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Spatial Analysis in Karst Geomorphology: An Example from Krk Island, Croatia

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Spatial Analysis in Karst Geomorphology: An Example from Krk Island, Croatia

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Supervisors' Foreword

Karst geomorphology as a science of the surface, and speleology as a science of the underground, has developed rather independently as individual spheres driven by different mechanisms and characterized by different features. The concept of surface denudation was the breakthrough that induced the integration of underground features onto the karst surface. Only then, the essence of the karst system's three dimensionality has been fully adopted, bringing numerous new insights into the concepts deeply rooted in the traditional karst geomorphology.

This thesis is a comprehensive research of karst surface founded on such a new perception of a karst system. It is based on a large data set of the variety of karst surface features acquired remotely and supported by the extensive fieldwork. The research employs contemporary GIS techniques and modern approaches in spatial analysis, yet it is aware of their limitations. Karst surface features had been discussed in the context of local environmental settings, comprising the detailed overview on geological, geomorphological, hydrological, speleological and climatological data of the study site. Morphometric and distributive analyses have served as a tool for classification of surface features, some of them being fully discussed or even recognized for the first time.

This study is the first comprehensive, yet detailed investigation of the karst surface of Krk Island in Croatia. It gives insights into the local karst surface features, processes and overall evolution of the karst surface in the study area. More importantly, it presents a methodological example of the holistic approach in karst geomorphology that can be adopted in the research of any karst landscape. Finally, the most valuable outcome of this thesis that concerns karst geomorphology on a global scale is the discussion on the principles valid in modern research, as well as a presentation of yet undefined karst surface features.

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Rijeka, Croatia — Prof. Emerit. Dr. Čedomir Benac
September 2020

Abstract

The intriguing spatial variability of surface features on Krk Island has stimulated the research of this karst area located in the coastal zone of the Dinaric karst in Croatia. Field inspection, orthorectified aerial photos (0.5 m resolution) and a topographic map (1:5000) were used for the detection and delineation of karst surface features appearing on the island with the area of 405.5 km^2. This method resulted in the identification of several yet undefined types of surface features occurring on karst, requiring the revision of the existing classification and re-establishment of a new classification system compatible with the particular field reality. Several morphologic and distributive parameters that had been calculated for each reclassified type of surface feature provided insight into the surface features elementary characteristics, their spatial variability and the correlation to the other types of surface features and to the recent karst relief. This analysis based on a large, accurate data set, contributed to the general knowledge on karst surface features, the conditions of surface features in Dinaric karst and to the understanding of the karst surface evolution on Krk Island.

Keywords Karst geomorphology · GIS · Spatial analysis · Krk Island · Dinaric karst · Adriatic Sea

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- ŠEGINA, Ela, BENAC, Čedomir, RUBINIĆ, Josip, KNEZ, Martin. Morphometric analyses of dolines: the problem of delineation and calculation of basic parameters. Acta Carsologica, 2018, 47/1, 23–33. https://doi.org/10.3986/ac.v47i1.4941
- ČERU, Teja, ŠEGINA, Ela, KNEZ, Martin, BENAC, Čedomir, GOSAR, Andrej. Detecting and characterising unroofed caves by ground penetrating radar. Geomorphology: an international journal of pure and applied geomorphology, 2018, 303, 524–539. https://doi.org/10.1016/j.geomorph.2017.11.004
- ČERU, Teja, ŠEGINA, Ela, GOSAR, Andrej. Geomorphological dating of pleistocene conglomerates in Central Slovenia based on spatial analyses of dolines using LiDAR and ground penetrating radar. Remote sensing, 2017, 9/12, 1–23. https://doi.org/10.3390/rs9121213
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- ČERU, Teja, ŠEGINA, Ela, KNEZ, Martin, BENAC, Čedomir, GOSAR, Andrej. Možnosti in omejitve metode nizkofrekvenčnega georadarja za raziskavo kraških pojavov - primer meritev na otoku Krku. In: ROŽIČ, Boštjan (ed.). Treatises, reports, 22nd Meeting of Slovenian Geologists, Ljubljana, November 2015, (Geološki zbornik, 23). Ljubljana: Univerza v Ljubljani, Naravoslovnotehniška fakulteta, Oddelek za geologijo, 2015, 30–34.
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Introduction

The karst surface duality on Krk Island was first exposed in the study published by Benac et al. (2013). They noticed the exclusive occurrence of karst depressions in one and abandoned surface streams in the other karst areas. This peculiar spatial heterogeneity of surface features was the starting point for the present research. The main idea was to implement spatial analysis accessible by the modern computer-based programs to the entire karst surface to reveal the variability of karstification conditions, processes or mechanisms that may have contributed to the geomorphic heterogeneity. Even though the approach seemed straightforward, three main problems arose:

(i) lack of clear definitions of karst surface features,
(ii) unknown reliability of detecting and delineating karst surface features and
(iii) presence of surface features with linear geometry in relatively pure karst conditions.

