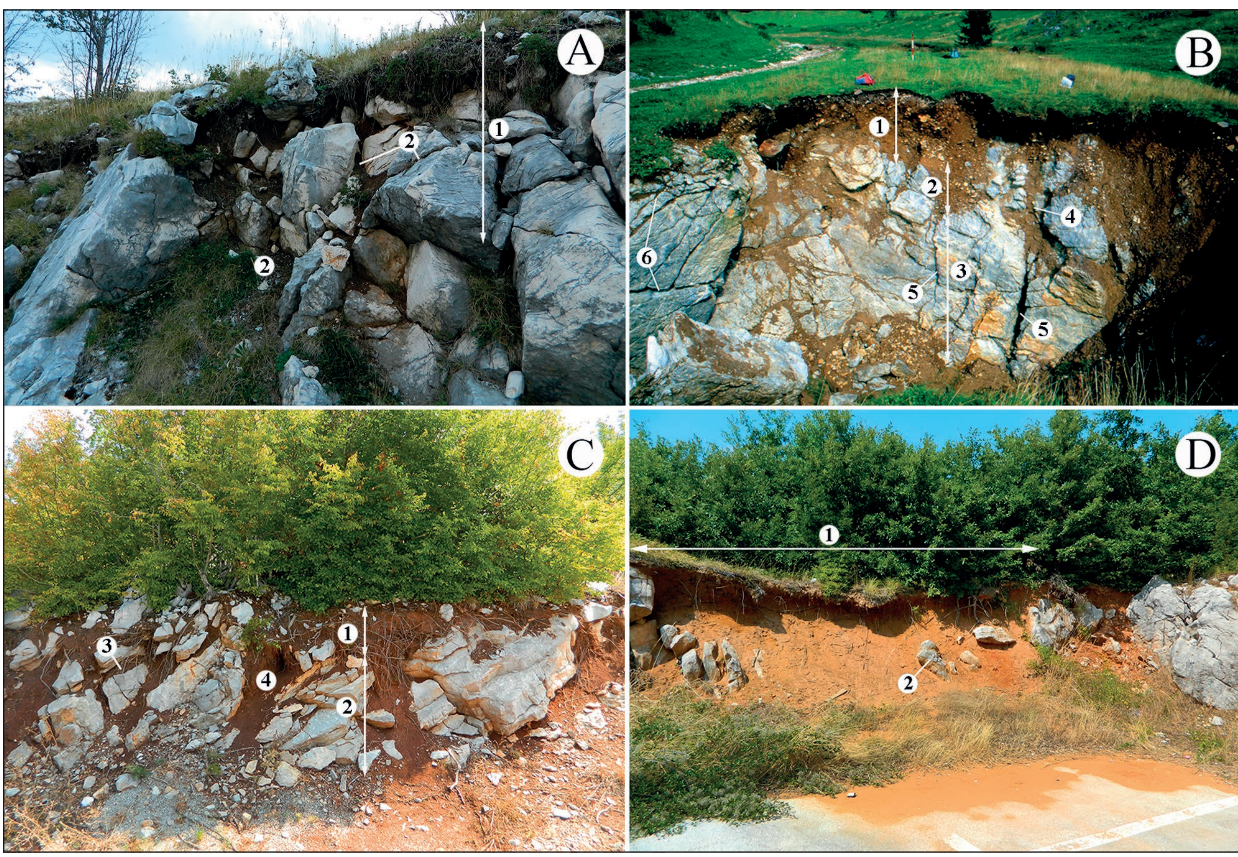


*Figure 2: Epikarst with various maturity degree and environment.* **A**: *Epikarst below soil-covered karst in the side of a road-cut (near the village of Galečic, The Dinarides, Bosnia): 1. epikarst part that was separated into blocks with soil wash, 2. grikes with different inclination and width.* **B**: *Epikarst of covered karst in the side of a doline (Pádis, Romania) 1. cover, 2. filled-in epikarst part, 3. unfilled epikarst part or only filled to a small degree, 4. wide filled-in grike opening to the bedrock surface, 5. narrow grike, 6. grike along bedding plane.* **C:** *Mature epikarst that developed below weathering residue on a karst exposed to intensive dissolution in the side of a road-cut (the Dinarides, Bosnia), 1. the upper part of the epikarst that is separated into debris, 2. epikarstic part of the bedrock, 3. grikes along the bedding plane, 4. grikes that developed along fractures.* **D:** *Epikarst below weathering residue that is separated into parts (the Dinarides, Bosnia), 1. wide, filled-in grike, the site where the epikarst is separated into parts, 2. the block of the bedrock in the weathering residue.*

elevated blocks (for example the Dudar Basin) their roof level is uniformly covered with superficial deposit, those with a larger elevation are covered in bigger patches (for example Mester-Hajag, Tés Plateau), while the most elevated ones are uncovered or only small patches of the cover survived (for example Kőris Block). On the peneplains of the blocks, abrasion peneplains, pediments (Pécsi, 1963, 1970, 1980) and epigenetic valleys (these are often gorges or of gorge character) are widespread, while on terrains covered mostly with thin, permeable cover, suffosion dolines occur frequently (Veress, 2022). Under superficial unconsolidated (?) deposits, the bedrock became karstified to a various degree and in different periods (Mindszenty & Sebe, 2022), which resulted in the development of terrains with dolines (Bíró, 1969), and poljes (Szabó, 1956).

Among the studied karstic terrain sections, the eastern part of the Tés Plateau is on the Tés Plateau, the Homód Valley karst area is in the Hárskút Basin, while the Eleven-Förtés doline group can be found on the Kőris Block. The Mester-Hajag is a block with a small area, its northern part was studied (further on Mester-Hajag Northern karst area), the area next to Fehérkő Valley is the marginal area that was separated from Középső-Hajag and Felső- Hajag by Fehérkő Valley. The last two areas belong to the Hajag mountain group (Figure 3). The eastern part of Tés Plateau is separated into three parts: Tés 1 includes the Tábla Valley, Tés 3 involves its tributary valley, while Tés 2 includes the area between the two areas. The Homód Valley karst area is situated on an epigenetic valley floor at the southern part of Hárskút Basin, Eleven-Förtés is an areic part of Kőris Block.

