REVIEWS/RAZGLEDI

THE NEW PARADIGM OF SOLUTION DOLINES
NOVA PARADIGMA KOROZIJSKIH VRTAČ

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ABSTRACT
The new paradigm of solution dolines
The paper focuses on the morphogenesis of solution dolines from a theoretical aspect. First of all, the classical paradigm of solution dolines is evaluated, followed by a review of contemporary understandings of karst processes. The author seeks to examine the shift from old concepts within karstology to new concepts and paradigms, although obsolete ideas are still present in lecture books and curricula/syllabi. The problem of altering paradigms is presented using the example of solution dolines, the most typical karst landform, and discussed further through the prism of changing deeply rooted paradigms in the educational process.

KEY WORDS
karst, doline, solution doline, curriculum, syllabus, educational process

IZVLEČEK
Nova paradigma korozijskih vrtač
Članek obravnava teoretični pogled na morfogenezo korozijskih vrtač. V uvodnem delu je ovrednotena klasična paradigma nastanka korozijskih vrtač; sledi mu pregled sodobnih pogledov na tovrstne kraške procese. Avtorica želi prikazati prehod starih krasoslovnih konceptov v novejše koncepte in paradigme, medtem ko so zastareli koncepti še vedno prisotni v učbenikih ter učnih načrtih. Problem sprememb paradigem je predstavljen na primeru korozijskih vrtač, ki so najbolj tipične površinske kraške oblike, skozi prizmo sprememb globoko zakoreninjenih paradigem v izobraževalnem procesu.

KLJUČNE BESEDE
kras, vrtača, korozijska vrtača, kurikul, učni načrt, izobraževalni proces

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1 Introduction

Advances in contemporary karstologic research have provided completely transformed understanding of dynamics and mechanics of karst processes. Without a doubt, the most important milestone in karstology, altering most of the old concepts, was the defining of denuded caves (Mihevc 1996; 1998; 2001; 2007; Mihevc and Zupan Hajna 1996; Mihevc, Slabe and Šebela 1998). Since then karst surface has no longer been defined statically, in the sense that it has not changed significantly post the »pre-karstic phase« (Sweeting 1973). Contemporary interpretation of karst surface is much more dynamic and the great majority of middle-sized karst features are believed to be outcomes of subsurface speleogentic processes on the one hand and solutional lowering of the surface on the other hand (Mihevc 2001). In the last two decades since the new paradigm has been adopted, a variety of new interpretations of surface features and dolines – the most typical and well-recognised karst features – have been suggested.

From the beginning of karstic research, the doline has been considered a diagnostic karst landform (Ford and Williams 2007) or a fundamental unit of karst terrain, understood to replace the valleys found in fluvial systems (Sweeting 1973). Mallot (1939) described them (cv. Sweeting 1973, 52) as having *»gentle soil-covered sides and flattish bottoms… largely developed by solution under a soil mantle …«*.

The international term doline derives from »dolina«, a word of Slavic origin meaning valley, possibly because these were the most common hollows in the landscape of the Dinaric karst (Figures 1 and 2), where there are few fluvial valleys. The word doline entered international scientific literature largely through the writings of Cvijić (1893), whilst the more accurate local term, »vrtača«, – also introduced by Cvijić (cv. Šušteršič 1994) – continues to be used in the »classical« karst of Slovenia. The usage


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Figure 1: Dolines on NW part of the Glamočko polje.

of the term doline is now so embedded in karstic literature that it would, as Gunn (2004) says, be fruitless to try to change it.

Dolines are closed karst depressions of various shapes, ranging from ten to a thousand meters in diameter (Šušteršič 1994). Their formation is related to various processes with different dynamics that result in surface mass removal. Depending on the process, we can distinguish corrosion or solution dolines, collapse dolines, subsidence dolines, suffusion dolines etc. (Ford and Williams 2007).

This article discusses the most basic type of doline, which is the solution or corrosion doline. The aim of this paper is to reconsider the paradigm of the genesis of solution dolines. The introductory part of the article discusses the emergence of the paradigm of solution dolines and reviews the existing karstological literature that discusses the various methods of formation and hydrological function of solution dolines. The main objective is to review understandings of solution doline genesis in various publications. Subsequently, the problem of an obsolete paradigm being integrated into scientific and educational literature is examined. The main aim of the article is to discuss the problem of a deeply rooted obsolete paradigm.

2 Development of the solutional paradigm

The collapse of cave ceilings is the oldest morphogenetic explanation for all rounded depressions in the karst landscape. The pioneer of the collapse theory was Gruber (cv. Williams 2003), who used the terms *gruben* and *kessel* to describe these features. Subsequently, researchers of the Dinaric karst in the middle of 19th century, including Schmidl, Tietze, Stache, Reyer and Marenzi, confirmed the collapse theory for these closed depressions (cv. Gams 2003). Based upon investigations of the kart landscape in Bosnia, Mojsisovics divided karstic depressions into two morphogenetic groups; those caused by collapse and those by corrosion (cv. Cvijić 1893). Later the theory of corrosion genesis of karstic depressions was gradually developed in the work of many researchers (Gams 2003). At the end of the 19th century, systematic geological and speleological investigations of various karst areas took place. A monograph about karst phenomena written by Cvijić (1893) had a great impact on karstology as a science and also gave a better understanding of karst depressions of different origin. Cvijić integrated features defined as karstic and presented the whole complexity of the karst landscape (Gams 2003). Among the many karst phenomena he discussed in detail were the medium-sized closed depressions called dolines. He identified dolines as forms that lend the karst topography its particular character (Šušteršič 1994). In his work, Cvijić subdivided dolines into four main groups, and his division has remained in general use until the present. Among these, solution dolines have been the most studied and yet, they remain the least understood. Although dolines might be formed in other ways, Cvijić insisted that the most characteristic dolines had been formed by the action of solution (Cvijić 1893). He explained these dolines as places of intense corrosion, with a corresponding lowering of the surface, all controlled by rock fracturing. He listed a number of examples from the whole area of the Dinaric karst and even offers one example of a doline cross-section profile; this example having evidence of a fractured zone offering a controlled runoff of rainwater and consequential accelerated corrosion, and on the basis of which he explains the morphogenetic formation of all solution dolines (Šušteršič 1994). The presented cross-section profile example of a doline was from a railway cutting at Logatec station in Slovenia. This illustration of a solution doline cross-section has become one of the most reproduced in all geomorphologic literature.

