CLASSIC DOLINES OF CLASSICAL SITE

KLASIČNE VRTAČE KLASIČNEGA KRASA

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Izvleček UDK 551.442 (497.12)

France Šušteršič: Klasične vrtače klasičnega krasa.

Ponovno je bilo proučenih nekaj vrtač, ki jih Cvijić navaja kot šolske primere. Izkazalo se je, da objekt, katerega presek je objavil v svojih monografijah, sploh ni vrtača. Zato je vrtža na lokaciji Skalčen Kamen, označena SK-022, predložena za novi holotip. Na istem kraju je bilo podrobno proučenih 17 vrtač. Kot kaže, so nastale z razpadom kaminov, ne pa kot zbirna območja krajevnih ponorov. Njihova podrobna oblikovanost je posledica pleistocenskega, perinivalnega preoblikovanja.

Ključne besede: vrtača, brezno Cvijić, statistika, klasični kras, pliocen

Abstract UDC 551.442 (497.12)

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Some karst depressions referred by Cvijić as examples of solution dolines were revisited. It came out that the structure presented in section in his works is not a doline at all. Consequently, doline matched SK-022, at the location Skalčen Kamen, is proposed to be new holotipe. 17 dolines at the same location were studied in detail. It appears that they originate from desintegration of dome pits, rather than they evolve from local sinks. The particular shape of their "bowls" is predominantly controlled by the pleistocene peiglacial processes.

Key words: (solution) doline, dome pit, Cvijić, statistics, Classical karst, pleistocene.

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As in many cases concerning the karst, the story began with Jovan Cvijić. This paper presents ideas which arose while revisiting the century old sites of Cvijić'c classical dolines research. The text reproduces my paper given at the session, as well as the topics covered by the field excursion to the sites in question.

ABOUT THE ROOTS

In 1893 (1895) J. Cvijić published his fundamental work, (the) Karst[1]. Among other karst phenomena he exhaustively discussed the medium sized closed karst depressions named dolines[2]. Since that time much work has been carried out on this topic. Surprisingly, at the moment, it does not seem that our understanding about dolines is any clearer. Rather than increased consistency, an overview of the literature reveals quite a divergenece in concepts. Sometimes it is evident that the students are not dealing with the same material, although they are using identical terminology. On such occasions one has to get back to the roots, reinspect the basic literature and - possibly - check the examples in situ.

J. Cvijić (1893, 1895) subdivided dolines into four main groups, and his divisions have in general remained used until the present (D.C. Ford, P.W. Williams, 1989, 398, Fig. 9.13), see also A. Bondesan & al. (1992, 6) . Among these, solution dolines[3] have been

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[1] The two books are of identical title and have essentially the same contents. It is sure that the German version (1893) is the one which set the fundamentals of modern karstology. The Serbian (1895) version is sligtly better elaborated and it presents some Cvijić's responses to the discussions inspired by the first one. I take in consideration the both.

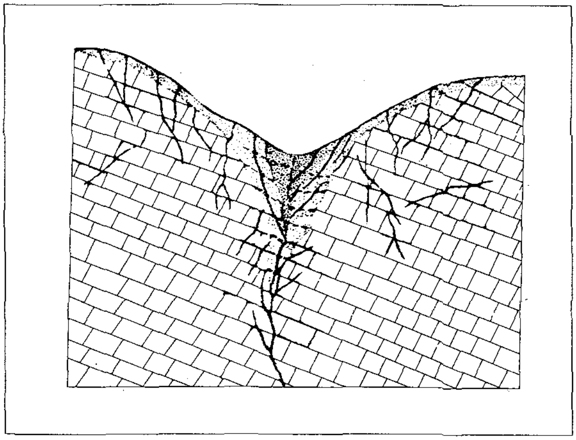
[2] For home use Cvijić introduced the term "vrtača" instead of "dolina(e)". (See footnote 8!) The term "vrtača" has been generally explained as to originate from the verb "vrteti" (= to rotate, to whirl). Two decades of field work in several parts of the classical Karst have convinced me that this explanation may not be proper. Though the expressions "dolina" and "vrtača" prevail, at several places local people use the term "vrt" (= garden). They explain it that a "polje" (= field) is ploughed but a "vrt" is done by hand. The modest extent of fertile soil at the bottoms of many dolines really does not permit any other way of cultivation than rudimentary gardening. However, this linguistic digression would be of little interest for a non-Slav reader, had the "whirling" explanation (tacitely, but selfunderstandably containing the idea of a swallet) not turned at least a part of the research of the dolines in wrong direction.