Wandering around the field, practical questions such as: is this topographically unclosed depression also a doline? or: is the edge of this depression here or there? or: how to classify this linear depression? revealed numerous inconsequentialities of theoretical background in karst geomorphology, as well as the deficiencies of methodological approaches, applied so far. The critical use of spatial analysis and the importance of the quality and consistency of input data are stressed out in the first part of this study. Here, the methodological deficiencies in obtaining and processing spatial data in karst geomorphology are discussed, and several new approaches are introduced to overcome these obstacles. An overview of regional settings of the study area, enriched by the supplementary investigations that filled up numerous gaps in so far existing knowledge on Krk Island, is presented in Chap. 1 as well.

Chapter 2 is dedicated to the theoretical background of karst surface geomorphology; to the discussion on reliability, stability and exactness of starting points that are valid in the modern karst research. Rather than searching for surface features that would satisfactorily fit into the traditional classifications, I created a suitable classification after identifying all the existing varieties of surface features.

Based on current knowledge, induced by the new opportunities that modern high-resolution technology provides, and inspired by the discussions with Prof. dr. France Šušteršič, I created a new classification of karst surface features. I discussed and placed in the existent karst context the overlooked and up to now barely discussed linear surface features occurring in relatively pure karst conditions. By fieldwork and examination of several data sources as a topographic map, digital orthophotography and digital terrain model, a great number of surface features have been noted: some were clearly defined; some were classified based on the similarities to the proved features, and some remained noticed but undefined. The current karstological knowledge cannot explain their appearance, yet their existence cannot be denied. Such are large-scale karst surface features that were detected by the manipulation of the 3-D spatial data and up to now remained unnoticed in the global karst research.

The results of spatial analysis, including numerous morphologic and distributive parameters calculated for both circular and linear surface features of all dimensions, are presented in Chap. 3. Spatial data were processed by the existent algorithms built in the *ArcGIS Desktop 10.2* software.

In Chap. 4 of the present thesis, the results of spatial analysis are interpreted and put in the spatial and temporal context of the study site, contributing to the understanding of karst evolution on Krk Island and in wider Dinaric area. The intriguing topics that were revealed during the research are discussed in Chap. 5 and the last chapter of this study. They offer numerous starting points for further research.

The main prospects of this study are:

(i) to recognize morphologic and distributive characteristics of surface features on the study site,
(ii) to understand the nature of their spatial variability,
(iii) to reveal the conditions, processes and mechanisms that may have induced such spatial variability and
(iv) to contribute to the understanding of the evolution of karst on Krk Island.

Contents

Chapter 1
Study Area and Methods

Abstract Krk Island is one of the largest Croatian islands, occupying an area of 405.5 km^2.

1.1 Natural Characteristics of Krk Island

Krk Island is one of the largest Croatian islands, occupying an area of 405.5 km^2. It is located in the northern Adriatic Sea between the Istria peninsula and the Vinodol coast, and together with the neighbouring islands of Cres, Lošinj, Rab, Pag and several other small islands constitutes the Kvarner area (Fig. 1.1).

1.1.1 Lithostratigraphy of Bedrock

Detailed geological inventory of Krk Island was registered between 1969 and 1970 during the Yugoslavia state field survey. Krk Island is presented on three sheets of the geological map at scale 1:100,000: Crikvenica [1], Rab [2] and Labin [3]. Due to inconsistency induced by several survey campaigns of different authors, generalized and verified geological data after Velić and Vlahović [4] and Benac et al. [5] were mostly applied in spatial analyses of this study (Fig. 1.2).

