THE PROBLEM OF DISSOLUTION DOLINE DEFINITION

Uroš Stepišnik, PhD.
Department of Geography, Faculty of Arts, University of Ljubljana
Aškerčeva 2, SI-1000 Ljubljana
E-mail: uros.stepisnik@ff.uni-lj.si

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Abstract
Dolines are regularly referred as diagnostic karst landforms, as their formation is usually attributed to chemical weathering or dissolution, which is the most typical karst process. In this paper, we re-evaluate the formation of the two most typical dissolution dolines, provided by Cvijić. Within this study, we stated that both cases, which constitute the foundations of interpretation of dissolution dolines formation, are actually not caused by dissolution of the surface. The purpose of the article is to provide a doubt about the understanding of formation of the most common karst landform.

Key words: geomorphology, karst, doline, dissolution, ERI (electrical resistivity imaging), Dinaric karst, Slovenia

PROBLEM DEFINICIJE KOROZIJSKIH VRTAČ

Izvleček
Vrtače so najbolj pogoste kraške oblike zmerno toplega pasu, saj njihov nastanek navadno pripisujemo kemičnem preperevanju oziroma koroziji, ki je najbolj tipičen proces na krasu. V članku smo ponovno ovrednotili nastanek dveh najbolj tipičnih primerov korozijskih vrtač, ki jih je podal Cvijić. V raziskavi smo ugotovili, da oba primera, ki predstavljata temelje korozijske razlage nastanka vrtač, pravzaprav nista nastala s korozijo površja. Namen članka je podati dvom o razumevanju nastanka najbolj tipičnih kraških oblik.

Ključne besede: geomorfologija, kras, vrtača, korozija, ERI (električna upornost tal), dinarski kras, Slovenija

1 INTRODUCTION

Dolines are small to middle-sized closed depressions of various shapes. They are the most typical unit landform in the temperate latitude karst since they are giving the relief distinctive pitted character. The term *doline* was first used by Austrian geologists in the middle of 19th century (Šušteršič, 1994; Gams, 2003) while studying the Classical karst in Carniola. At that time a number of different typologies of dolines appeared. Scholars recognized several different types according to their morphographic and morphometric properties. On the other hand, there was extensive disagreement about morphogenesis of dolines, whether they form by a collapse of cave chamber ceiling or predominantly by a dissolution action on the surface. The oldest description introduced by early researchers of the Classical karst in Carniola connected the doline origin to a collapse (Cvijić, 1893). They recognized the role of dissolution action on the surface mostly in a role of doline slope remodeling. Other group of scientists supported the findings of Cvijić (1893) who claimed that middle-sized surface depressions are formed solely by surface dissolution. They supported his statements with variety of examples from different karst environments, which were confirming dominant role of dissolution in a dolines formation.

The most influential karstologic publication written by Cvijić at the end of 19th century was the monograph titled *Das Karstphänomen* (1893). Among other topics, he discussed morphogenesis of dolines in detail. He claimed that although dolines might be formed by other mechanisms, the most characteristic dolines are formed by the action of dissolution (Cvijić, 1893). He listed a number of examples from the Dinaric karst but he presented only one example of a doline cross-section profile. This example was the evidence of a fractured zone that is contributing to a concentrated runoff of rainwater and consequential accelerated dissolution on which he explained the morphogenetic formation of all dissolution dolines. This illustration of a dissolution doline cross-section became one of the most reproduced in all geomorphologic literature. Cvijić did mention a number of areas where comparable examples of dissolution dolines appear. Among other examples of such areas he specified only one location where typical examples of dissolution dolines are situated. This is an area named Skalčen kamen close to Logatec, Slovenia.

The aim of the article is to re-evaluate classical examples of dissolution dolines provided by Cvijić (1893). The first objective is to discuss and re-evaluate morphogenesis of the doline cross-section that became classical example of dissolution doline presented by Cvijić (1893). Morphogenesis of this doline at Logatec train station will be established through earlier findings recorded in a literature. The second objective is a geomorphologic analysis of the doline in the Skalčen kamen area. It will be studied through morphographic and sediment analysis as well as by application of electrical resistivity imaging (ERI). The results of the article will not present a new proposal of doline morphogenesis mechanism. However, it will bring to focus reasonable doubt about contemporary understanding of dissolution doline formation.