Cvijić claims that when a closed depression is formed on the surface, the dissolving of the rock into a solution is also assisted by residual clay and alluvial material collected in the depression (Cvijić 1893). Major fissures capture most of the flow and therefore are the foci of solvent attack on the bedrock. This results in yet more rock being removed in solution from these locations rather than in other areas, and this gradually gains a topographic expression as closed depressions, whilst the overall surface is lowered by chemical denudation (Cvijić 1893). In instances where dissolution is the prevailing mechanism, a bowl-shaped doline will probably form. The amount of limestone that can be removed in solution depends upon the concentration of the solvent and the volume of the solute. Variations in either or both of these variables can be responsible for the focusing of dissolution near the centre of the depression. However, when this process begins, doline formation is self-perpetuating (Cvijić 1893; Sweeting 1973; Šušteršič 1994; Williams 2003).

It became obvious that although dissolution is the initiating and dominant process, other factors, such as collapse may also contribute to the formation of dolines (Ford and Williams 2007). But local variations in solute concentration alone were not sufficient to explain the occurrences of solution dolines. If so, they would be found on every type of limestone in a given climatic zone, which is not the case (e.g. in England, dolines are most frequently found on Carboniferous limestone and tend to be less prevalent on Cretaceous and Jurassic limestone) (Ford and Williams 2007). Therefore, it follows that local spatial variations in water flow must be responsible for focusing corrosion attack (Ford and Williams 2007). According to Ford and Williams (2007), it is important to distinguish between doline initiation where there has been no proto-cave development, from that where a ready-made permeable vadose zone is inherited from an earlier phase of karstification.

Permeability and porosity of limestone may also affect doline formation. High permeability and hydraulic conductivity, along with high spatial variance of permeability within the upper vadose zone result in the development of solution dolines (Williams 2003; Ford and Williams 2007).

Likewise, corrosion is influenced by the distribution of soil layers and other non-carbonate sediments (Sweeting 1973). The next important factor is vegetation, particularly trees, which also assist in doline formation. Around trees carbon dioxide in the soil is greatly enriched because of the mechanical and

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Figure 2: Doline on the Biokovo Mountain.

chemical action of their roots, the accumulation of organic debris and the increased growth of fungi and other plants. This is particularly important in the Alps where dolines tend to cease to occur altogether at the tree line – so forested zones in the Alps are also doline zones (Sweeting 1973).

3 Contemporary understanding of solution doline morphogenesis

Increasing understanding of the properties of karst forms and processes gradually led to an entirely new approach towards the interpretation of doline formations. Completely accepted explanations of solution doline morphogenesis through differences related to surface denudation were slowly upgraded by new paradigms. Bahun (1969) suggested a two phase formation of dolines. The first phase is lowering of the karst surface due to exogenic processes, subsurface chemical weathering and expansion of a variety of cavities. With denudation of the surface, cavities emerge, which results in formation of different