Krk Island is located on over 4-km-thick carbonate bedrock [1]. The oldest exposed rocks are several hundred meters thick Lower Cretaceous (Albian) limestones and dolomites that form cores of large anticlines in the central and western parts of the island [1]. They are characterized by thin-layered mudstones, peloid packstones to grainstones, with rare occurrences of thin layers of emersion breccias [5]. They are overlaid by Albian–Cenomanian dolomites and diagenetic breccias occurring in minor outcrops [1, 3]. Most of the island is built of over 200 m tick Upper Cretaceous (Cenomanian) carbonates containing rudists and index foraminifera [6–8]. These bright limestones, almost white in colour are often recrystallized and thickly bedded (60–120 cm), and belong to mudstones, foraminiferal bioclasts, intraclast grainstones and rudist bioclast floatstones [5]. Paleogene foraminiferal limestones

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Fig. 1.1 Kvarner area and location of Krk Island

and siliciclastic rocks mainly occupy the major syncline structure crossing the entire island from Omišalj to Baška. Short and narrow stretches of both units are also found related to other minor synclines, namely along the eastern and western coasts of the island and in Stara Baška in the SW [1, 2]. Small outcrops also appear in isolated zones over the entire island. They are preserved inside larger karst depressions or compressed within the tectonic structures. The lower part of the foraminiferal limestones consists of mudstones and wackestones. Packstones prevail in the upper part of the limestones [9].

Eocene siliciclastic rocks consist of marls in the lower part and flysch on top. The thickness of the siliciclastic rocks spatially varies. It increases from the north (320 m) [6] to the south (750 m) [8]. According to the borehole data, the thickness of recently exposed siliciclastic rocks in the main syncline extending from Omišalj to Baška varies from approximately 35 m in the centre [10, 11] to 118 m in the south of the island [12].

Oligocene–Miocene carbonate breccias overlay Cretaceous and Paleogene rocks in the SW and W. They are presumed to be a part of the Jelar formation [5, 9] linked to the late-orogenic uplift of the Mt. Velebit anticline [13]. Depressions have been filled by the Quaternary deposits of fluvial, colluvial and lacustrine origin [1–3]. Borehole drilling revealed over 60 m of Quaternary deposits in the bottom of Ponikve [14]. Pleistocene breccias and brecciocongolomerates are preserved in the

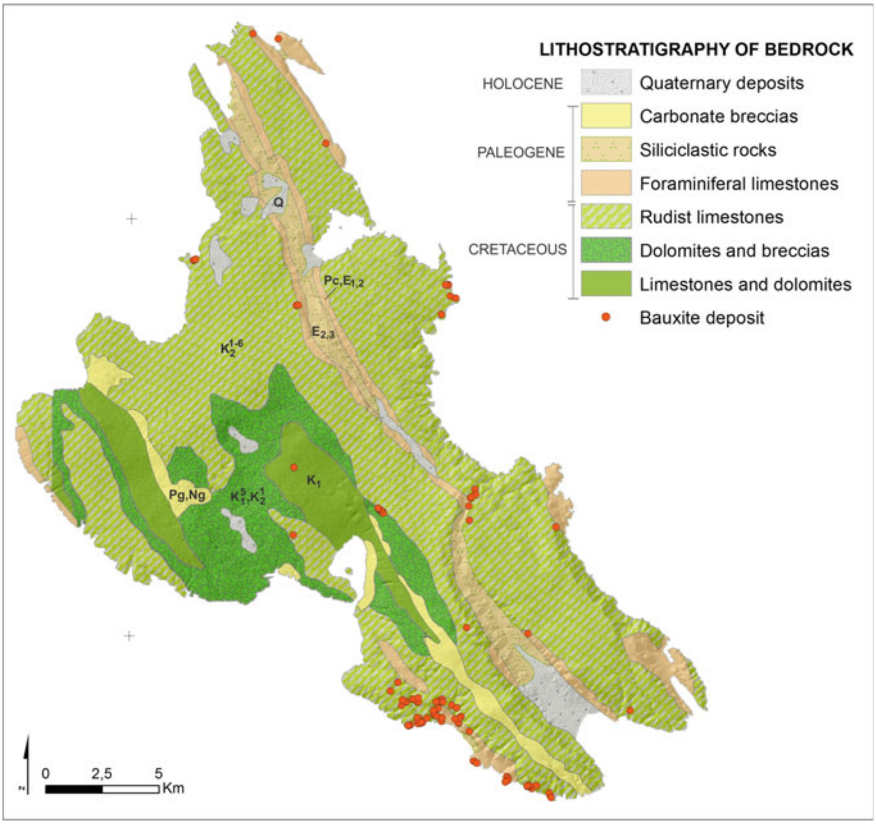


Fig. 1.2 Lithostratigraphical map of Krk Island according to Velić and Vlahović [4] and Benac et al. [5]. Bauxite deposits after Šušnjar et al. [1], Mamužić et al. [2], and field inspection

major syncline Omišalj-Baška [15] and in the minor syncline Stara Baška [15–17]. They are deposited on flysch and marls that are filling both syncline structures. Isolated outcrops of Quaternary breccias are preserved on the flanks and in the floors of abandoned surface streams.