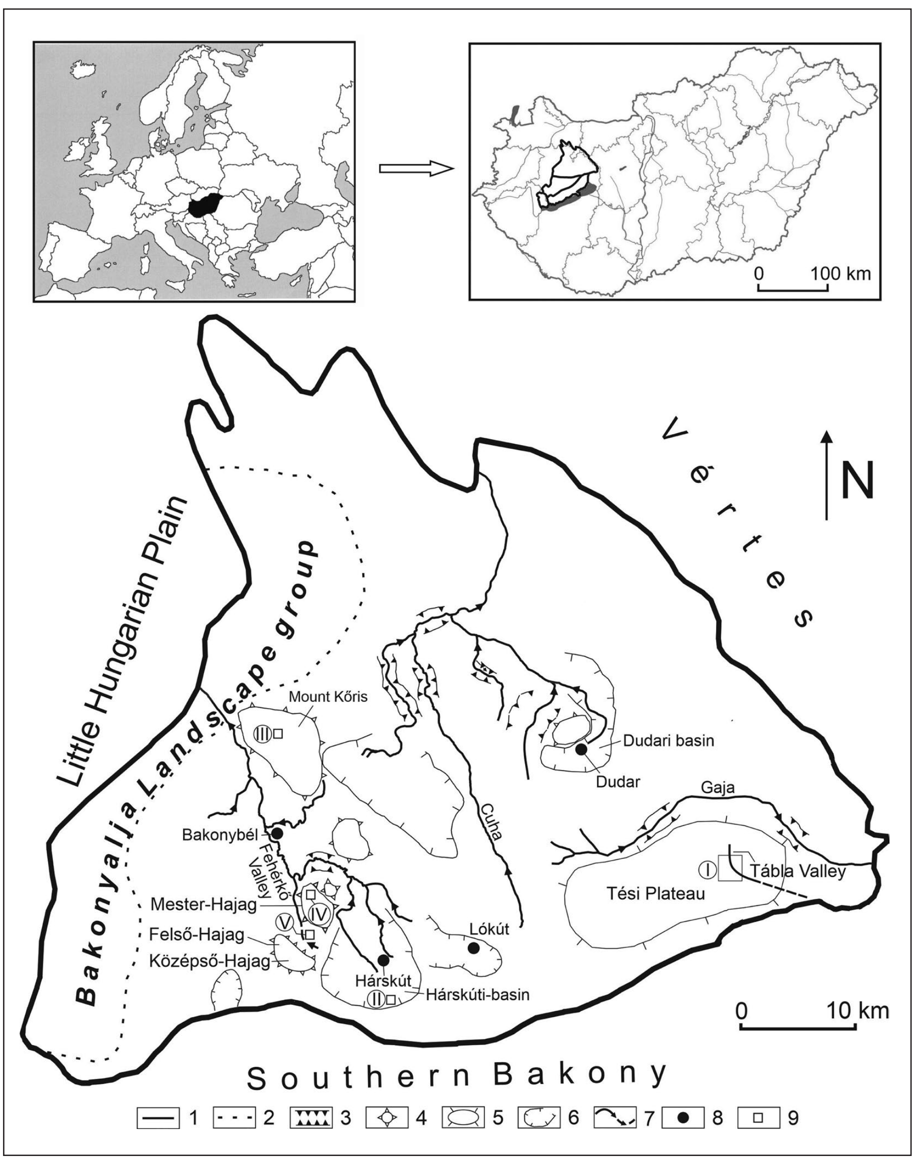


*Figure 3: Research sites. Legend: 1. boundary of the Bakony Region, 2. boundary of the micro region group, 3. gorge, 4. block roof, 5. plateau, 6. basin, 7. stream and its valley, 8. settlement, 9. research site, I. Tábla Valley and its environment, II. Homód Valley, III. Eleven-Förtés, IV. Mester-Hajag North, V. margin of Fehérkő Valley.*

*Table 1: Characteristics of sample sites.*

| Name | expansion ($m^2$) | altitude (m) | rock and morphology of bedrock | morphology | number of subsidence dolines |
|---|---|---|---|---|---|
| eastern part of Tés Plateau, Tés Plateau | 312000 | 440-480 | Jurassic karstified[2] | epigenetic valleys, with subsidence dolines on their floor, some of them are connected by creeks | 19 (137[5]) |
| Homód Valley doline group | 117967 | 430-440 | Middle Eocene, karstified | epigenetic valley floor, some of them are connected by creeks, with several filled subsidence dolines and lake on their floor | 22 |
| Eleven-Förtés doline group | 50000 | 670-680 | Jurassic, karstified[1] | areic area deepening into a flat terrain, its subsidence dolines are mainly on flat terrain, a valley leads to one of them, there are also dolines on its floor, several filled dolines with lakes occur | 9 |
| Mester-Hajag North | 216528 | 470-480 | Upper Cretaceous karstified[3]: some mounds of the bedrock became exposed | terrains covered with superficial deposit between exposed mounds, with small subsidence dolines without creek on the mounds, some dolines occur in more expanded, narrow depressions | 32 (85[6]) |
| area next to Fehérkő Valley | 10053 | 340-360 | Upper Cretaceous weakly karstified[4] | small subsidence dolines aligned in a larger depression which is enclosed by partly exposed mounds | 4 |

[1] mounds and depressions on the bedrock
[2] at Table Valley, valley inheritance also take place in the bedrock
[3] the presently covered bedrock is less karstified (smaller mounds, less deep, more expanded depressions)
[4] depressions on the bedrock
[5] on the entire Tés Plateau
[6] on the entire Mester-Hajag

On the karst areas of Mester-Hajag and Fehér-kő Valley, the terrains between mounds becoming exhumed are karstifying, where the cover has become thin as a result of its denudation.

These karst areas are covered karsts where the cover thickness is predominantly 1-15 m. According to its composition, the cover may be loess (and its clayey and limestone debris variety), clay (limestone debris varieties also occur in this case), limestone debris and sand (mixed with any of the above mentioned rocks) in a smaller expansion. The above superficial deposits are either features of dust waves (loess) or reworked or may have developed by fluvial transport and the dissolution residues of limestone (clay) or they were formed by the physical weathering of the bedrock (limestone debris). Based on the data of VES measurements, the bedrock was karstified and it is dissected by mounds and depressions. Some characteristics of sample areas are presented in Table 1.