[3] As in many papers covering the same topic, in the following text the expression "doline" is used in the sense of "solution doline".

the most studied, but also remain the most obscure. Cvijić (o.c.) explained them as the places of more intensive corrosional lowering of surface, controlled by rock fracturing. Obviously such an explanation requires intensive studies of doline cross sections. Though he lists a number of examples from the whole area of former Yugoslavia, he offers only one example of a doline section (J. Cvijić, 1893, 43; 1895, 63). This figure has become one of the most reproduced in the all geomorphological literature (Fig. 1). The remark (o.c.) "Ich habe solche angeschnittene Dolinen in dem zweiten Eisenbahneinschnitt suedlich von Unterloitsch[4] in Krain[5] beobachtet (Siehe Profil)" promises an easy check of our understanding of his ideas.

Unexpectedly, my first visit to this location was fruitless. Even though I searched a number of railroad cuttings some kilometers south of Logatec, no location fitted the drawing. Later I learned that since Cvijić's times the Logatec railway station has been enlarged. Eventually, the first cutting completely disappeared and the last remains of the second one are now part of the station complex. It came out that the object (Fig. 2) is the present state of the "doline", described by Cvijić.

A closer inspection and the map[6] of pre-reconstruction state revealed that Cvijić (Fig. 3, double circle) had observed a section of longitudinal terrain lowering along a



Sl. 1: Cvijićeva skica, ki jo je pomotoma imel za središčni prerez vrtače (J. Cvijić, 1893, 43; 1895, 63).
Fig. 1: Reproduction of Cvijić's drawing, by mistake explained as the central section of a doline (J. Cvijić, 1893, 43; 1895, 63).

4 "Unterloitsch" is the German form of the Slovene place name "Dolenji Logatec". Logatec is Slovene derivation from Roman expression "Longaticum", marked in Tabula Peutingeriana.

5 "Krain" is German form of the Slovene expression "Kranjska" (= Carniola), covering the central part of Slovenia, predominantly the basin of the river Sava.

6 Fig. 3 is redrawn and slightly simplified after the 1:1000 map used during the main reconstruction in the fifties.

crushed zone[7], rather than a doline. If the parent rock were not a quite dolomitized limestone, a good example of a bogaz (Fig. 3, see the linar depression behind the cutting face!) would develop there.

Undoubtedly, Cvijić had seen a number of sagittally transected dolines, and the structure he believed to be a centrally transected doline did not differ a great deal from them. So he was able to continue the former citation (o.c.): "Unter denselben kommen keine Hoehlen vor, der Schichteverband ist nirgends gestoert; vor dem Dolinenboden setzen sich aber zahlreiche Kluefte durch eine Zone verwitterter Kalksteine fort und sind bis in das frisch aussehende, wenig zersetzte Gestein zu verfolgen, welches die Unterlage bildet und ebenfals entbloesst ist.... Alle durchschnittenen Dolinen zeigen dieselben Erscheinungen in groesserem oder kleinerem Masstabe." This is well illustrated by his sketch, and its constant reprinting has only proliferated his notion. But he never did actually see a central section of a doline!

The further expansion of his ideas is easily understood. For him, dolines were the attack-points of surficial waters on the parent rock (o.c., 57 (81): "In den sproeden, reinen Kalksteinen finden sich zahlreiche Angriffspunkte, naemlich verschiedenartige Fugen und Kluefte, es findet laengs derselben eine starke vertikale Erosion oder eine Intensive Aufloesung des Kalksteines statt und bleiben dabei unbedeutenede Loesungsrueckstaende, durch welche die Erweiterung und Vertiefung der entstandenen Dolinen nicht wesentlich beschraenkt wird. In solchen Kalksteinen werden oft die Absorptionsspalten und schmale Roehren zu Ponoren erweitert".

Combined with general belief of the time that the karst is just an episode between two fluvial phases in relief development his misobservation introduced several notions which have become almost axioms. A. Bondesan & al. (1992, 1) say: "From a morphodynamic point of view the doline constitutes an elementary hydrographic unit, comparable to a simple basin, which, with its system of slopes, conveys water to the absorbing points at the bottom into an underground network." Only few readers of Cvijić's later citation (o.c., 57, (81)) feel that the expression "Ponor" is not used in the way it is used elsewhere in the book, i.e.: a swallet, leading to a well formed karst channel, but is used in the way local people do, i.e.: any, even the tiniest, opening able to receive water.

