Geomorphology 303 (2018) 524–539

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Detecting and characterizing unroofed caves by ground penetrating radar

Teja Čeru [a,*], Ela Šegina [b], Martin Knez [c,d,e], Čedomir Benac [f], Andrej Gosar [a,g]

[a] University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva 12, 1000 Ljubljana, Slovenia
[b] Miklošičeva 4a, 1230 Domžale, Slovenia
[c] Karst Research Institute, Research Centre of the Slovenian Academy of Sciences and Arts, Titov trg 2, 6230 Postojna, Slovenia
[d] UNESCO Chair on Karst Education, University of Nova Gorica, Glavni trg 8, 5271 Vipava, Slovenia
[e] Yunnan University International Joint Research Center for Karstology, Xueyun rd. 5, 650223 Kunming, China
[f] University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, 51000 Rijeka, Croatia
[g] Slovenian Environment Agency, Seismology and Geology Office, Vojkova 1b, 1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 10 March 2017
Received in revised form 2 November 2017
Accepted 6 November 2017
Available online 22 November 2017

Keywords:
Ground penetrating radar (GPR)
Karst
Unroofed cave
Doline
Krk Island (Croatia)

ABSTRACT

The bare karst surface in the southeastern part of Krk Island (Croatia) is characterized by different surface karst features, such as valley-like shallow linear depressions and partially or fully sediment-filled depressions of various shapes and sizes. They were noticed due to locally increased thickness of sediment and enhanced vegetation but had not yet been systematically studied and defined. Considering only the geometry of the investigated surface features and the rare traces of cave environments detected by field surveys, it was unclear which processes (surface karstification and/or speleogenesis) contributed most to their formation. The low-frequency ground penetrating radar (GPR) method using a special 50 MHz RTA antenna was applied to study and describe these karst features. Three study sites were chosen and 5 km of GPR profiles were positioned to include various surface features. The results obtained from the GPR investigation lead to the following conclusions: (1) an increased thickness of sediment was detected in all the investigated depressions indicating their considerable depth; (2) areas between different depressions expressed as attenuated zones in GPR images reveal their interconnection; (3) transitions between surface and underground features are characterized by a collapsed passage visible in the GPR data; and (4) an underground continuation of surface valley-like depressions was detected, proving the speleogenetic origin of such features. Subsurface information obtained using GPR indicates that the valley-like depressions, irregular depressions completely or partially filled with sediment, and some dolines are associated with a nearly 4 km-long unroofed cave and developed as a result of karst denudation. In the regional context, these results suggest long-lasting karstification processes in the area, in contrast to the pre-karstic fluvial phase previously assumed to have occurred here. This research is the first application of the GPR method to survey unroofed caves worldwide and the first detailed study of such karst features in Croatia. The low-frequency GPR proved to be an efficient method not only for detecting underground continuations but also for distinguishing and identifying surface features and transition zones between surface and subsurface segments of unroofed caves and can therefore be used for recognizing similar geomorphological features.

1. Introduction

Depressions on karst surfaces can be of various origin, including denudation of underground cavities and enhanced surface dissolution (Ford and Williams, 2007). However, they tend to exhibit a locally specific and highly uniform morphology (Šušteršič, 2006) and the origin of a particular feature in its later stages often becomes unrecognizable (Mihevc, 1998).

Historically, karst surfaces and subsurfaces were typically studied as separate systems with little to no interplay, and the various types of surface depressions have usually been interpreted as types of dolines or as the result of the lithological properties of rock and its fracturing. The recognition of unroofed caves that appear on the karst surface due to its denudation (Knez and Slabe, 1999) has linked karst surface and subsurface features and brought an important turnabout in the understanding and interpretation of karst surface morphology (Knez and Šebela, 1994; Mihevc, 1996, 2001, 2011; Mihevc et al., 1998; Šušteršič, 1998; Knez and Slabe, 1999, 2002, 2016).

Unroofed caves are karst phenomena that constitute a relatively common karst landform (Knez and Slabe, 2016). The extent and importance of underground formations in shaping recent surfaces have been thoroughly and systematically studied mostly in the Classical karst of Slovenia, although some published literature describes various

* Corresponding author.
E-mail address: teja.ceru@ntf.uni-lj.si (T. Čeru).

https://doi.org/10.1016/j.geomorph.2017.11.004
0169-555X/

processes and mechanisms leading to the formation of unroofed caves elsewhere in the world (Mais, 1999; Osborne, 2001; Bosák et al., 2002; Klimchouk, 2006; Ufrecht, 2008).

Given the strong surface reshaping that masks the origin of the initial karst depression and the scarcity of cave sediment and rock sculpturing as typical proofs of speleogenesis, geophysical methods can help identify the origin of this particular karst feature by demonstrating linkages between the surface and the underground. Among all geophysical methods, ground penetrating radar (GPR) has been used increasingly in the last decade in karst areas to solve various issues related to environmental, hydrogeological, and geotechnical research. It helps identify and locate subsurface features such as cavities, conduits, and fractures (Chalikakis et al., 2011). Most of the published studies have focused on the detection of shallow cavities, their location and geometrical extent (e.g. Chamberlain et al., 2000; Beres et al., 2001; Mcmechan et al., 2002; Mochales et al., 2008; Pueyo-Anchuela et al., 2009; Gosar, 2012; Seren et al., 2012; Vadillo et al., 2012; Łyskowski et al., 2014; Martínez-Moreno et al., 2014; Gosar and Čeru, 2016). According to the overview of several studies published by Martínez-Moreno et al. (2013), GPR has proven to be an appropriate method for detecting cavities with a depth of up to 30 m. Geoelectrical methods integrated with magnetic and/or gravity methods should be applied to detect deeper caves (40–80 m) (Martínez-Moreno et al., 2013).