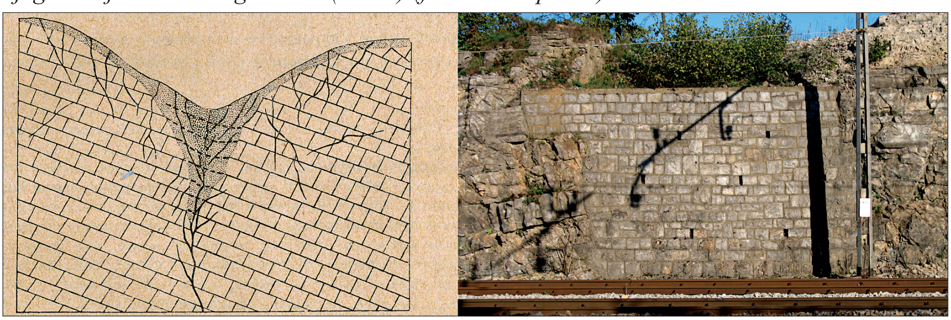
2 THEORETICAL CONCEPTS OF DISSOLUTION DOLINES

Contemporary understanding of dissolution doline formation dates back in the end of 19th century. The monographs *Der Karstphänomen* in German language, followed by a slightly updated version with title *Karst* in Serbian language, both written by Cvijić (1893; 1895) have had great impact on karstology as a science. Among many karst phenomena, he discussed in detail geomorphologic properties of dolines. He recognized a couple of doline forming processes but he finally concluded that the most common dolines are formed by dissolution and he even terms them as *true dolines* (in German: die echte Dolinen; Serbian: лраве вртаче) (Cvijić, 1893; 1895). He explained them as the places of more intensive dissolution lowering of the surface, which is controlled by bedrock fractures.

Cvijić (1893) even proposed several arguments and evidences against theories of collapse origin of dolines. He stated that there are no reliable reports in the literature in which a bedrock doline would be disturbed by a collapse. In addition, he claimed that majority of typical bowl- and funnel-shaped dolines are not connected to caves. Even if dolines lead to caves that does not mean that they are automatically to be explained as a product of collapse. In addition, existence of detritus cones and other debris in the caves does not justify the conclusion that dolines are sited over them. Such accumulations may be formed for a variety of reasons (Cvijić, 1893). On the other hand, Cvijić offered detailed reports about bedrock dolines from various parts of the Dinaric karst. He claimed that those examples are a proof that majority of dolines are surface features formed by dissolution. The presented examples have no connection with subsurface cavities since bedrock strata beneath them are not repositioned. Additionally, bedrock beneath them is fractured by numerous cracks that are enlarged by dissolution and filled by terra rossa and fragments of limestone.

Though Cvijić presented many areas where dissolution dolines appear, he offered only one example of doline cross-section as an explanatory model of dissolution doline formation. The example is positioned within a railway cut at the Logatec train station, Slovenia. This doline cross-section has become the most reproduced figure of doline cross-section in the following literature (Fig. 1).

Figure 1: Original sketch of the cross-section of a dissolution doline (Cvijić, 1893, p. 63) (left) along with photo of present situation of the railway cut (right) (photo: U. Stepišnik)
Slika 1: Izvirna skica profila korozijske vrtače (Cvijić, 1893, str. 63) (levo) s fotografijo današnjega stanja železniškega useka (desno) (foto: U. Stepišnik)



By this cross-section example Cvijić (1893) noted that there is no evidence of underlying cavity, since all underlying strata are undisturbed. Nevertheless, the bedrock is intensively fractured directly under the lowest point of the doline. An area of limestone fragments is positioned just below the doline floor in a shape of a wedge (on Fig 1 left marked with dotted lines). The wedge is completely fractured and limestone fragments are embedded in terra rossa (Cvijić, 1893; 1895).