## 3. METHODS

Measurements were carried out in the chosen sample areas by the Terratest Ltd. During VES measurement (Veress, 2009), electric current is conducted into the bedrock through two grounded electrodes, other two electrodes measure the potential difference which is created by the current dispersion (Veress, 2009). The dispersion of the current power, the measured potential difference and the calculated apparent specific resistance depend on the specific resistance and the thickness of the beds. Curves can be constructed based on the measured potential difference values considering the distance between the electrodes and thus, with the help of an inverse program, in ideal case the specific resistances and thicknesses of the row of beds can be determined. Measurements were

*Table 2: Specific resistance values in the bedrock in various sample sites of the Bakony Region.*

| area | profile number | number of VES measurement | profile density [profile/ km$^2$] | approximate penetration into the bedrock [m] | average of specific resistance [Ohmm] | shaft | specific length of shafts[1] |
|---|---|---|---|---|---|---|---|
| eastern part of Tés Plateau (Tés Plateau) | 14 | 104 | 0.02 | 3-10 | 315 | 46 | 2.73 (Veress 2019) |
| Homód Valley | 2 | 33 | 0.06 | 4-20 | 303 | 1 | 1.73[2] |
| Eleven-Förtés doline group | 10 | 68 | 0.09 | 5-7 | 611 | 4 | 1.0 |
| Mester-Hajag | 18 | 137 | 0.01 | 3-8 | 1273 | - | - |
| marginal area of Fehérkő Valley | 2 | 17 | 0.005 | 3-7 | 1875 | - | - |

[1] specific shaft length: $\frac{total\ length}{vertical\ depth}$

[2] on the entire area of the plateau

[3] cave of Homód Valley (of the entire karst area, of the Hárskút Basin: 2.04)

carried out along planned and marked, in some cases intersecting lines which went through the subsidence dolines of the studied areas. Geoelectric-geological profiles were constructed with the help of the data of VES measurements situated next to each along a certain direction. On these profiles the quality and the thickness of the cover and the morphology of the bedrock were described taking into consideration the measured specific resistances. The VES measurements penetrating into the bedrock provide information on the extent of cavity, formation of the bedrock and the degree to which the cavities are filled, to the penetration depth. In the case of rocks without cavities and unfilled cavities, the specific resistance of the bedrock is higher than at sites where more cavities occur and these are filled with water or wet sediment. Along the profiles of the latter sites, the specific resistances are lower. The lengths of the profiles were 40-750 m and their number is included in Table 2. A profile comprised 1000-4000 m$^2$. For example, an area of 3800 m$^2$ belonged to the Eleven-Förtés karst area, while an area of 25000 m$^2$ belonged to Tábla Valley 2 area.

The data of three areas (the eastern part of Tési Plateau, Mester-Hajag North, Eleven-Förtés) were studied with the ANOVA method (Falus & Olé, 2008; Fodor, 2022). The karst area of Homód Valley and the marginal karst area of Fehérkő Valley were not included in the study with the ANOVA method due to the small number of cases.

## 4. RESULTS

Specific resistance values were read from the profiles (specific resistances along two profiles are described in Figures 4 and 5 as an example), and the average of these values were calculated by karst areas (Table 2). The minimum and maximum values of specific resistances were chosen by profiles and their average was calculated. The average maximum and average minimum differences were calculated at each studied area. This is called the average largest differences of specific resistances (Table 3).

It was investigated whether the mean values of specific resistances by profiles (the averages of maximum and minimum values) differ significantly from each other. The definitions that were used for the procedure are given in Table 4.

The significance of mean values can be determined if we calculate the F and p values of standard deviation intervals in the studied areas. If $F_{calculated}$ is larger than $F_{critical}$ and p is smaller than 0.05, then the studied data sets differ significantly from each other. In case of the three areas, the average specific resistances along the profile were graphically described (Figure 6) as well as the mean values calculated from specific resistances ($\bar{x}$) and the standard deviation of specific resistances (S). The mean values of the above areas, the averages of mean values ($\bar{x}$), the graphs of mean values and the standard deviation of specific resistances (S) were described in Figure 6.

Bedrock specific resistances are lower (Figure 4), and higher at different profiles (Figure 5). The averages of specific resistance values show significant differences and alternate between wide values, however the different specific resistances are not profile specific, but show significant differences by sample areas. Among the studied areas, the lowest specific resistance average (303 Ohmm) can be detected on the Homód valley karst area, while the highest average (1875 Ohmm) can be found in the karst area near Fehérkő Valley (Table 2).

Based on their specific resistance values, the studied karst areas can be put into two groups. The Homód Valley karst area and the eastern part of Tés Plateau belong to the group with low specific resistance value. The area of Mester-Hajag North and the marginal karst area of Fehérkő Valley are of high specific resistances. The area of the Eleven-Förtés doline group is of transitory specific resistance, but it may rather be put into the former group.