1.1.1.1 $CaCo_3$ Content in Rock Samples

The dissolution rate of carbonate rock generally decreases with the increase of impurities in carbonate rocks [18]. The highest limit of insoluble content for worth karstification has been estimated to 20–30%. However, the purity of carbonate rocks is only one among lithological, and the lithology is only one among the geological factors that control the rock liability to the karstification factors [19]. Other characteristics as type and degree of carbonate rock fissuring [20] can prevail over rock purity and mask its influence in the process of dissolution.

The results of complexometric titration indicate very high and uniform $CaCO_3$ content in all lithostratigraphic units outcropping on Krk Island. Negligible differences prevent evaluation of the possible correlation between $CaCO_3$ content and distribution, size or shape of karst features (Table 1.1).

New data on $CaCO_3$ content for all lithostratigraphic units on Krk Island improve the data from state geological mapping of Yugoslavia in 1969 and 1970 [1, 2, 3] (Fig. 1.3).

Concerning lithostratigraphic properties of rock in the context of karstification, it is important to stress (i) high and uniform $CaCO_3$ content characteristic for all exposed lithostratigraphic units, and (ii) the occurrence and the duration of terrestrial phases inducing karstification processes. The sedimentation in the study area has been interrupted by two fairly long terrestrial periods (Fig. 1.4).

Nearly 20 Ma long terrestrial period is presumed to exist between the Cretaceous and Paleogene. Since the Eocene up to the present, the approximately 35 Ma long terrestrial period occupying the entire Krk Island enabled the deposition of fluvial, colluvial and lacustrine sediments. For fairly long periods, the carbonate rocks of high purity were exposed to the sub-aerial conditions and subject to the processes of karstification.

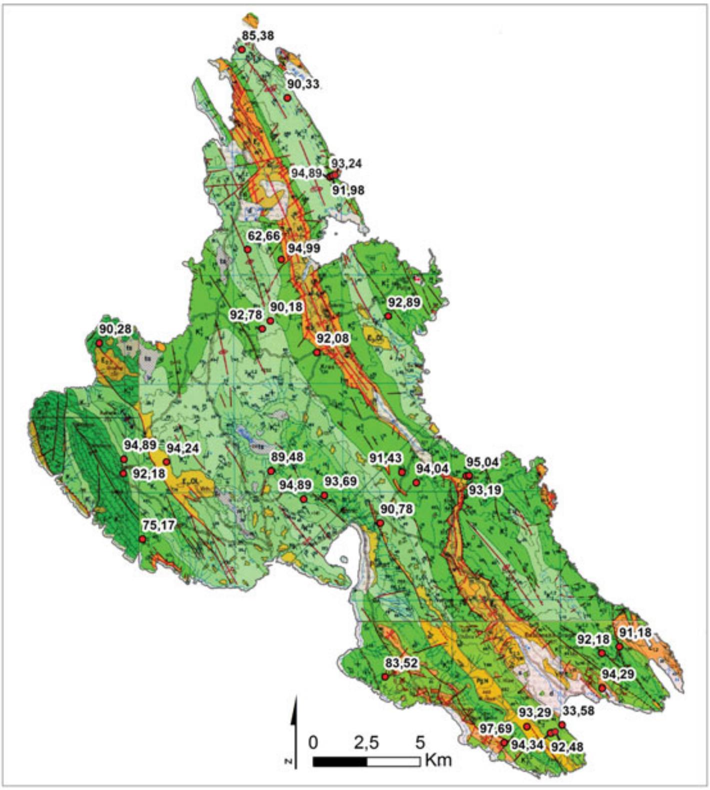
1.1.2 Tectonics

Krk Island is a part of the External Dinarides with the major orographic axis and geological structures of the Dinaric strike (NW–SE to NNW-SSE) [4, 21] (Fig. 1.5). Its early tectogenesis is related to the subduction of the Adriatic carbonate platform beneath the Dinaric during the Paleogene and Neogene [22].

During the larger part of the Jurassic and Cretaceous, the area of Krk Island was a part of the Adriatic carbonate platform. Platform disintegration was initiated in the Cenomanian, when Krk Island emerged and remained under terrestrial conditions until the start of a new marine transgression in the Paleogene [23]. Intense younger tectonic movements destroyed most of older structural forms but based on preserved Cretaceous structures in neighbouring Istria [24, 25], it is presumed that compressional tectonic stress with similar orientation (WNW–ESE) also affected the area of Krk Island [5]. However, the folding structures in the Cretaceous rocks were formed before the deposition of the Paleocene–Eocene sediments which is evidenced in the numerous erosive remnants of flysch that are angular-discordant to the Cretaceous rocks of various ages (Čar [26]). During the Eocene, wide basins were formed under the influence of the regional stress of NE-SW orientation [27]. Uplift and re-working of sedimentary masses originating from the Internal Dinarides provided sources of clastic deposits that were deposited in such basins during the Paleocene and Eocene [13]. In the Pliocene, the tectonic phase finished with the orogenic uplift of Dinarides [28]. The major structures on Krk Island originated from this phase and are characterized by the Dinaric strike (NW–SE) [1–3]. The dominant NW–SE strike has been disturbed by younger diagonal and transverse strike-slip faults during the Pliocene