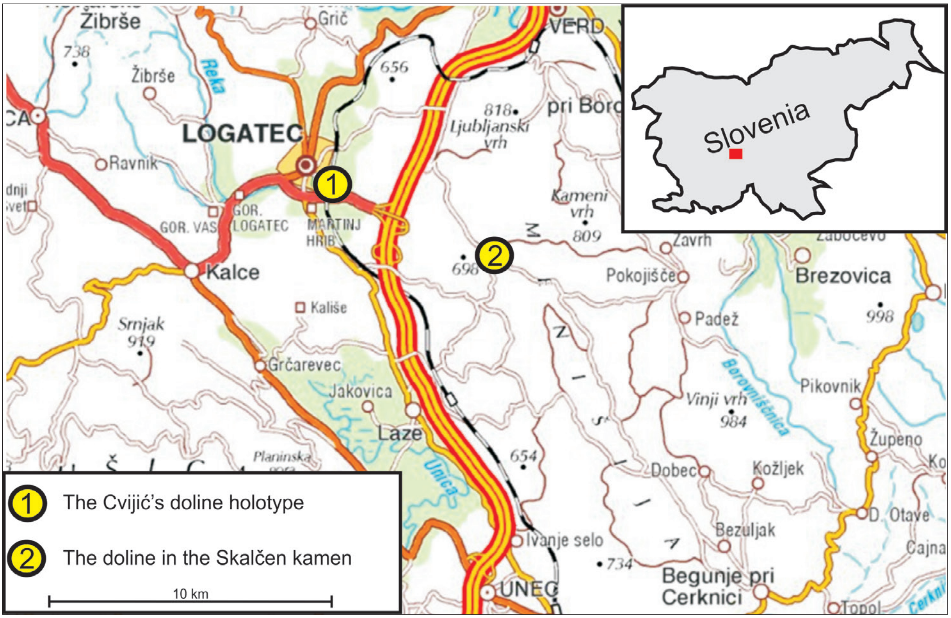
The definition and cross-section sketch of dissolution dolines provided by Cvijić (1893) had a tremendous impact on subsequent theories about doline morphogenesis. Following literature did not question the presented dissolution morphogenesis but it was more concerned with distribution and morphometry of dolines. Even contemporary literature (e.g. Gams, 2000; Sauro, 2003; 2012; 2013; Williams, 2003) defines dissolution dolines following theoretical background of Cvijić (1893) as closed surface depressions which were formed in the areas of focused chemical attack on bedrock.

Modern interpretations of dissolution dolines morphogenesis were summarised by Sauro (2012) into three types. The first type is a point-recharge doline which is strongly connected to outflow of surface streams into karst subsurface. The second type is a drawdown doline. The formation of later is result of focusing of the dissolution inside the water infiltration zone of the rock through centripetal convergence of the mainly subsurface water held inside the epikarst. This type of morphogenesis exactly corresponds the dissolution dolines proposed by Cvijić (1893). The third type is an inception doline that also originates from the centripetal convergence of water; this occurs inside a pre-existing hydrogeological structure and is triggered by a change of hydraulic conductivity due to lithological and structural factors.

The cross-section of the doline at the Logatec train station was partially destroyed and built up by a protective wall, so cross-section is not visible any more. But according to Šušteršič (1994), who studied morphometry of the surrounding area in detail, the doline ground plan is not circular but it is rather lengthened depression along a tectonic crushed zone. Therefore, the basic example of the doline cross-section is accordingly not a doline but preferably a type of a karst channel termed bogaz (Šušteršič, 1994) or karst corridor (Tîrlă, Vijulie, 2013). It means, that most cited and reproduced example of dissolution doline is not a dissolution doline at all.

Since the structure presented by Cvijić is not a doline, a new holotype of a dissolution doline was required. Cvijić did mention numerous areas where similar examples of dissolution dolines appear. Among a large number of general locations, he specifically noted the area of typical dissolution dolines in the Skalčen kamen about 6 km southeast of Logatec, Slovenia. The area is densely covered by dolines of various shapes so it was not completely clear which doline Cvijić specifically mentioned. Detailed morphometric analysis of dolines in the area was performed by Šušteršič (1994). One doline that is positioned closest to the road crossing at the Skalčen kamen with study name SK-022 was determined as the most typical and was defined as a new holotype of the dissolution doline (Šušteršič, 1994).