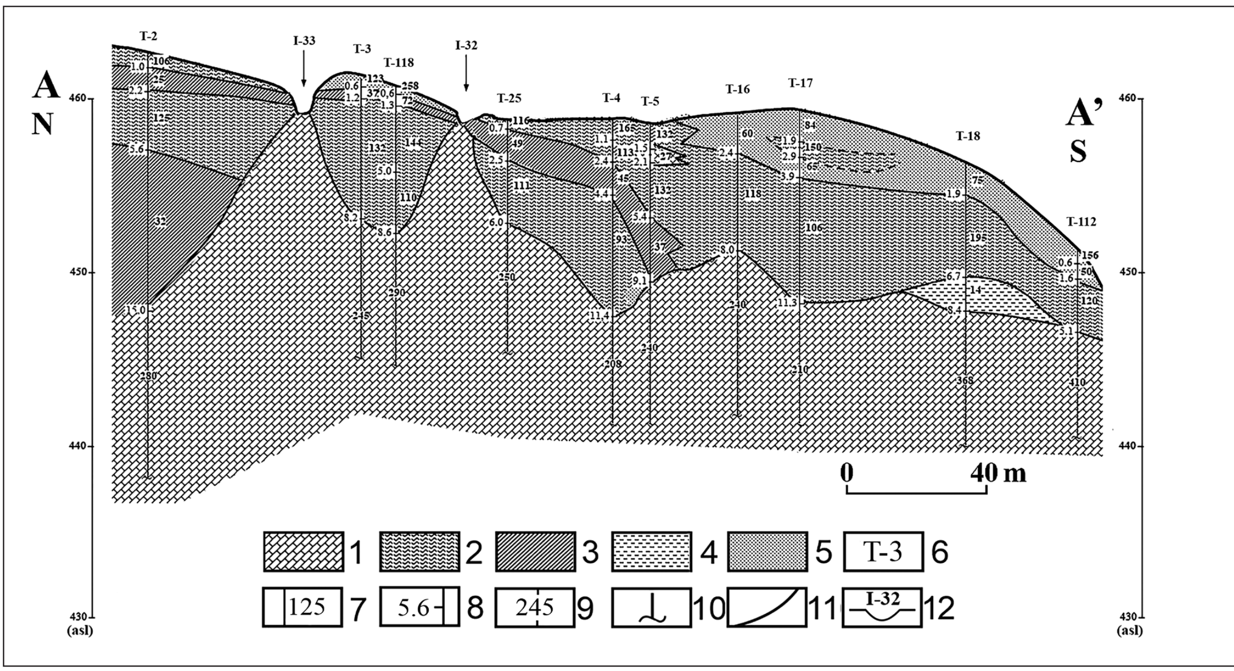


*Figure 4: Geoelectric-geological profile from a bedrock part of low specific resistance (Tábla Valley, Tés Plateau). Legend: 1. limestone, 2. limestone debris (clayey), 3. loess (sandy or with limestone debris), 4. loess (clayey-silty), or clay with limestone debris, 5. clay, 6. number of VES measurement, 7. geoelectric specific resistance of the series (Ohmm), 8. basal depth of the geoelectric series (m), 9. geoelectric specific resistance of the bedrock (Ohmm) 10. approximate penetration of VES measurement, 11. boundary of geoelectric series, 12. code of depression.*

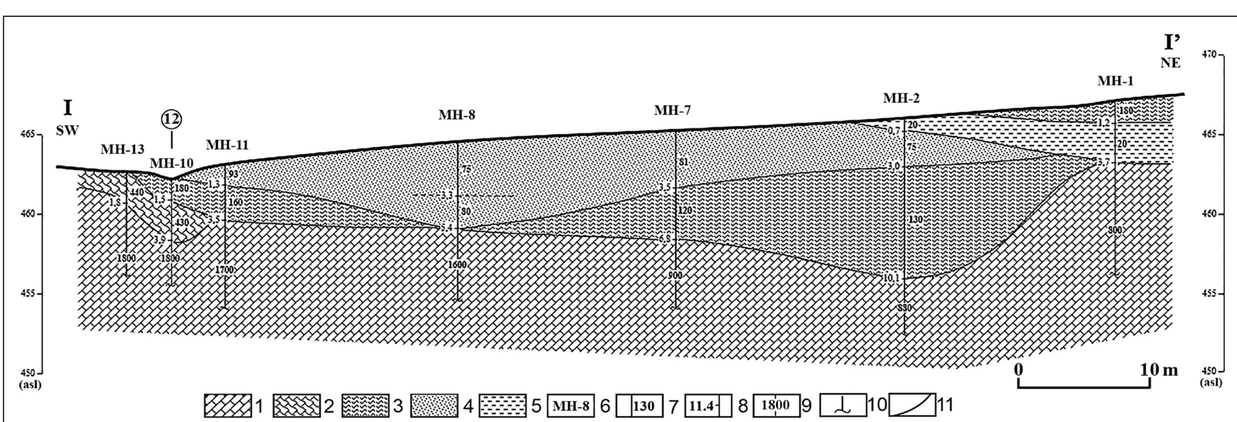


*Figure 5: Geoelectric-geological profile from a bedrock part with high specific resistance (Mester-Hajag). Legend: 1. limestone, 2. limestone debris, 3. limestone debris (clayey), 4. loess (sandy or with limestone debris), 5. clay, 6. number of VES measurement, 7. geoelectric specific resistance of the cover (Ohmm), 8. basal depth of the geoelectric series (m), 9. geoelectric specific resistance of the bedrock (Ohmm), 10. approximate penetration of VES measurement, 11. boundary of geoelectric series, 12. subsidence doline.*

*Table 3: Maximum and minimum differences of bedrock specific average specific resistances in the studied areas.*

| karst area | average maximum | average minimum | difference | profile number | total VES measurements |
|---|---|---|---|---|---|
| Tábla Valley and its environs | 430.5 | 238.5 | 192.1 | 14 | 90 |
| Homód Valley | 470 | 170 | 300 | 2 | 33 |
| Eleven-Förtés | 8810 | 405 | 476 | 10 | 68 |
| Mester-Hajag | 1750 | 911 | 835 | 18 | 137 |
| margin of Fehérkő Valley | 2925 | 740 | 2185 | 2 | 17 |

*Table 4: Theory of variance analysis calculation with the ANOVA method.*

| name of sum of squares | Variance | Degree of freedom | Estimation of standard deviation | F value | p value |
|---|---|---|---|---|---|
| between groups | $\sum_{i=1}^{r} n_i(\bar{x}_i - \bar{x})^2$ | r - 1 | $S_k^2$ | $S_k^2 / S_b^2$ | p |
| within group | $\sum_{i=1}^{r}\sum_{j=1}^{n_i} n_1(x_{ij} - \bar{x}_j)^2$ | n - r | $S_b^2$ | - | - |
| total | $\sum_{i=1}^{r}\sum_{j=1}^{n_i} n_1(x_{ij} - \bar{x})^2$ | n - 1 | - | - | - |

r number of groups
n number of profiles within the group (Mester-Hajag 17; Tés 14; Eleven Förtés 10)
$\bar{x}_i$ mean value of i group calculation
$\bar{x}_{ij}$ j member of i group
$S_k^2$ sums of squares between groups
$S_b^2$ sum of squares within group
p value: j member of i group, at an error of 0.05 with what probability can it be fitted into the standard deviation interval of i+1 group (into +/-S)

*Table 5: A comparison of mean values of the measurements of Mester-Hajag North and the Eastern part of Tés Plateau.*

| Groups | Number of profiles | Sum of measured values | Mean value of measured values | Variance |
|---|---|---|---|---|
| Mester-Hajag North (1) | 17 | 22427.5 | 1319.26 | 86777.94 |
| Eastern part of Tés Plateau (2) | 14 | 4693 | 335.21 | 709.14 |

*Table 6: ANOVA probe results of Mester-Hajag North and the eastern part of Tés Plateau.*

| Factors | $S^2$ | Degree of freedom (n-1) | $\frac{S^2}{n-1}$ | $F_{calculated}$ | P value | $F_{critical}$ |
|---|---|---|---|---|---|---|
| Between groups (1.2) | 7434469 | 1 | 7434469 | 154.25 | 3.91E-13 | 4.18 |
| Within group | 1397666 | 29 | 48195.58 | - | - | - |
| Total | 8832135 | 30 | - | - | - | - |

Since $F_{calculated}$ (194.25) is larger than $F_{critical}$ (4.18) and p value is smaller than 0.05 (0,0062E-13), the mean values of the samples are significantly different.