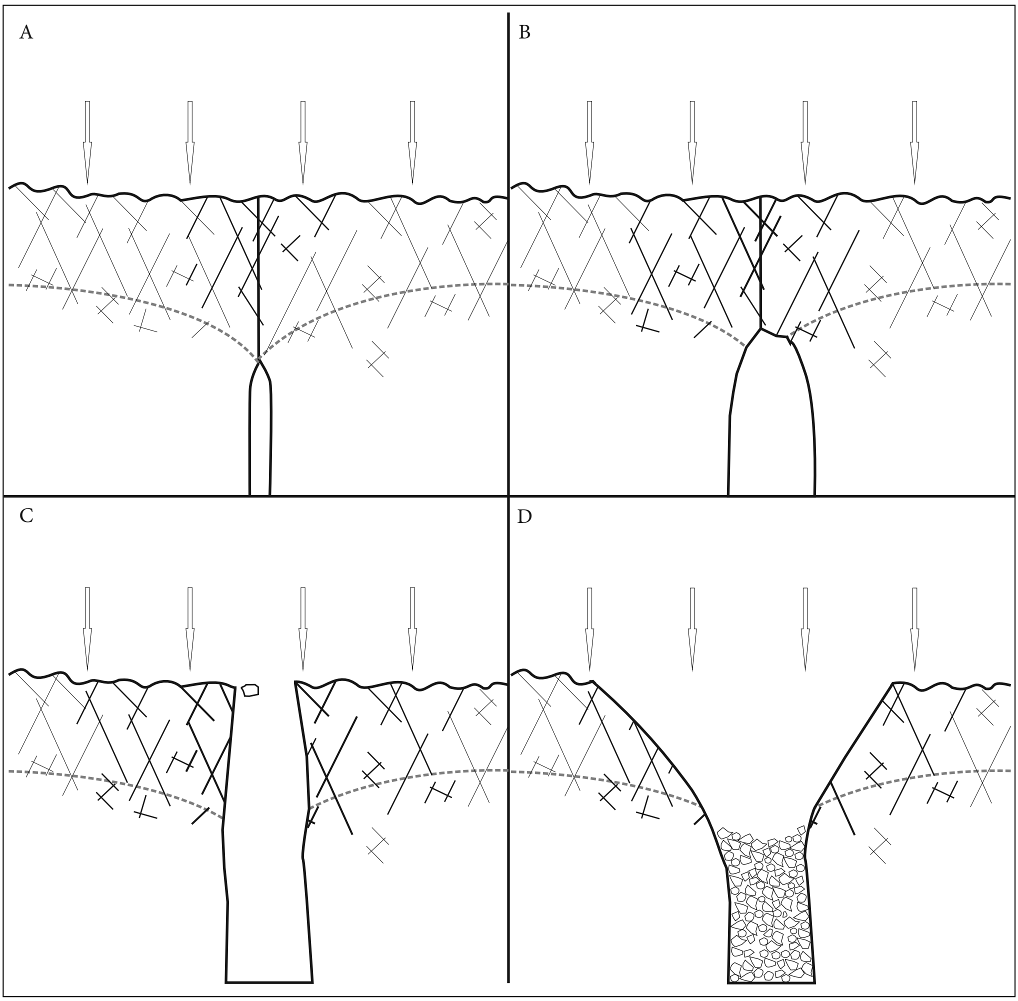

Figure 3: The mechanism of a doline formation as a result of a vadose shaft disintegration (Klimchouk 2004).

depressions on the karst surface. The second phase is pure modification of surface feature due to corrosion processes, gradual alternation of morphology and slope retreat (Bahun 1969; Stepišnik and Kosec 2011).

More recent interpretations of solution dolines place more significance on processes in the epikarst and vadose zone. It became obvious that epikarst functions as a collector of dispersed water flows, concentrating them, which leads to the formation of vertical shafts within the vadose zone (Klimchouk 2004; Ford and Williams 2007). Denudation of the surface eventually results in local collapse of the shaft celling and aperture of the shafts to the surface. Subsequent slope retreat of the shaft walls leads to the formation of a funnel shaped depression, termed a doline (Klimchouk 2004; Figure 3).

Investigations of subsurface structure of dolines and doline-like depressions through various methods within the Dinaric karst revealed (Stepišnik 2008; 2011; Stepišnik and Mihevc 2008; Mihevc and Stepišnik 2011; 2012) that most dolines are filled with fine grain sediments. Loamy and silty fill within dolines prevents subsurface outflow that causes local lowering of the surface. In addition, detail study of minerals revealed that loamy sediments within doline floors are mostly allogenic, flysch derived minerals. An almost complete absence of Aeolic deposits revealed that most of the dolines are a result of disintegration of subsurface voids due to denudational lowering of the surface (Mihevc 2001; 2007; Stepišnik 2004; Mihevc and Zupan Hajna 2007; Zupan Hajna 2007; Zupan Hajna, Bosák and Pruner 2007; Stepišnik 2011). Additionally, a detailed morphographic study of an area densely covered by dolines within the Dinaric karst in western Slovenia was performed (Grlj and Grigillo 2014), where it turned out that a great majority of the dolines are filled with sediment and flowstone which clearly justify the paradigm proposed by Bahun (1969). If we summarise contemporary descriptions of doline morphogenesis, we can label most dolines as *intersection dolines*, as defined by Sauro (2012). Dolines of this type are depressions formed when subsurface cavities, partially or totally filled with sediments, are completely denuded due to dissolutional lowering of the surface. The opening of such fossil caverns leads to evacuation of infill and formation of closed depressions. On the bottom of such dolines, relicts of cave fillings and pieces of flowstone have been found (Sauro 2003; 2012; Grlj and Grigillo 2014).

Furthermore, re-examination of the solution doline cross-section at the Logatec train station provided by Cvijić (1893) revealed that the most reproduced example of a solution doline is not a doline at all (Šušteršič 1994). It turned out that the most important illustration of a doline cross-section is actually a bogaz or a karst corridor (Tîrlă and Vijulie 2013). Since it was established that the structure presented by Cvijić is not a doline, a new holotype of a solution doline has been defined (Šušteršič 1994). The area of Skalčen Kamen about 6 km southeast of Logatec (Slovenia) was among the numerous examples of solution dolines provided by Cvijić (1893). Šušteršič (1994) defined it as the new holotype of a solution doline. Detail study of sediments and application of subsurface electrical resistivity tomography also proved that the new holotype was not a doline but rather a denuded cave (Stepišnik 2015).

4 Discussion

The most important process on the karst surface is chemical weathering. Logical deduction implies that the most common forms on the karst surface will also be formed by the actions of solutions. Since Cvijić (1893) mistakenly described the cross-section of a bogaz as the cross-section of a doline (Šušteršič 1994; Stepišnik 2015), karstological literature has subsequently summarized that dolines are forms developed by the action of solution. In addition, since determining the new holotype for a solution doline, no one has subsequently questioned the paradigm that medium-sized closed depressions in the karst are formed by solution, even though it has been established that such features are actually of a different origin (Stepišnik 2015).