Figure 2: Location of the doline cross-section in railway cut in Logatec (1) and doline SK-022 in the Skalčen kamen area (2)
Slika 2: Lokacija profila vrtače v useku železnice v Logatcu (1) in vrtače SK-022 v Skalčnem kamnu (2)



Source/Vir: GURS, 2015

3 RESEARCH METHODS

Morphometric analysis of the doline in Skalčen kamen with study name SK-022 provided by Šušteršič (1994) was used to prepare cartographic background for further morphographic survey. Morphographic analysis included identification of micro-scale features, types of slopes (Stepišnik, Kosec, 2011) as well as identification of the sediments exposed on the surface.

Since the formation of the dissolution doline cannot be interpreted solely by surface morphology, the geophysical method of electrical resistivity imaging (ERI) was applied to identify the subsurface structures. The SuperSting R1/IP Earth resistivity meter developed by Advanced Geosciences Inc. was used for the data collection. The survey was conducted with a dipole-dipole array and 20 electrodes were used simultaneously with alternation of two currents and two potential electrodes. The data were processed to generate two-dimensional resistivity models, using EarthImager 2D resistivity inversion software developed by Advanced Geosciences Inc. The root-mean-square (RMS) error quantifies the difference between the measured resistivity values and those calculated from the true resistivity model. A small RMS value indicates small differences. The minimum RMS error in the survey was 5.8%, and the maximum error was 13.56%. The method turned out to be appropriate for subsurface tomography of karst terrains where significant differences of electrical resistivity values of material within the profile exist (Stepišnik, Mihevc, 2008; Kaufmann, Deceuster, Quinif, 2012; Mihevc, Stepišnik, 2012; Yeboah-Forson, Comax, Whitman, 2014).

4 GEOMORPHOLOGIC ANALYSIS OF A DISSOLUTION DOLINE

Within our study we performed detailed geomorphologic analysis of the doline SK-022 in the area of Skalčen kamen, which was defined as the new holotype of dissolution doline (Šušteršič, 1994). The doline is positioned in the northern part of an extensive levelled karst area named Logaški ravnik that is morphogenetically interpreted as corrosion plain or a relict polje (Šušteršič, Šušteršič, 2003; Šušteršič, 2004). The whole area is levelled at elevation of about 530 m. The doline is positioned in close proximity of the only road crossing in the area of Skalčen kamen at coordinates 45.883° N 14.296° E (WGS 84).

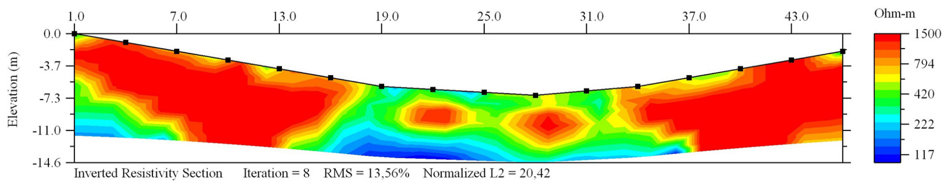
Figure 3: The doline SK-022 in the Skalčen kamen area from the southwest (photo: U. Stepišnik)
Slika 3: Vrtača SK-022 v Skalčnem kamnu od jugozahoda (foto: U. Stepišnik)

Detailed survey of the doline revealed that the doline longer axis is 50 m and shorter axis 45 m. The depth of the doline is 7.5 m and it covers an area of about 8000 m^2. The doline is positioned completely within Upper Jurassic limestone with dip of strata about 30 degrees towards east. Slopes of the doline are mostly balanced (Stepišnik, Kosec, 2011) with inclinations up to 20 degrees. Only southern slopes are steeper, with inclination up to 30 degrees and covered by coarse material which is prone to limited mass wasting. On the southern slope, there is a section with about 1.5 m high vertical wall. Loamy material is exposed in the lower sections of the northern slope as well as in the floor of the doline.

Within loamy material fragments of flowstone and up to fine pebble size grains of bauxite are to be found.