*Table 7: A comparison of the mean values of Mester-Hajag North, the eastern part of Tés Plateau and Eleven-Förtés.*

| Groups | Number of profiles | Sum of measured values | Mean value of measured values | Variances |
|---|---|---|---|---|
| Mester-Hajag North (1) | 17 | 22427.9 | 1319.26 | 86777.94 |
| Eastern part of Tés Plateau (2) | 14 | 4693 | 335.21 | 709.14 |
| Eleven-Förtés (3) | 10 | 6425 | 64.25 | 20823.61 |

*Table 8: Mester-Hajag North, eastern part of Tés Plateau, Eleven Förtés ANOVA probe.*

| Factors | $S^2$ | degree of freedom (n-1) | $\frac{S^2}{n-1}$ | $F_{calculated}$ | P value | $F_{critical}$ |
|---|---|---|---|---|---|---|
| Between groups (1,2,3) | 7842676.96 | 2 | 3921338.48 | 94.01 | 1.94E-15 | 3.24 |
| Within group | 1585078.41 | 38 | 41712.59 | - | - | - |
| Total | 9427755.37 | 40 | - | - | - | - |

Since $F_{calculated}$ (94.01) is larger than $F_{critical}$ (3.24) and P value is smaller than 0.05 (1.94E-15), the mean values of the samples are significantly different.

It can be established that the average highest specific resistance differences of the studied areas are significantly different. In case of the areas with high specific resistances, the average largest differences are big, while in case of the areas with low specific resistances, the average largest differences are small (Table 3).

The eastern part of Tés Plateau and the northern part of Mester-Hajag are significantly different at p<0.05 random variable level since $F_{calculated}$ is larger than $F_{critical}$ and value p is smaller than 0.05 (Tables 5 and 6). The significant difference can also be established in mean values regarding the eastern part of Tés Plateau, the Mester-Hajag North and Eleven-Förtés since $F_{calculated}$ is larger than $F_{critical}$ and the p value is smaller than 0.05 when the three areas are compared (Tables 7 and 8). In case of these areas, the lower the specific resistance (Figure 6), the smaller its deviation from the mean value ($\bar{x}$) and partially from the standard deviation (S). In case of smaller and smaller averages of mean values ($\bar{x}$), which expresses the absolute value of the specific resistances of the areas, the mean values of certain areas and partly their standard deviation are smaller and smaller (Figure 6). With the decrease of specific resistances, these gather more and more along the line of the average of mean values ($\bar{x}$).

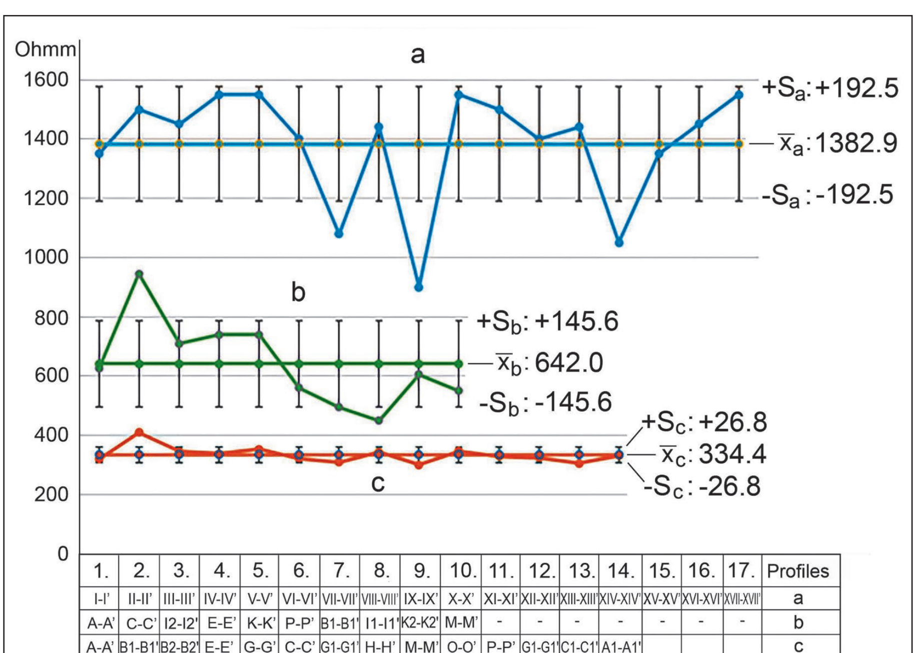


*Figure 6: Average of mean values ($\bar{x}$), graphs of mean values and standard deviations (S) per profiles from the areas of Mester-Hajag North (a), Eleven-Förtés (b) and Tés Plateau East (c).*

## 5. DISCUSSION

The epikarst has not been studied by VES measurements yet. However, the statistical method used for the evaluation of measurements (ANOVA) has not been applied either. The analysis of specific resistances and the statistical analysis are suitable for the objective differentiation or the determination of the similarity of the epikarst of certain areas. By the applied measurement method and the statistical data processing, the epikarst of different karst areas can be compared. To our knowledge, no comparative epikarst studies or no attempts on drawing a parallel between the maturity of the epikarst and surface karstification (the frequency and size of surface karst features) have been made yet. The essence in the relationship between the epikarst and surface karstification (is that there is more water at the level of penetrations in areas of lower specific resistance thus, they were more karstified. Areas of higher specific resistance were karstified to a larger degree (since there is less water at the level of penetrations) because there are no cavities or only some cavities occur in them since there is less water in the epikarst and no piezometric surface occurs either. Since during sounding, electrical penetrations reached the bedrock in a depth of 5-10 m from its surface, the specific resistance provide information on the epikarst of the research sites.