Although GPR has significant limitations in depth range compared to other geophysical methods, particularly where karst rock is covered by unconsolidated sediment, it provides the most detailed information about near-surface features. Because of this advantage, several recent studies have successfully combined the GPR method with other geophysical methods (mainly various resistivity methods) to describe the internal geometry of dolines and to locate areas prone to the collapse of underground cavities, especially in urban areas (e.g. Batayneh et al., 2002; Kruse et al., 2006; Delle Rose and Leucci, 2010; Valois et al., 2011; Gómez-Ortiz and Martín-Crespo, 2012; Carbonel et al., 2014; Rodriguez et al., 2014; Pueyo-Anchuela et al., 2015; Margiotta et al., 2016; Fabregat et al., 2017). The GPR method is also commonly used in investigations of karst aquifers to locate and determine structural features related to the hydrodynamic mechanism of aquifers (e.g. Beres and Haeni, 1991; Al-fares et al., 2002; Carriere et al., 2013; Mount et al., 2014).

In Croatia, 43.7% of the country's surface consists of karst and fluviokarst relief (Bognar et al., 2012). Krk Island is an example of a predominantly karst landscape exhibiting very different karst forms, where two distinct types of karst relief have been identified: one as a typical doline karst and the other as bare (paleo)fluviokarst relief (Benac et al., 2013). On the basis of analysis of data provided from topographic maps and aerial photographs in combination with field investigation, Benac et al. (2013) hypothesized that differences in the recent morphology are the result of varying thickness of the Paleogene impermeable marly cover and/or the intensity of tectonics. However, the bare karst plateau and its related surface karst features in the southeastern part of Krk Island presented in this paper were not included in their study. In general, the various shallow (partially or completely sediment-filled) depressions of different shapes and sizes (Fig. 1) occurring in the studied area are poorly understood and have not previously been systematically analyzed or defined. Most of them, particularly those of circular shape, have been considered dolines, recognizable as closed depressions on the karst surface, with some of them identified as cryptodolines (Čeru et al., 2015; Šegina et al., 2015). On the basis of feature geometry, partially preserved cave sediment and flowstones, and a preliminary GPR survey, we hypothesized that some of the sediment-

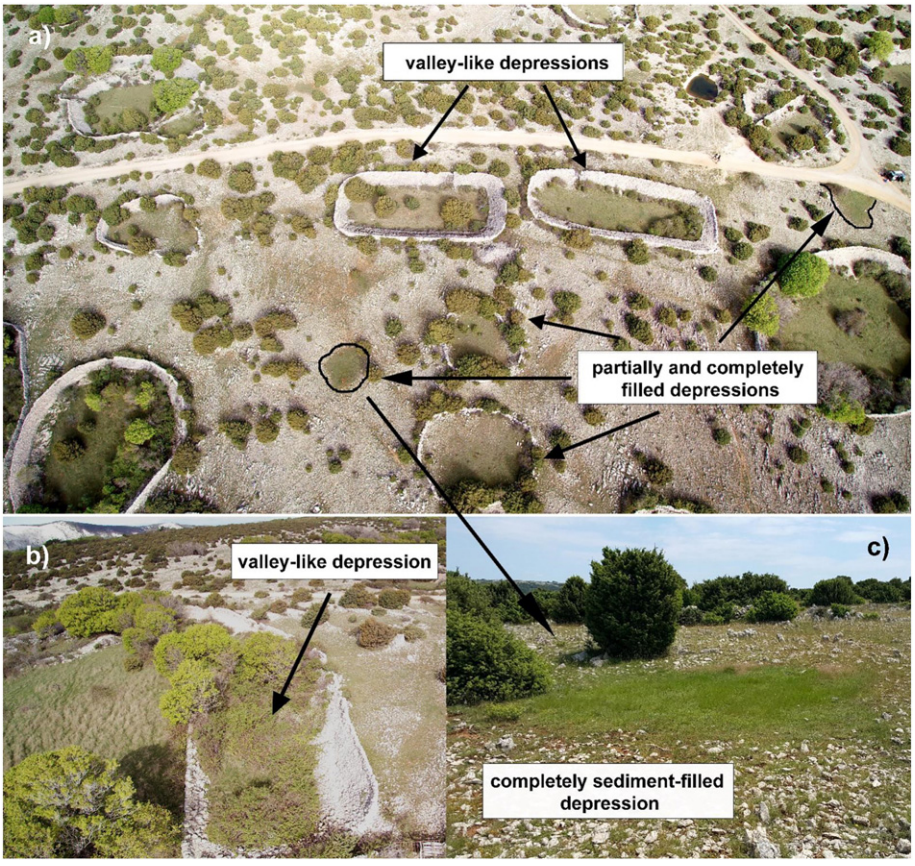

Fig. 1. a) Typical landscape with surface karst features of different shapes and sizes on the bare karst land in SE part of Krk Island. b) Valley-like linear shallow depressions are very common in the study area. c) Occurrences of the completely sediment-filled features are mostly recognizable due to enhanced vegetation.