Thus, there are at least two weak points jeopardizing the present expansion of Cvijić's ideas:

1. From his false example it follows that dolines result from locally intensified surficial, possibly subcutanean karstification.

2. Too rigid understanding of the term "ponor" brought about the notion that dolines[8] are small catchement areas.

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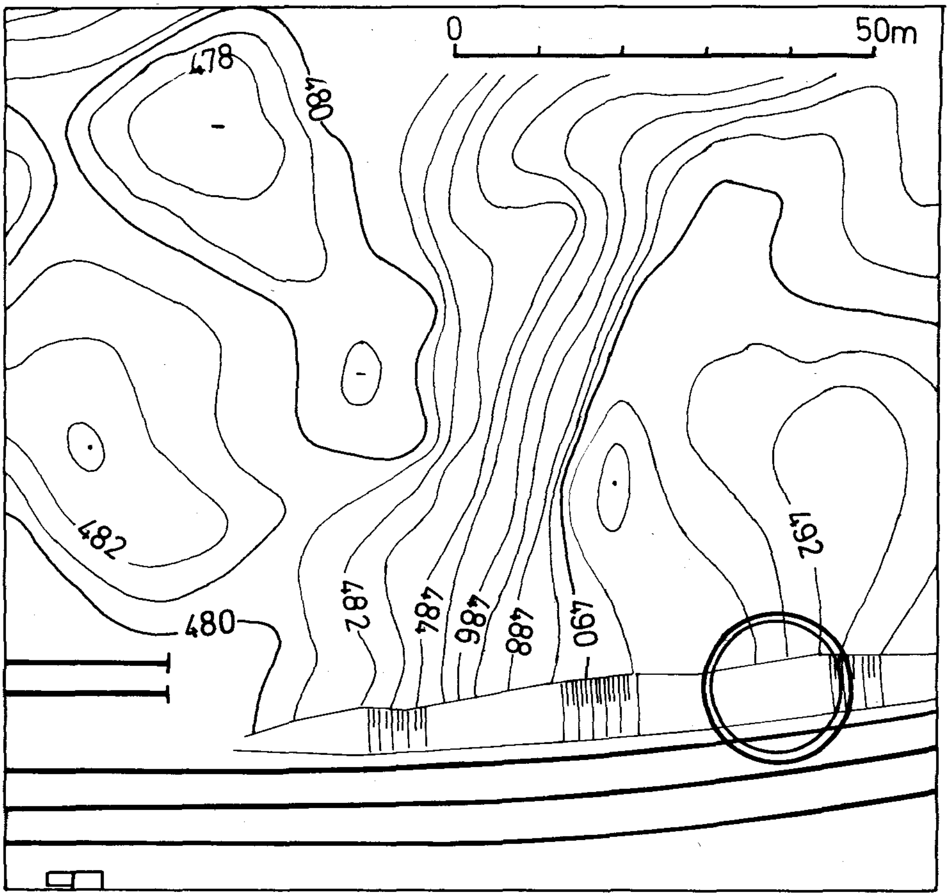
[7] The expression is meant in the sense of S. Šebela and J. Čar (1991, 221).

[8] Even the term "doline" seems to be misunderstood in the least detail. A. Bondesan & al. (1992, 4) wrote "Cvijić (1893) first introduced the name "doline" which means "small valley", to underline the analogy between this form and a small normal hydrographic basin." Cvijić just followed the terminology introduced in 1848 by Morlot (I. Gams, 1974, 20). He was completely aware of very vague meaning of this term in Slav languages, so he used the expression "vrtača" (see footnote 2!) in his Serbian text. "Dolina" (see Fairbridge, R. W., 1968) primarily



Sl. 3: Tloris Cvijićeve "vrtače" in soseščine pred širitvijo postaje v šestdesetih letih.
Fig. 3: Plan of the Cvijić's "doline" and its neighbourhood, before the reconstruction works in the sixties.

means any negative relief form. In the fluvial circumstances it is any stream valley, in the high mountains it is its glacier analogue. In the karst, where surface fluvial features are unknown, it predominantelly means solution or collapse "doline", but sometimes even polje (popularly, the Planinsko polje is called "Planinska dolina"). Cvijić found no reason why to abandon the term "doline" in the scientific language, but he did not intend to stress the analogies with the fluvial system. It was Grund (1914) who "considered their place in the karst landscape to be similar to that of valleys in fluvial terrain" (Ford, D. C., P. W. Williams, 1989, 396). Yet, it is questionable whether the notion of catchment area was so precisely defined at his time as it is today.