In study areas of high specific resistance which include two karst areas (Table 2), the size of subsidence dolines is small (their diameter and depth does not exceed 1-2 m). The bedrock does not crop out on the floors of dolines in no cases, at most there is a drainage passage (a passage that developed in the karst rock) in the cover of the floor at some of them (Mester-Hajag northern part). The water catchment area of dolines is small (it is often absent), there are no connecting creeks. The significant part of both Mester-Hajag North karst area and Fehérkő Valley marginal karst area have a surface drainage.

The small size of dolines and the absence of bedrock outcrop on the floor refers to low suffosion. This can be traced back to the fact that little water arrives at the dolines, and the sediment receiving capacity of the bedrock is small (high specific resistances refer to the fact that there are small and few cavities in the epikarst). The lack of shafts in the two karst areas also refers to this. However, the low degree of water inflow also indicates that only a small proportion of the cavities of the epikarst is filled with water and washed-in superficial deposit or if they are filled, it is of low degree.

In areas of low specific resistance which also involve two areas (Table 2), the size of subsidence dolines is large (those with a diameter of 5-10 m and deeper than 2 m are frequent). The bedrock often crops out on doline floors and shafts also occur. For example, in the eastern part of Tés Plateau, surface karst is characterised by the followings. There are 19 dolines in the karst area of the eastern part of Tés Plateau. On the floor of 9 dolines, the limestone crops out and there are shafts in case of 8 dolines. The specific shaft length, which is the quotient of the shaft length and the vertical depth, is large (Table 2; Veress, 2019), which refers to a significant degree of cavity formation. The water catchment area of the dolines is large, creeks are often connected to them. Creeks, lakes that developed in depressions during rainfalls refer to intensive water inflows in these karst areas. The karst areas of the eastern part of Tés Plateau and Homód Valley, but also the area of Eleven-Förtés are areic. Thus, the meteoric waters of these areas infiltrate into the karst, which results in significant water surplus in the epikarst.

The large size of dolines, the great degree of water transport refers to significant suffosion, the low specific resistance, the large number of shafts and the high average specific shaft length indicate a significant degree of cavity formation particularly on Tés Plateau. Here, there are 6 shafts, the depth of which exceeds 50 m, but the average shaft depth is also 30.13 m (Veress, 2019). The high degree of shaft frequency and their large depth also refer to the maturity of the epikarst and according to Klimchouk's classification (2004) it is in the old epikarst phase regarding its maturity. Intensive infiltration increases the chance of the filling of cavities with water, while intensive suffosion results in a higher chance of the filling of the cavities with sediment at the epikarst of the area.

Figure 7 describes the interpretation of the relationship between different specific resistances and the maturity of the epikarst.

In the karst area of Mester-Hajag North and Fehérkő Valley marginal karst areas which are of high specific resistance, the quantity of waterless (dry), but unfilled cavities is large as compared to the proportion of cavities filled with water as well as to cavities which are waterless, but filled with sediment (Figure 7a). The reason for this is that because of lower water level, there are less cavities with water, but more dry cavities. This is caused by surface infiltration of lower degree, but less water arrives at the bedrock too because there are fewer cavities opening to the bedrock surface as a result of a lower degree of cavity formation. However, it is also contributed by the fact that in narrower (smaller) cavities, the degree of water level subsidence is higher even in case of the same quantity of water drainage than at wider cavities. The presence of cavities without superficial deposit is the result of suffosion of lower degree.

The eastern part of Tés Plateau and the Homód Valley karst areas which are of low specific resistance, the

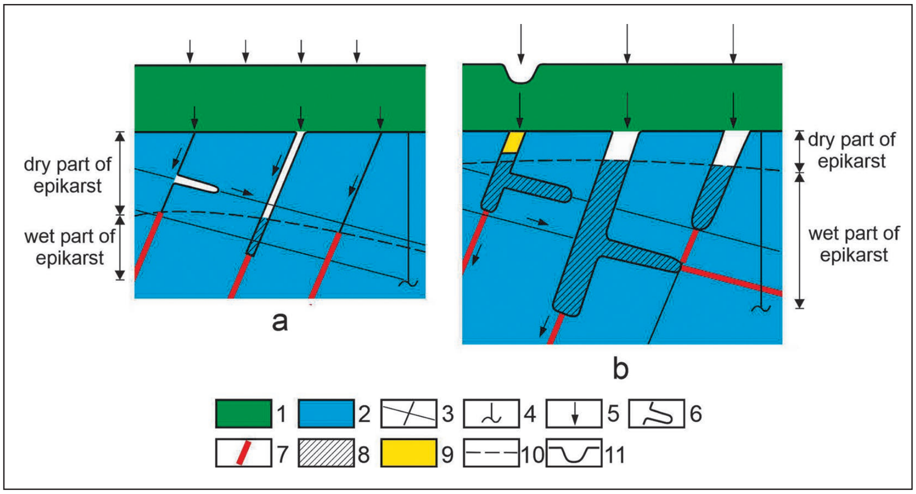


*Figure 7: Models of immature (a) and more mature (b) epikarst. Legend: 1. caprock, 2. bedrock, 3. fracture, bedding plane, 4. approximate penetration of VES measurement, 5. water motion, 6. cavities, 7. water along the fractures and on the rock surfaces that border the bedding planes, 8. cavity parts that are filled with water, 9. cavity part filled with washed-in sediment, 10. piezometric surface, 11. doline.*

proportion of cavities of the bedrock which are filled with water is larger than that of dry cavities, and also the proportion of dry, but filled cavities is larger as compared to that of unfilled cavities (Figure 7b). This can be explained by the fact that because of the infiltration with larger degree and thus, due to the effect of more elevated water level, the number of cavities with water increases and the number of dry cavities decreases. However, another reason is that in wider cavities, the degree of water level decrease is lower than at narrower cavities even in case of the same degree of drainage. The degree to which dry cavities are filled increases due to a larger degree of suffusion (Figure 7b). The absolute value of specific resistances and the average of mean values ($\bar{x}$) refer to the degree and state of cavity formation, while the mean value and the standard deviation indicate the expansion of the degree of cavity formation. In case of areas with low specific resistances and in case of low averages of mean values ($\bar{x}$), the degree of cavity formation is larger, while if the mean values and the standard deviation show a smaller difference from the average of mean values (), the degree of cavity formation is evener.