This selection of Cvijić's paradigm has occurred through a misinterpretation of the formation of surface features (Šušteršič 1994). As a consequence, it has been cited in karstological literature for more than 100 years.

A careful overview of all the geomorphologic literature proved that all definitions of solution dolines, although later slightly altered and upgraded, are derived from Cvijić's definition written in 1893.

What does all that mean from an educational perspective? Although we are aware that the karst terminology is not widely taught around the world at primary or secondary school levels, we can still find quite a considerable amount of specific karst definitions (e.g. doline) written in school textbooks (see Table 1) of some countries where karst phenomena can be found.

Table 1: Examples of a definition of a doline in selected geography textbooks.

AUTHOR/PUBLICATION	DEFINITION
Bethemont, J. 1967: Géographie générale: classe de seconde.	»*La surface du plateau est creusée de cavités souvent circulaires: on les appelle dolines.*« »The surface of the plateau is often dug with circular cavities named dolines.«
Podgórski, Z., Marszelewski, W., Becmer, K. 2002: Geografia część 1. Zarys wiedzy o Ziemi.	»*Lej krasowy – forma wklęsła o kolistym lub owalnym zarysie powstała w wyniku zawalenia się stropu niewielkiej groty.*« »Sinkhole – concave form with a circular or oval contour resulted from the collapse of the ceiling of a small cave.«
Waugh, D. 2009: Geography: An Integrated Approach.	»*If the area above an individual cave collapses, a small surface depression called a doline is formed.*«
Cook, I. et al. 2000: Geography in Focus.	»*Smaller depressions, from a few metres to over a kilometre in diameter, are called 'dolines'.*«
Whittow, J. 2000: The Penguin Dictionary of Physical Geography.	»*Doline, a term for a circular hollow or depression in the surface of karstic terrain (karst), in which the funnel-shape may or may not lead down into a vertical shaft descending into the limestone. It varies in size from 10 m to 100 m in diameter and is initially caused by solution. It is usually the site at which a stream disappears underground (sink-hole, swallow-hole).*«

Obviously, the definition, rooted in scientific and educational literature for more than 100 years, is going to be hard to change. Although the use of modern measuring techniques and scientific apparatus has confirmed the error, a paradigm shift is yet to occur.

The models sometimes break down when extrapolated (Simanek 2000) and this also happens in the case of solution dolines. If Cvijić had rigorously tested his model for validity, in a wide range of situations, these tests should have been capable of exposing any flaws in the model. Even if his model survived such testing, so many years ago, this should only have granted it conditional acceptance, because there is always a strong possibility that in the future, people with more sophisticated techniques and a more advanced scientific conceptual framework, may expose deficiencies in the model that went unnoticed (Simanek 2000).

The challenge then – and it is especially important for educators to appreciate this – is learning how to deal with the information (Allchin 2004). Regarding the definition of solution dolines, Cvijić did not think critically enough about his claims, and he probably did not use a variety of study methods, nor enhance his observations with quantitative measurements, which would reinforce his claims with multiple lines of evidence.

We agree that the remedy for tentativeness in science is the active analysis of potential errors, guided by an awareness of error types, and that analysis may qualify the scope or certainty of conclusions and guide policy accordingly (Allchin 2004). However, the most important question remains: How can we reach teachers and educators at different educational levels if they tend not to read scientific literature or have no professional urge to follow the development of the science they teach? First, in the countries where curricula and/or syllabi are very precisely written (when sometimes not only concepts but also notions are included) we should start with curriculum and/or syllabus changes. They are the basis (at least in many European countries) for textbooks and other teaching tools used in schools (especially at primary and secondary levels). Teachers sometimes stick to textbooks without seriously considering the possibility that all their contents might not be correct, or might change, due to developments in science.

The analysis of some textbooks proved that once made, an obsolete interpretation could remain unchanged and unchallenged for decades. Such old paradigms are still present in many English language textbooks (e.g. Waugh 2003) as well as in textbooks from countries within the Dinaric karst (Cunder et al. 2001; Senegačnik, Drobnjak and Vovk Korže 2002; Gams 2003). Those textbooks sustain the old outdated explanation of solution dolines provided by Cvijić (1893).

If a teacher does not embrace the life-long learning process, they might make serious mistakes in their teaching. Part of the answer undoubtedly lies in a thoughtful higher education (especially in the education of future teachers) that should implement and evolve the idea of constantly questioning everything and accepting nothing on trust. On the other hand, experts should strive harder to bring their new discoveries, ideas and concepts into everyday educational practice. They should also be more involved in the whole educational sphere from primary to tertiary level, particularly in curricula/syllabi development as well as in the development of textbooks and other teaching tools.

5 Conclusion

Science is continually uncovering new findings, ideas, concepts and paradigms. In some cases, rather awkward situation can occur when old obsolete paradigms are strongly accepted by scientific and general community. Such a situation concerning solution dolines, presented in this paper, is still ongoing. Even though there is an abundance of evidence, which supports the ideas that solution dolines are not formed primarily due to solution of the karst surface, the new ideas and concepts are not generally accepted, neither within the scientific nor the general community.