The two ideas are hardly consistent, if not contradictory. Nevertheless, a tenet is common for both: dolines are product of surficial processes and the role of underground voids is completely passive.

In order to avoid ambiguity if the holotype of a fossil is lost, paleontologists define paratypes. Cvijić did not reason in this way, but, fortunately, he did mention a number of locations where examples of dolines appear. Among them, the citation (o.c. 44 (65)) "Die Karstplatten und Karstplateaus sind die wichtigsten Obeflaecheformen, auf welchen Dolinen in der Regel in ungeheuerer Menge auftreten. .., wie die Umgebung von Unterloitsch (Ravnik und Scalcen Kamen), ... u.s.w." is very useful, as the location Skalčen Kamen lies only 6 km SE from Logatec station, and it is a well known road crossing.

The location lies in the middle of a forest and it is practically untouched by human activity. In order to check what kind of closed depressions he really did mean when using the term "doline", a detailed study of 17 dolines at this location was carried out in 1992 and 1993.

THE METHOD

In this paper, I present and discuss primarily the results of morphometry. Within a 150 m wide strip in the direction 95° all karst phenomena, including 17 dolines, were studied in detail, and within an about 1 km wide area along the same line, all dolines were mapped. Their position attributes are the locations of the lowest elevation (= "bottom point" in the following text), which were surveyed by compass and meter tape, and later related to the spot elevation points (given grid coordinates), marked on the technical map 1:5000.

The dolines which centres lie within the inner strip were measured, and data processed according to the method described in F. Šušteršič (1985, 1987, and 1989), and discussed by A. Bondesan & al. (1992, 31). The elevation data of 72 measuring points within the doline, arranged in a regular pattern, are shrunk in a small number of Fourier coefficients. It permits a comprehensive reconstruction of the whole doline and computation of practically all descriptive parameters ever defined (see A. Bondesan, o.c.).

When determining the dolines the definition of the perimeter is crucial. If the surrounding terrain were absolutely flat it would probably be no problem. However, clints and other forms of surface karstification induce short wave undulations of about 1 m amplitude, to say nothing about longer waves, or the general trend of the relief. Many authors advocate two boundaries:

1. The terrain divides betwen dolines, as the borders between their influence areas.
2. The actual contour of the closed depression (overflow contour).

According to the experience of my previous work (F. Šušteršič, 1985, 1987), both can be abandoned. The primary reason is operative. Despite the opposite opinion, based predominantly on the use of aerial photos or large scale maps (1:5000), it is relatively easy to determine the doline perimeter on the spot. It is marked by an abrupt change of the slope, though small in its value, dividing the "normal karst surface" and the area influenced by slope processes, induced by local centrical mass defficiency (doline)[9].

On the other hand, there are more substantial reasons. In the karst of the Skalčen Kamen (and the large karst area hundreds of kilometers around it, too) there are no traces of any recent subaerial or epikarstic drainage. The karst is "pure" in the sense of F. Šušteršič (1982, 1986) and the notion of stable divide is untenable. The "overflow contour" would be of paramount importance if the doline depressions operated as lakes during at least one stage of their development. Opposingly, the study of their slopes (F. Šušteršič, 1987) revealed a number of indications of processes which do not respect the "overflow" contour at all.

The method is oriented in the presentation of dolines as a whole, rather than evaluation of single, possibly linear parameters. Nevertheless, the program "VRT" computes 30 simple parametres, some of which are discussed in the following. The numbers, which are used in tables also relate to the numbering in the program output.

(5), (6) - The shortest and the longest radius of the perimeter, according to the bottom point. In Šušteršič(F., 1987) I showed that the opposite slopes of a doline are usually the most different, too, and there is no reason to discuss the diameter.

(8), (9) - The lowest and the highest elevation of the perimeter, according to the bottom point. The measured dolines lie in, although undulating, predominantelly flat terrain, and these parameters express the surface roughness rather than the slope of the general surface.

(10) - Relative volume of the doline, i.e. the volume of the space between the doline sides and the general relief trend. The doline is cut into 360 slices which partial volumes are computed analytically and then added together. However, the notion of the volume depends on dolines history. If they are superimposed in a relatively inert relief the definiton is fair. But if the dolines display different lowering rates between different spots the idea becomes untenable.

(11) - Planimetric area. The doline area within the horizontal projection of the perimeter is cut in 360 slices which partial areas are computed analytically and then added together.