The epikarst of more karstified areas has more cavities and is more mature (Tés Plateau and its environs, Homód Valley). The epikarst of less karstified areas has less cavities and is less mature (Mester-Hajag North and Fehérkő Valley marginal area). A direct evidence for the degree of cavity formation of areas with high and low specific resistances is the different number of shafts and different specific shaft lengths. Different degree of cavity formation results in different doline frequency. Thus, for example in the area of Homód Valley, doline density is 0.6889 dolines/100 m$^2$ due to the mature epikarst, while this value is only 0,0339 dolines /100 m$^2$ in the area of Mester Hajag North which has a little quantity of water supply.

In the area of Eleven-Förtés, although there is complete lack of surface runoff, specific resistance is higher than in the eastern part of Tés Plateau and in the area of Homód Valley. This is an evidence for the fact that water supply of high degree is not a sufficient condition for the development of low specific resistances of the bedrock. The different development age and different development rate of the epikarst may contribute to different specific resistances. Different development rate may be increased by the different degree of primary porosity (for example fracture density or the type of fractures).

Different surface denudation may contribute to the development or activation of the epikarst with different duration. Mester-Hajag North and Fehérkő Valley marginal karst areas are enclosed and bordered by valleys. In these areas, karstification may have become active by the thinning out of superficial deposits that took place during their partial transportation. Here, the present epikarst and may have developed from an inactive epikarst preceding covering following a longer development break. However, in the karst area of the eastern part of the Tés Plateau and the karst area of Homód Valley, the thinning out of the cover is less intensive due to arheism (which did gradually develop by the already beginning karstification). Thinning out is local under the dolines because the superficial deposit is transported into the karst. Therefore, in the latter areas, the activation of former epikarst (paleoepikarst) began earlier or it did not reach an inactive state at all.

Average largest differences indicate anomalies of the epikarst zone. In case of great differences, there are significant differences in the degree of cavity formation and filling of the epikarst, while in case of small differences, the epikarst is more uniform. This value is the lowest in the eastern part of the Tés Plateau in spite of the fact that (while average specific resistance is the lowest in the

Homód Valley area) although shafts separated the epikarst into parts, they were not able to change the uniform image of the epikarst. All in all, it can be established that in case of mature epikarst with several cavities, the average largest differences are small. In other words, during its development, the epikarst is more and more uniform even if it is separated into parts regarding its area. Even the subsidence dolines that were formed in the cover are not able to change it probably because their effect (water surplus, sediment transportation) prevails not only directly below them, but also in their environs. The relatively great difference value occurring at Homód Valley is notable. This refers to the fact that although the epikarst also receives a lot of water here, it is not as uniform as in the area of the eastern part of the Tés Plateau thus, it does not reach its maturity.

The epikarst of the studied areas can be put into a development order based on the different degree of coveredness and on the exposure and infiltration that trigger coveredness as follows: Fehérkő Valley marginal area, Mester-Hajag North, Eleven-Förtés, Homód Valley area, and the eastern part of Tés Plateau.

## 6. CONCLUSIONS

The epikarsts of various karst areas may be significantly different on the same karst (Bakony Region) since the epikarst of karst areas became differentiated during karstification. The epikarst of certain karst areas could stay in the early phase of its development, while the epikarst of other areas may reach a more mature stage. The epikarst of karst areas of lower specific resistance has more cavities, but at the same time these cavities may be filled to a larger degree, and surface karstification is more intensive. During its development, the epikarst has a more and more uniform face. Taking into consideration the different specific resistances and their statistical characteristics, the epikarst of the studied areas can be put into a development order. The specific resistance of the epikarst of more karstified areas is lower, which can be traced back to the fact that during its penetration, the VES measurement reaches the piezometric surface. Thus, the areas with a greater degree of karstification have more cavities and the piezometric surface is of higher elevation. In areas which were karstified to a lesser degree, the epikarst has less cavities and the piezometric surface is below the penetration depth of VES measurements or the epikarst is without water fill.

Different maturity can be traced back to the fact that the epikarst of different part areas had different development onset, the epikarst sections became active differently, and the development rate of epikarst parts was also different. The former can be explained by different exposure, the latter by different water supply, but the different primary porosity of certain areas may also contribute to this. Different water supply is controlled by surface runoff conditions and the composition of the cover.

Since in the area of Homód Valley, where the specific resistance is a bit lower than in the eastern part of Tés Plateau, low specific resistance values do not necessarily coincide with the abundance and maturity of features which directly represent karstification (for example the number of shafts is much higher on the Tés Plateau than in the area of Homód Valley. This refers to the fact that the average highest specific resistance values, which are lower on Tés Plateau than in the area of Homód Valley better describe the maturity of the epikarst of the karst than the average values of specific resistances.

## REFERENCES

Bakalowicz, M., 2005. A challenge for new resources. Hydrogeology Journal, 13(1): 148-160. https://doi.org/10.1007/510040-004-0402-9

Bakalowicz, M., 2019. Epikarst. In: White, W.B., Culver, D.C., Pipan, T. (Eds.), Encyclopedia of Caves, pp. 394-398.

Bakalowicz, M., Blavoux, B., Mangin, A., 1974. Apports du traçage isotopique naturel à la connaissance du fonctionnement d'un système karstique. Teneurs en oxygène 18 de trois systèmes des Pyrénées, France. Journal of Hydrology, 23: 141-158.