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NOVA PARADIGMA KOROZIJSKIH VRTAČ

1 Uvod

Napredek sodobnega krasoslovja je prinesel popolnoma nove poglede na razumevanje dinamike in mehanike kraških procesov. Najpomembnejši mejnik v krasoslovju, ki je zamajal nekatere starejše koncepte, je nedvomno opredelitev brezstropih jam in njihovega nastanka (Mihevc 1996; 1998; 2001; 2007; Mihevc in Zupan Hajna 1996; Mihevc, Slabe in Šebela 1998). Danes kraškega površja več ne razumemo kot statičnega, ki naj se ne bi spremenil od nekdanje hipotetične predkraške faze (Sweeting 1973). Sodobna interpretacija kraškega površja je veliko bolj dinamična. Hkrati morfogenezo velikega deleža srednje velikih kraških kotanj po eni strani pripisujemo speleogenetskim procesom v podzemlju in po drugi strani denudacijskemu zniževanju kraškega površja (Mihevc 2001). V zadnjih dveh desetletjih se je pojavila tudi cela vrsta interpretacij nastanka površinskih kraških oblik, vključno z vrtačami kot enimi najbolj tipičnih in prepoznavnih površinskih oblik.

Vse od začetka raziskovanja krasa so bile vrtače pojmovane kot diagnostična kraška oblika (Ford in Williams 2007) ali kot osnovna enota kraškega površja, ki nadomešča doline v fluvialnih sistemih (Sweeting 1973). Mallot (1939 v: Sweeting 1973, 52) jih je opisal kot obliko z »… *blago padajočimi, s prstjo pokritimi pobočji in ravnim dnom … ki se je v veliki meri razvila s korozijo pod prstjo …*«.

Mednarodni termin *doline* je slovanskega izvora in v osnovi pomeni dolino, verjetno zato, ker so bile to najbolj pogoste kotanje v pokrajini dinarskega krasa (sliki 1 in 2), v kateri je le nekaj pravih rečnih dolin. Termin *doline* je v mednarodni znanstveni literaturi uveljavil Cvijić (1893), medtem ko se bolj pravilen krajevni izraz »vrtača«, ki ga je prav tako uvedel Cvijić (Šušteršič 1994), uporablja na slovenskem klasičnem krasu. Uporaba termina *doline* je zdaj že tako zakoreninjena v kraški literaturi, da bi ga bilo, kot pravi Gunn (2004), brezplodno spreminjati.

Vrtače so zaprte kraške kotanje različnih oblik, ki v premeru merijo od nekaj deset do tisoč metrov (Šušteršič 1994). Njihov nastanek je posledica različnih procesov z različno dinamiko, katerih posledica je umik materiala s površja. Glede na proces nastanka ločimo korozijske vrtače, udorne vrtače, udornice, pogrezne vrtače, sufuzijske vrtače (Ford in Williams 2007).

Slika 1: Vrtače na severovzhodnem delu Glamočkega polja.
Glej angleški del prispevka.

Članek se ukvarja s korozijsko vrtačo kot najbolj osnovno vrsto vrtač. Namen članka je ponovno prevetriti paradigmo nastanka korozijskih vrtač. Uvodni del članka se ukvarja z nastankom paradigme korozijskih vrtač ter podaja pregled obstoječe kraške literature, ki se ukvarja z različnimi načini nastanka ter s hidrološko funkcijo korozijskih vrtač. Glavni cilj je pregled razumevanja morfogeneze korozijske vrtače v različnih publikacijah. Hkrati obravnavamo pregled integracije zastarele paradigme v današnjo znanstveno in izobraževalno literaturo z glavnim namenom osvetliti problem zakoreninjenosti zastarele paradigme.

2 Razvoj korozijske paradigme

Udor jamskega stropa je najstarejša morfogenetska razlaga za vse krožne kotanje v kraški pokrajini. Začetnik udorne teorije je bil Gruber (Williams 2003), ki je za opis teh oblik uporabil termina *gruben* in *kessel*. Pozneje so raziskovalci dinarskega krasa, vključno z Schmidlom, Tietzejem, Stacheom, Reyerjem in Marenzijem, v sredini 19. stoletja za te zaprte kotanje potrdili udorno teorijo (Gams 2003).

Na podlagi raziskovanja kraške pokrajine v Bosni je Mojsisovics razdelil kraške kotanje v dve morfogenetski skupini in sicer v tiste, katerih nastanek povzroči udor, in tiste, katerih nastanek je posledica korozije (Cvijić 1893). Kasneje se je teorija korozijske geneze kraških kotanj postopoma razvijala v delih številnih raziskovalcev (Gams 2003). Konec 19. stoletja je zaznamovalo sistematično geološko in speleološko raziskovanja kraških območij. Monografija o kraških oblikah, ki jo je napisal Cvijić (1893), je imela velik vpliv na krasoslovje kot znanost, obenem pa je omogočila boljše razumevanje kraških kotanj različnega nastanka. Cvijić je združil vse kraške oblike v celoto in predstavil celotno kompleksnost kraške pokrajine (Gams 2003). Med številnimi natančno razloženimi kraškimi pojavi so bile opisane tudi srednje velike zaprte kotanje, ki jih je poimenoval vrtače. Vrtače je prepoznal kot oblike, ki dajejo kraški pokrajini specifičen značaj (Šušteršič 1994). Cvijić je v svojem delu vrtače razdelil v štiri glavne skupine in ta razdelitev je ostala v splošni rabi vse do danes. Med vsemi oblikami so bile vrtače najbolj proučevane, a ostajajo najmanj razumljene. Čeprav vrtače nastanejo na različne načine, je Cvijić trdil, da najbolj tipične vrtače nastanejo z delovanjem korozije (Cvijić 1893). Trdil je, da naj bi na mestu vrtače prihajalo do intenzivne korozije s posledičnim zniževanjem površja ter razpadanjem kamnine. Navedel je številne primere s celotnega območja dinarskega krasa ter celo ponudil primer prereza vrtače; gre za območje prelomne cone, po kateri odtekajo padavine, in je posledično pospešeno raztapljanje, na podlagi katerega je razložil morfogenetski nastanek vseh korozijskih vrtač (Šušteršič 1994). Izbran primer prereza vrtače se nahaja ob železniškem vseku pri postaji v Logatcu. Ta skica prereza korozijske vrtače je postala ena od najpogosteje navajanih v vsej geomorfološki literaturi.