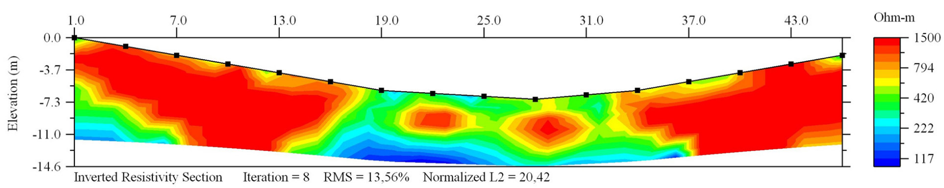
Two ERI profiles were measured through the doline. The first profile (Fig. 4) was conducted approximately along east-west axis across the lowest point of the doline floor. The azimuth of the profile was 260 degrees. Results from the electrical resistivity imaging, with electrodes at 3 m spacing, exhibited subsurface resistivity values on the slopes of more than 1000 ohm-m. The floor of the doline and its subsurface has resistivity values less than 500 ohm-m to a depth of 8 m and more. Below the floor in depth of about 3 m there are two circular structures with a diameter of 4 to 5 m and resistivity more than 1000 ohm-m (Fig. 5).

Figure 4: The first ERI profile of the doline SK-022 in east-west direction
Slika 4: Prvi ERI profil vrtače SK-022 od vzhoda proti zahodu



The second ERI profile (Fig. 5) was conducted approximately across south-north axis across the lowest point of the floor. The azimuth of the profile was 170 degrees. Electrical resistivity imaging profile was conducted by electrode spacing 3 m. The southern and the upper section of the northern slope have resistivity values higher than 1000 ohm-m. The same values are in the subsurface below them. Lower section of the northern slope and the floor along it exhibit resistivity vales lower than 500 ohm-m. The depth of low resistivity structure below it is at least 8 m (Fig. 6).

Figure 5: The second ERI profile of the doline SK-022 in south-north direction
Slika 5: Drugi ERI profil vrtače SK-022 od juga proti severu



5 DISCUSSION

Dolines are natural enclosed depressions of different shapes and sizes found in karst landscapes. They are considered a diagnostic karst landform. We recognize several different types of dolines, but the most common are formed due to dissolution, so they are termed dissolution dolines (Ford, Williams, 2007). They are believed to have a similar function to the drainage basin in fluvial landscape. Dolines are discharging rainwater into underground via enlarged fissures in the lowest point of the doline (Williams, 2003). This interpretation was initiated in 19th century understandings which were summarized in work of Cvijić (1893). Contemporary literature recognises several types of dissolution dolines (e.g. Gams, 2000; Williams, 2003; Sauro et al., 2009; Sauro, 2012; 2013) which have foundation in definition provided by Cvijić (1893).

The doline morphometry at Skalčen kamen was initially well documented by Šušteršič (1994). We conducted morphographic analysis, which revealed that southern slope is active while other slopes are balanced. The floor and lower sections of northern slopes are covered by loamy material. Within the loamy material fragments of flowstone and up to fine pebble size grains of bauxite are to be found. Flowstone in the local climate cannot be generated on the surface, but only in cave environment. Bauxite deposits were not formed in situ. Their only location in the area is about 15 kilometers towards southeast in the watershed of the Cerkniščica River (Šušteršič, Šušteršič, 2003). Bauxite is being transported into karst aquifer by the Cerkniščica River from the area of the Cerkniško polje. The only spots where bauxite-derived deposits can be found in the area are fillings of caves and denuded caves (Geršl, Stepišnik, Šušteršič, 1999; Šušteršič, Šušteršič, 2003). Therefore, sediments fill analysis suggests that the doline is filled with sediments which are typical for caves in the area (Šušteršič, 2004). Those kinds of sediments are typical for cave environment and could not be formed inside a dissolution doline that is functioning as a vertical drainage for rainwater.

ERI profiles exhibit two different sets of electrical conductivity in the doline subsurface. Bedrock has resistivity values higher than 1000 ohm-m while loamy material and weathered or fractured bedrock has values lower than 500 ohm-m. Lower resistivity values are located beneath the floor of the doline as well as beneath lower sections of the northern slopes exactly where patch of loamy sediment is positioned on the surface. Therefore, we know that subsurface profile values with resistivity less than 500 ohm-m are as well of loamy material. Slopes as well as subsurface in those sections are built of limestone bedrock which exhibits resistivity values higher than 1000 ohm-m. Consequently, we assume that subsurface structure with those values is relatively undisturbed bedrock. Span of those two electrical resistivity values sets are comparable to previous applications of this method in various karst surface features on the Slovenian karst (Stepišnik, 2007; Stepišnik, Mihevc, 2008; Stepišnik, 2009). Earlier applications of the method revealed that the resistivity value for carbonate rock exceeds 1000 ohm-m. Soil and weathered bedrock exhibit the resistivity values between 200 and 1000 ohm-m. Loamy material has resistivity values lower than 500 ohm-m (Stepišnik, 2007; Stepišnik, Mihevc, 2008; Stepišnik, 2009).