Bíró, B., 1969. A Halimbai és Nyírádi bauxit előfordulások karsztos fekvője (The karstic bedrock of bauxite occurrences of Halimba and Nyírád). Bull. of the Hungarian Geol. Soc., 99: 98-204. (in Hungarian)

Bulla, B., 1968. A magyar föld domborzata fejlődésének ritmusai, az újharmadkor óta a korszerű geomorfológiai szemlélet megvilágításában (The phases of the Terrain Development of Hungary since the Lower Tertiary in perspective of the modern geomorphological view). Válogatott természeti földrajzi tanulmányok, Akadémia Kiadó, Budapest: 90-104. (in Hungarian)

Császár, G., Csereklei, E., Gyalog, L., 1981. A Bakony-hegység földtani térképe (szerk.) (Geological map of the Bakony Mountains). Magyar Állami Földtani Intézet, Budapest (in Hungarian)

De Waele, J., Gutierrez, F., 2022. Karst Hydrogeology, geomorphology, and caves. John Wiley & Sons Ltd, 912 pp. https://doi.org/10.1002/9781119605379

Falus, I., Olé, J., 2008. Az empirikus kutatások gyakorlata. (The practical aspects of empirical research, data processing, and statistical analysis). Adatfeldolgozás és Statisztikai elemzés. Nemzeti Tankönyvkiadó, Budapest, pp. 285-288. (in Hungarian)

Fodor, B,. 2022. docplayer.hu/42491756-Kiserlettervezesi alapfogalmak-varianciaelemzes-analysis-of-variance-anova.html [Accessed 18 November 2022].

Jaskó, S., 1961. A balatonfelvidéki és északbakonyi patakok vízhozamának kapcsolata a földtani felépítéssel (The relation of discharge of the streams of Balaton Highlands and Northern Bakony with geological structure). Hidrológiai Közlöny, 41(1): 75-84. (in Hungarian)

Jones, W.K., 2013. Physical Structure of the Epikarst. Acta Carsologica, 42 (2-3): 311-314. https://doi.org/10.3986/ac.v42i2-3.672

Kercsmár, Z., Selmeczi, I., Budai, T., Less, G., Konrád, G., 2022. Geology of the Karst Terrains in Hungary. In: Veress, M., Leél-Őssy, S. (Eds.), Cave and Karst Systems of Hungary. Cave and Karst Systems of the World. Springer, Cham, pp. 63-116. https://doi.org/10.1007/978-3-030-92960-2_4

Klimchouk, A.B., 1987. Conditions and peculiarities of karstification into near surface zone of carbonaceous massives. Caves of Georgia, 11: 54-65. (Russian with English summary).

Klimchouk, A.B., 2004. Towards defining, delimiting and classifying epikarst: its origin, processes and variants of geomorphic evolution. In: Jones, W.K., Culver, D.C., Herman, J.S. (Eds.), Epikarst. Special Publication 9, Karst Waters Institute, Charles Town, WV, pp. 23-35.

Korpás, L., 1981. A Dunántúli-középhegység oligocén-alsó-miocén képződményei (Oligocene-Lower Miocene features of the Transdanubian Mountains). MÁFI Évkönyve 64, 142 pp. (in Hungarian)

Mangin, A., 1975. Contribution a l'etude hydrodynamique des aquiferes karstiques. Univ. Dijon These Doct. es. Sci. [Annales et Speleologie, 29(3): 283-332; 29(4): 495-601, 1974; 30(1): 21-124, 1975.]

Mindszenty, A., Sebe, K., 2022. Paleokarst in Hungary. In: Veress, M., Leél-Őssy, S. (Eds.), Cave and Karst Systems of Hungary. Cave and Karst Systems of the World. Springer, Cham. https://doi.org/10.1007/978-3-030-92960-2_5

Palmer, A.N., 2004. Growth and modification of epikarst. In: Jones, W.K., Culver, D.C., Herman, J.S. (Eds.), Epikarst. Special Publication 9, Karst Waters Institute, Charles Town, WV, pp. 56-61.

Pécsi, M., 1963. Hegylábi (pediment) felszínek a magyarországi középhegységekben (Pediment Surfaces in Hungarian Central Mountains). Földrajzi Közlemények 11(3): 195-212. (in Hungarian)

Pécsi, M., 1970. Surfaces planation in the Hungarian Mountains and their relevance pedimentation. Akadémia Kiadó, Budapest. Studies in Geography in Hungary, 8: 29-40.

Pécsi, M., 1980. A Pannóniái-medence morfogenetikája (The Morphogenesis of the Pannonian basin). Földrajzi Értesítő, 29: 105-127. (in Hungarian)

Pécsi, M., 1991. Geomorfológia és domborzatminősítés. (Geomorphology and relief classification). Földrajz Tudományi Kutató Intézet, Budapest, pp. 296. (in Hungarian)

Szabó, P., 1956. Magyarországi karsztformák klímatörténeti vonatkozásai (Relations between climate and karst features in Hungary). Földrajzi Közlemények, 80: 183-189. (in Hungarian)

Szabó, P.Z., 1968. A magyarországi karsztosodás fejlődéstörténeti vázlata (An evolutionary outline of Hungarian karstification). Dunántúli Tud. Gyűjtemény, 80: 13-25. (in Hungarian)

Tobin, B.W., Polk, J.S., Arpin, S.M., Shelley, A., Taylor, C., 2021. A conceptual model of epikarst processes across sites, seasons, and storm events. Journal of Hydrology, 596: 1-12. https://doi.org/10.1016/j.jhydrol.2020.125692.

Veress, M., 2009. Investigation of covered karst form development using geophysical measurements. Zeitschrift für Geomorphologie N.F., 53(4): 469–486. DOI: 10.1127/0372-8854/2009/0053-0469

Veress, M., 2019. Shaft Lengths and Shaft Development Types in the Vadose Zone of the Bakony Region (Transdanubian Mountains, Hungary). Journal of Soil and Water Science, 3(1): 167-186.

Veress, M., 2022. The surface morphology of karsts in Hungary. In: Veress, M., Leél-Őssy, S. (Eds.), Cave and Karst Systems of Hungary. Cave and Karst Systems of the World. Springer, Cham, pp. 179-247. DOI:10.1007/978-3-030-92960-2_8

Williams, P. W., 1972. Morphometric analysis of polygo-

nal karst in New Guinea. Geol. Soc. of America Bulletin.
Williams, P. W., 1983. The role of the subcutaneous zone in karst hydrology. Journal of Hydrology, 61: 45-67. https://doi.org/10.1016/0022-1694(83)90234-2
Williams, P.W., 1985. Subcutaneous hydrology and the development of doline and cockpit karst. Zeitschrift für Geomorphologie, 29(4): 463-482.
Williams, P.W., 2008. The role of the epikarst in karst and cave hydrogeology. A review. International Journal of Speleology, 37(1): https://doi.org/10.5038/1827-806X.37.1.1