Table. 1.1 $CaCO_3$ content of samples from Krk Island analysed in Chemical Analytical Laboratory of the ZRC SAZU Karst Research Institute, Postojna. See Sect. 1.4.4.1 for details on methodology

Sample id	$CaCO_3$ (%)	Lithostratigraphic unit
27	93.29	Eocene–Oligocene carbonate breccias
30	33.58	Paleogene marls
33	91.18	Paleogene Foraminiferal limestones
10	92.08	Paleogene Foraminiferal limestones
5	93.24	Paleogene Foraminiferal limestones
16	89.48	Upper Cretaceous limestones and dolomites
24	90.78	Upper Cretaceous limestones and dolomites
15	94.24	Upper Cretaceous limestones and dolomites
13	94.89	Upper Cretaceous limestones and dolomites
17	94.89	Upper Cretaceous limestones and dolomites
6	62.66	Upper Cretaceous limestones
23	75.17	Upper Cretaceous limestones
25	83.53	Upper Cretaceous limestones
1	85.38	Upper Cretaceous limestones
9	90.18	Upper Cretaceous limestones
12	90.28	Upper Cretaceous limestones
2	90.33	Upper Cretaceous limestones
19	91.43	Upper Cretaceous limestones
4	91.98	Upper Cretaceous limestones
32	92.18	Upper Cretaceous limestones
29	92.48	Upper Cretaceous limestones
8	92.78	Upper Cretaceous limestones
11	92.89	Upper Cretaceous limestones
22	93.19	Upper Cretaceous limestones
20	94.04	Upper Cretaceous limestones
31	94.29	Upper Cretaceous limestones
28	94.34	Upper Cretaceous limestones
3	94.89	Upper Cretaceous limestones
7	94.99	Upper Cretaceous limestones
21	95.04	Upper Cretaceous limestones
26	97.69	Upper Cretaceous limestones
14	92.18	Cretaceous carbonate breccias
18	93.69	Cretaceous carbonate breccias



Authors	Age	Lithostratigraphic unit	CaCO (%) Mamužić et al. 1969, Šušnjar et al. 1970, Šikić et al. 1969	CaCO (%) – new data
Mamužić et al. (1969)	Paleogene-Neogene	Limestone breccias	/	93
Mamužić et al. (1969)	Paleogene	Marls and sandstones	/	34
Mamužić et al. (1969)	Paleogene	Foraminifera limestone	/	91
Šušnjar et al. (1970)	Paleogene	Foraminifera limestone	95-99	92-93
Šušnjar et al. (1970)	Upper Cretaceous (Turonian)	Ridge limestone	/	75-95
Šušnjar et al. (1970)	Upper Cretaceous (Cenomanian, Turonian)	Dolomite with limestone interlayer	95-100	85-93
Šušnjar et al. (1970)	Upper Cretaceous (Cenomanian, Turonian)	Limestone, dolomite and dolomite breccias	/	63-94
Mamužić et al. (1969)	Upper Cretaceous (Turonian, Cenomanian)	Bright grey and white rudist-rich limestone	/	84-98
Mamužić et al. (1969)	Upper Cretaceous (Cenomanian Turonian)	Limestone with dolomite interlayer	up to 100	92
Šikić et al. (1969)	Upper Cretaceous	Grey and bright coarse-grained sandy dolomite	/	90
Šikić et al. (1969)	Lower Cretaceous	Limestone-dolomite breccias and schist limestone	/	92
Šikić et al. (1969)	Lower Cretaceous (Barremian, Aptian, Albian)	Gray and brown bituminous, rarely brighter, homogeneous, flat to schist limestone and dolomite	/	95
Šušnjar et al. (1970)	Lower Cretaceous	Limestone and breccias	97-99	95
Šušnjar et al. (1970)	Lower Cretaceous	Limestone breccias and limestone	/	94

Fig. 1.3 $CaCO_3$ content for lithostratigraphic units on Krk Island: data by Šušnjar et al. [1], Mamužić et al. [2] and Šikić et al. [3] and new data