Cvijić trdi, da oblikovanju zaprtih kotanj na površju ter raztapljanju kamnine v raztopino botrujejo tudi glina in naplavina v kotanji (Cvijić 1893). Večje razpoke ujamejo večino odtoka in zato predstavljajo žarišče raztapljanja matične kamnine. Na teh točkah se tako raztopi večja količina materiala kot v okolici, kar postopoma oblikuje reliefne kotanje, medtem ko se celotno površje znižuje zaradi kemične denudacije (Cvijić 1893). V primerih, kjer je raztapljanje prevladujoč mehanizem, se bodo najverjetneje oblikovale skledaste kotanje. Količina apnenca, ki ga korozija lahko odstrani, je odvisna od koncentracije topila in prostornine topljenca. Zaradi možnih variacij obeh spremenljivk lahko pride do fokusiranja raztapljanja v bližini središča kotanje. Kakorkoli, ko se enkrat ta proces začne, se oblikovanje vrtače nadaljuje samo od sebe (Cvijić 1893; Sweeting 1973; Šušteršič 1994; Williams 2003).

Slika 2. Vrtače na Biokovu.
Glej angleški del prispevka.

Čeprav je raztapljanje začeten in dominanten proces, lahko tudi drugi dejavniki, kot je na primer udor, prispevajo k nastanku vrtač (Ford in Williams 2007). Vendar le z lokalnimi razlikami v koncentraciji topila ne moremo razložiti pojava korozijskih vrtač. Če bi bilo tako, bi jih morali najti na vsaki vrsti apnenca v danih podnebnih območjih, čemur pa ni tako (na primer v Angliji so vrtače najbolj pogoste na karbonskem apnencu ter manj pogoste na krednem in jurskem apnencu) (Ford in Williams 2007). Iz tega sledi, da morajo biti lokalne prostorske variacije v vodnem toku odločujoče za to, kje se bo osredotočilo raztapljanje (Ford in Williams 2007). Po Fordu in Williamsu (2007) je treba razlikovati med nastankom vrtače tam, kjer ni bilo predhodnega razvoja jame, in tam, kjer je bila že obstoječa prepustna vadozna cona, podedovana iz zgodnejše faze zakrasevanja.

Prepustnost in poroznost apnenca tudi lahko vplivata na nastanek vrtač. Visoka prepustnost in hidravlična prevodnost, skupaj z velikimi razlikami v poroznosti zgornjega dela vadozne cone, vodi v razvoj korozijskih vrtač (Williams 2003; Ford in Williams 2007).

Podobno lahko na korozijo vpliva tudi porazdelitev prsti in drugih nekarbonatnih sedimentov (Sweeting 1973). Naslednji pomemben dejavnik je rastlinstvo, posebej drevesa, ki tudi sodelujejo pri nastanku vrtač. Okoli dreves je ogljikov dioksid v prsti zelo obogaten zaradi mehaničnega in kemičnega delovanja korenin, akumulacije organskih odpadkov in povečane rasti gliv in drugih rastlin. To je še posebej pomembno v Alpah, kjer se vrtače pogosto pojavljajo skupaj ob gozdni meji – tako so poraščena območja v Alpah tudi območja vrtač (Sweeting 1973).

3 Sodobno razumevanje morfogeneze korozijske vrtače

Vedno boljše razumevanje lastnosti kraških oblik in procesov je vodilo k popolnoma novemu pristopu v razlagi nastanka vrtač. Že sprejete razlage morfogeneze korozijske vrtače zaradi razlik, pogojenih s površinsko denudacijo, so bile počasi nadgrajene z novimi paradigmami. Bahun (1969) je govoril o nastanku vrtač v dveh fazah. Prva faza je faza zniževanja kraškega površja zaradi eksogenih procesov, kemičnega preperevanja pod površjem in razširitve različnih razpok. Z denudacijo površja se pojavijo votline, kar vodi v nastanek različnih kotanj na kraškem površju. Druga faza je čista modifikacija površinske oblike zaradi korozijskih procesov, postopne spremembe morfologije in umika pobočja (Bahun 1969; Stepišnik in Kosec 2011).

Najnovejše razlage korozijskih vrtač pripisujejo večji pomen procesom v epikraški in vadozni coni. Postalo je jasno, da epikraška cona deluje kot zbiralec razpršenih vodnih tokov, povečuje njihovo koncentracijo, kar vodi v oblikovanje brezen znotraj vadozne cone (Klimchouk 2004; Ford in Williams 2007). Zaradi denudacije površja sčasoma pride do lokalnega udora stropa brezna in njegovega odprtja proti površju. Naknadno zmanjševanje naklona sten brezna vodi v nastanek lijakaste kotanje, ki jo imenujemo vrtača (Klimchouk 2004).