The depth of loamy material below the doline in the Skalčen kamen area is well exhibited on both ERI profiles and it exceeds 8 m. Loamy material is not positioned only below the doline floor but also beneath a part of its northern slope. Thickness of this loamy fill is preventing vertical runoff of rainwater, thus the investigated doline cannot be a result of accelerated dissolution due to concentrated vertical runoff.

6 CONCLUSIONS

Most of the karstologic literature explains formation of dolines through dissolution effects of rainwater discharge via fissures in the lowest point of the doline (Williams, 2003; Ford, Williams, 2007). It is the most obvious deduction since the dominant process on karst is dissolution. Contemporary understanding of doline formation originates from a century old theories. Therefore, the aim of the article was to revaluate morphogenesis of the most common examples of dissolution dolines. The main objective of the article is not to propose new explanation of doline morphogenesis but to put focus upon understanding of dissolution doline formation.

A dissolution doline holotype introduced by Cvijić (1893) which became a basis for understanding dissolution formation of dolines as well as famous for its cross-section reproduced by many authors, turned out not to be a dissolution doline at all (Šušteršič, 1994). Since the first example of doline was recognized to be an elongated tectonic depression termed bogaz or corrosion corridor, another example of Cvijić (1893) was defined as a dissolution doline holotype (Šušteršič, 1994). The new holotype is positioned in the area of Skalčen kamen close to Logatec, Slovenia, and became a focus of our geomorphologic survey.

Morphographic analysis of the doline in the Skalčen kamen area revealed that a patch of loamy material is covering the floor and lower sections of the northern slope. This loamy material would not be uncommon if accelerated corrosion in the doline floor would result in formation of insoluble infill (Gams, 2003). Nevertheless, within the loamy material pebble size bauxite clasts as well as pieces of flowstone are found which are typical cave sediments in the area (Geršl, Stepišnik, Šušteršič, 1999; Šušteršič, 2004). Excessive amount of loamy material below the doline floor revealed by application of ERI also implies that it could not be solely a residual of a chemical weathering. Consequently, vertical runoff through the doline floor is not possible due to impermeable loamy material. Therefore, we must conclude that another holotype of a dissolution doline is rather a denuded cave (Mihevc, Slabe, Šebela, 1998; Mihevc, 2007).

Technically speaking, we do not have any particular example of a dissolution doline for which it was proven that it was formed by a process of dissolution. Furthermore, we do understand that epikarst zone seepage concentrated in a vadose zone is forming shafts (e.g. Ford, Williams, 2007). Enlarging of fissures in the subsurface beneath dissolution dolines would eventually lead to opening of the shaft. Since we have almost no examples from any karst area, where shaft entrances in doline floors would be common, we can conclude that it is highly unlikely that dissolution dolines would be formed by accelerated focused corrosion of epikarst.

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PROBLEM DEFINICIJE KOROZIJSKIH VRTAČ

Povzetek

Vrtače so majhne do srednje velike kraške kotanje različnih oblik. So najbolj tipična oblika krasa zmerno toplega podnebja. Začetek znanstvenega preučevanja vrtač sega v sredino 19. st., ko so različni krasoslovci pričeli s prvimi opisi in tipizacijami vrtač na osnovi njihovih morfografskih in morfometričnih značilnosti. Hkrati so se že takrat pojavila prva nesoglasja glede morfogeneze te najpogostejše kraške oblike. Najstarejše razlage pripisujejo nastanek vrtač procesu udiranja jamskih stropov. Učinek korozije so videli le v preoblikovanju vrtač in ne njihovem nastanku (Gams, 2004). Kasneje je Cvijić zavrnil udorni nastanek vrtač in zaključil, da nastanejo izključno z delovanjem površinske korozije (Cvijić, 1893). Njegovo interpretacijo je sprejela cela vrsta krasoslovcev v drugi polovici 19. st. (Cvijić, 1893).