Slika 3: Mehanizem nastanka vrtače kot rezultat razpada vadoznega brezna (Klimchouk 2004).
Glej angleški del prispevka.

Proučevanje zgradbe vrtač in vrtačam podobnih kotanj pod površjem s pomočjo različnih metod na območju dinarskega krasa dokazuje (Stepišnik 2008; 2011; Stepišnik in Mihevc 2008; Mihevc in Stepišnik 2011; 2012), da je večina vrtač zapolnjena z drobnozrnatimi sedimenti. Glina in melj v vrtačah preprečujeta podzemni odtok, ki povzroča lokalno zniževanje površja. Poleg tega je natančno proučevanje mineralov pokazalo, da so glineni sedimenti v dnu vrtače večinoma alogeni, ki izvirajo iz fliša. Skoraj popolna odsotnost eolskih sedimentov dokazuje, da je večina vrtač rezultat razpadanja jamskih prostorov zaradi denudacijskega zniževanja površja (Mihevc 2001; 2007; Stepišnik 2004; 2011; Mihevc in Zupan Hajna 2007; Zupan Hajna 2007; Zupan Hajna, Bosák in Pruner 2007). Natančna morfografska študija (Grlj in Grigillo 2014) območja na dinarskem krasu zahodne Slovenije, gosto pokritega z vrtačami, je pokazala, da je velika večina vrtač napolnjena s sedimenti in sigo, kar jasno potrjuje Bahunovo paradigmo (1969). V kolikor povzamemo sodobne opise morfogeneze vrtač, lahko večino označimo kot *presečne vrtače,* kot jih je definiral Sauro (2012). Vrtače tega tipa so kotanje, ki so nastale, ko so votline pod površjem, ki so delno ali v celoti zapolnjene s sedimenti, popolnoma denudirane zaradi korozijskega zniževanja površja. Odprtje takšnih fosilnih votlin vodi do izpraznitve polnila in nastanka zaprtih kotanj. Na dnu takšnih vrtač so našli ostanke jamskih polnil in kose sige (Sauro 2003; 2012; Grlj in Grigillo 2014).

Poleg tega je ponovna preučitev prereza korozijske vrtače ob železniški postaji v Logatcu, ki ga je navedel Cvijić (1893), pokazala, da ta najbolj citiran primer korozijske vrtače sploh ni vrtača (Šušteršič 1994). Izkazalo se je, da je najbolj pomembna ilustracija prereza vrtače dejansko prerez preko bogaza oziroma kraškega jarka (Tîrlă in Vijulie 2013). Ko je bila Cvijičeva zmota pojasnjena, je bil določen nov holotip korozijske vrtače (Šušteršič 1994). Območje Skalčnega kamna, ki se nahaja približno 6 km jugovzhodno od Logatca, je bilo med Cvijićevimi (1893) najbolj pogosto navajanimi primeri korozijskih vrtač. Šušteršič (1994) je to območje definiral kot nov holotip korozijske vrtače. Natančna proučitev sedimentov in uporaba podpovršinske tomografije z metodo električne prevodnosti pa dokazuje, da nov holotip ni vrtača, temveč prej brezstropa jama (Stepišnik 2015).

4 Razprava

Najbolj pomemben proces na kraškem površju je kemično preperevanje, iz česar bi sklepali, da bodo tudi najbolj tipične oblike na kraškem površju nastale z delovanjem korozije. Odkar je Cvijić (1893) zmotno opisal prerez bogaza (kraškega jarka) kot prerez vrtače (Šušteršič 1994; Stepišnik 2015), krasoslovna literatura navaja, da vrtače nastanejo s korozijo. Tudi kasneje, ko je bil določen nov holotip korozijske vrtače (Šušteršič 1994), nihče ni podvomil o paradigmi korozijskega oblikovanju zaprtih kotanj na krasu, čeprav je bilo ugotovljeno, da gre dejansko za drugačen nastanek teh oblik (Stepišnik 2015).

Cvijićeva paradigma, ki je nastala zaradi napačne interpretacije nastanka površinskih oblik (Šušteršič 1994), se že več kot stoletje citira v krasoslovni literaturi. Pregled geomorfološke literature dokazuje, da vse definicije korozijskih vrtač, čeprav nekatere nekoliko spremenjene in dopolnjene, izhajajo iz Cvijićeve definicije, zapisane leta 1893.

Kaj vse to pomeni z vidika izobraževanja? Čeprav se zavedamo, da se po svetu le redko učijo o kraški terminologiji tako na osnovnošolski kot na srednješolski ravni, pa vendar lahko v šolskih učbenikih predvsem tistih držav, v katerih se nahajajo kraški pojavi, najdemo precejšen delež specifičnih kraških definicij, na primer vrtače (preglednica 1).

Preglednica 1: Primeri definicij vrtače v izbranih geografskih učbenikih.

AVTOR/PUBLIKACIJA	DEFINICIJA
Bethemont, J. 1967: Géographie générale: classe de seconde.	»*La surface du plateau est creusée de cavités souvent circulaires: on les appelle dolines.*« »Površje planote je pogosto izdolbeno s krožnimi kotanjami, imenovanimi vrtače.«
Podgórski, Z., Marszelewski, W., Becmer, K. 2002: Geografia część 1. Zarys wiedzy o Ziemi.	»*Lej krasowy – forma wklęsła o kolistym lub owalnym zarysie powstała w wyniku zawalenia się stropu niewielkiej groty.*« »Vrtača – konkavna oblika s krožnimi ali ovalnimi obrisi, ki je nastala z udorom majhne jame.«
Waugh, D. 2009: Geography: An Integrated Approach.	»*Če se območje nad posamezno jamo udre, nastane majhna površinska kotanja, imenovana vrtača.*«
Cook, I. in sod. 2000: Geography in Focus.	»*Manjše kotanje, ki v premeru merijo od nekaj metrov do več kot kilometer, se imenujejo vrtače.*«
Whittow, J. 2000: The Penguin Dictionary of Physical Geography.	»*Vrtača, ime za krožno kotanjo ali kotanjo na kraškem površju (kras), katere lijakasta oblika lahko ali pa tudi ne vodi navzdol v navpično brezno, ki se spušča v apnenec. Razlikujejo se v velikosti premera od 10 m do 100 m in v osnovi nastanejo zaradi korozije. V njej običajno vodni tok izgine pod površje (požiralnik, ponikev).*«

Očitno bo definicijo, ki je zakoreninjena v znanstveni in izobraževalni literaturi že več kot 100 let, izjemno težko spremeniti. Čeprav je uporaba modernih merilnih tehnik in znanstvenega aparata potrdila napako, bo moralo do spremembe paradigme šele priti.

Ob ekstrapolaciji modeli pogosto ne držijo (Simanek 2000) in ravno to se dogaja v primeru korozijskih vrtač. V kolikor bi Cvijić natančno preizkušal veljavnost svojega modela v različnih razmerah, bi testiranje gotovo izpostavilo napake v modelu. Tudi če bi njegov model prestal takšno testiranje, bi to lahko zagotovilo le njegovo pogojno sprejetje, saj vedno obstaja velika verjetnost, da bodo v prihodnosti z bolj izpopolnjenimi tehnikami in bolj naprednim znanstvenim okvirom odkrili pomanjkljivosti modela, ki prvotno niso bile zaznane (Simanek 2000).

Zato je predvsem za tiste, ki izobražujejo, zelo pomembno, da se zavedajo izziva in vedo, kako se spopasti z novimi informacijami (Allchin 2004). Cvijić morda ni dovolj kritično razmišljal o svojih trditvah in verjetno tudi ni uporabil različnih metod preverbe ali nadgradil svojih opažanj s kvantitativnimi meritvami, ki bi potrdile njegova opažanja.

Zavedati se moramo, da je v znanosti nujna aktivna analiza potencialnih napak z namenom preverbe ugotovitev in posledičnega ravnanja (Allachin 2004). Ob tem še vedno ostaja odprto ključno vprašanje: kako doseči učitelje in ostale na različnih ravneh izobraževanja, če ti premalo posegajo po strokovni literaturi ali pa ne čutijo potrebe slediti razvoju znanosti, ki jo poučujejo? V državah, v katerih so kurikuli in/ali učni načrti napisani zelo natančno (ko so poleg vsebin in ciljev podani tudi pojmi), bi bilo treba težiti k redni prenovi/preverbi kurikulov ter/ali učnih načrtov. Ti predstavljajo osnovno izhodišče (vsaj v večini evropskih držav) tako za učbenike kot za ostala učila, ki jih uporabljamo v šoli (še posebej na osnovnošolski in srednješolski ravni). Učitelji pogosto nekritično sledijo zapisu v učbenikih, ne da bi podvomili v njegovo morebitno nepravilnost oziroma se zavedali dejstva, da je z razvojem znanosti morda prišlo do sprememb.

Analiza nekaterih učbenikov dokazuje, da lahko zastarela razlaga ostane nespremenjena desetletja. Stare paradigme, vključno s Cvijićevo razlago (1893) korozijskih vrtač, so še vedno zapisane v številnih angleških učbenikih (na primer Waugh 2003) kot tudi v učbenikih držav z dinarskim krasom (Cunder s sodelavci 2001; Senegačnik, Drobnjak in Vovk Korže 2002; Gams 2003).

V kolikor učitelj ne ponotranji vseživljenjskega učenja, lahko dela pri poučevanju vsebinske napake. Del rešitve je gotovo v domišljenem visokošolskem izobraževanju (še posebej pri izobraževanju bodočih učiteljev), ki bi moralo ves čas gojiti idejo stalnega izpraševanja vsega in ničesar ne jemati za samoumevno. Obenem bi se morali strokovnjaki bolj truditi za prenos novih ugotovitev/spoznanj, idej in konceptov v vsakodnevno šolsko rabo. V večji meri bi morali biti vključeni v celotno izobraževalno sfero od osnovnošolskega do visokošolskega izobraževanja, še posebej na področju razvoja kurikulov/učnih načrtov kot tudi na področju učbenikov in ostalih učil.

5 Sklep

Znanost neprestano odkriva nove stvari, ideje, koncepte in paradigme. V nekaterih primerih se soočamo tudi z razmerami, ko so zastarele paradigme tako močno zakoreninjene v strokovni in laični javnosti, da jih je le s težavo mogoče spremeniti. Tako je tudi s korozijskimi vrtačami, katerih problematika je predstavljena v članku. Čeprav je na voljo mnogo dokazov, ki govorijo v prid idejam, da »korozijske vrtače« ne nastanejo primarno zaradi korozije, ne strokovna in ne laična javnost še nista povsem sprejeli novih idej ter konceptov.

6 Viri in literatura

Glej angleški del prispevka.