Najpomembnejše delo iz konca 19. st., *Das Karstphänomen*, je objavil Cvijić (1893). Med drugimi oblikami in procesi se je Cvijić (1893) podrobno ukvarjal tudi z nastankom vrtač. Priznaval je, da lahko vrtače nastanejo na različne načine, tudi z udorom, daleč najpomembnejši in najpogostejši proces oblikovanja vrtač pa je po njegovih ugotovitvah korozija. Ta tip vrtač je Cvijić (1893) poimenoval *korozijske vrtače* oziroma celo *prave vrtače* (nemško *die echte Dolinen*). V svojem delu je navedel celo vrsto primerov korozijskih vrtač iz dinarskega krasa, vendar je predstavil le en primer prečnega profila vrtače (slika 1). V tem profilu, ki se nahaja v useku železniške postaje Logatec, je pod vrtačo jasno vidna zdrobljena cona, ki naj bi delovala kot zbiralec koncentriranega odtoka padavinske vode v podzemlje in posledično tudi pospešene korozije (Cvijić, 1893). Skico tega profila danes najdemo skoraj v vseh krasoslovnih knjigah in učbenikih. Cvijić je v svojih delih omenil številna območja, na katerih se pojavljajo podobni primeri vrtač, ampak je posebej imenoval le vrtačo v Skalčnem kamnu na Logaškem ravniku kot tipičen primer korozijske vrtače (Cvijić, 1893).

Šušteršič (1994) je podrobno preučil profil vrtače pri logaški železniški postaji in ugotovil, da opisana oblika pravzaprav ni vrtača, ampak podolgovato znižanje v reliefu, ki je nastalo ob tektonsko zdrobljeni coni. Torej, največkrat navajan primer profila korozijske vrtače pravzaprav ni vrtača. Šušteršič (1994) je tako za nov holotip korozijske vrtače predlagal vrtačo v Skalčnem kamnu, ki jo je omenil že Cvijić (1893).

Naša geomorfološka analiza vrtače v Skalčnem kamnu je pokazala, da sta njeno dno in del severnega pobočja prekrita z zaplato ilovnatega materiala. Prisotnost ilovic ni nič nenavadnega, saj naj bi v dneh vrtač zaradi pospešene korozije ostajal netopni material (Gams, 2003), vendar so v ilovnatem materialu prisotni tudi posamezni manjši prodniki boksita in kosi sige. Tako smo lahko zaključili, da sediment v vrtači najverjetneje ni netopni ostanek, pač pa alogeni material, značilen za jamska polnila na celotnem območju Logaškega ravnika (Šušteršič, 2004; Geršl, Stepišnik, Šušteršič, 1999). Pri analiziranju zgradbe vrtače pod površjem, ki smo jo opravili z metodo električne upornosti tal (ang. *electrical resistivity imaging*; ERI) smo ugotovili, da je ilovnati sediment v dnu vrtače in pod severnim pobočjem globok najmanj 10 metrov. Takšna količina ilovnatega sedimenta ne more biti netopni ostanek kemičnega preperevanja, saj hkrati preprečuje odtok padavinske vode skozi dno vrtače v podzemlje. Zaključili smo, da je drugi, novi holotip korozijske vrtače najverjetneje brezstropa jama (Mihevc, Slabe, Šebela, 1998).

Kljub temu da razumemo nastanek vrtač kot rezultat korozije kraškega površja in dela epikraške cone, nimamo primera, ki bi nedvomno dokazoval ta proces. Poleg tega sodobno krasoslovje razume funkcijo epikraške cone kot območje združevanja razpršenih vodnih curkov, ki vodi v oblikovanje vertikalnih votlin vadozne cone oziroma brezen. Ker pa so primeri, kjer bi bili v dneh vrtač vhodi v brezna, izredno redki, lahko zaključimo, da je malo verjetno, da bi vrtače nastale s korozijo površja oziroma s točkastim raztapljanjem razpoklinskih območij epikrasa.