(15) - Shift of the gravity center. Grid coordinates, relative to the bottom point, of the gravity center of the planimetric area are computed. The shift is their Pythagorean sum.

(16) - Azimuth of the shift of the gravity center. In general, dolines are neither symmetric nor of regular shape, and this results in the shift of the gravity center. If there exist preferred directions, the shift may result from some oriented process.

(17) - Normalized shift of the gravity center. When divided by square root of the planimetric area, the shifts of dolines of different sizes become comparable.

(20), (21) - Lengths of the major and minor axis of the (normative) ellipse with equal planimetric area and equal momentum of inertia to the doline ground plane is

[9] It holds true only for the dolines which remained untouched by man. In cultivated land, farmers had obtused their "lips" a long time ago in order to facilitate ploughing or mowing.

computed. Axes of the ellipse were introduced instead of various "diameters" which are highly unstable parameters.

(22) - Direction (azimuth) of the major axis of the normative ellipse.

(23) - Elongation of the normative ellipse. Ratio between the major and the minor axis.

(24) - Length of the axis of the normative cone. The doline is approximated by a rotational cone of equal volume and equal planimetric area of its basal plane. Beacause dolines do not generally lie in flat terrain, the basal plane is obtained by truncation of a vertical cone by the plane, best fitting to the elevations on the doline perimeter. The length of the axis is the vertical distance between the apex and the basal plane. This parameter was introduced instead of various "depths" of the doline.

(25) - Inclination of the normative cone surface. Replaces "average inclination of slopes".

(28) - Shift of the apex. Similar to (15), taking the apex of the cone instead of the planimetric area gravity center.

(29) - Normalized shift of the apex. Similar to (17), taking coordinates of the cone's apex instead of the planimetric area gravity center.

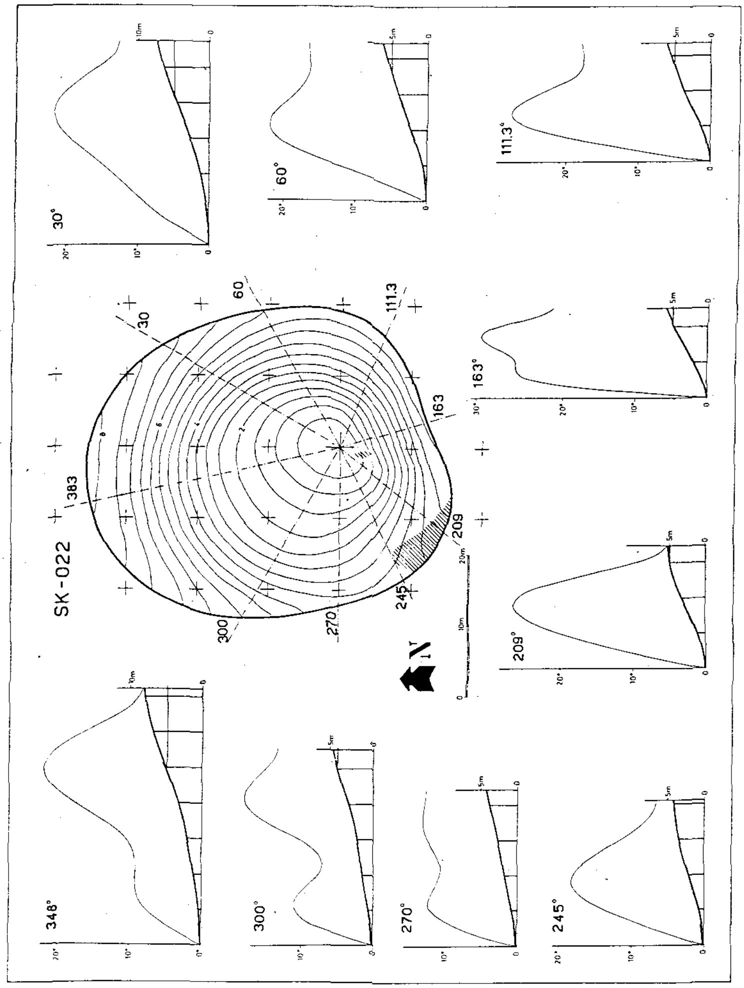
(30) - Direction of the apex position. Similar to (16), taking coordinates of the cone's apex instead of the planimetric area gravity center.

(V/A) - Relative denudation (d) within the doline space may be viewed as the thckness of a slab of equal planimetric area (V = A*d).

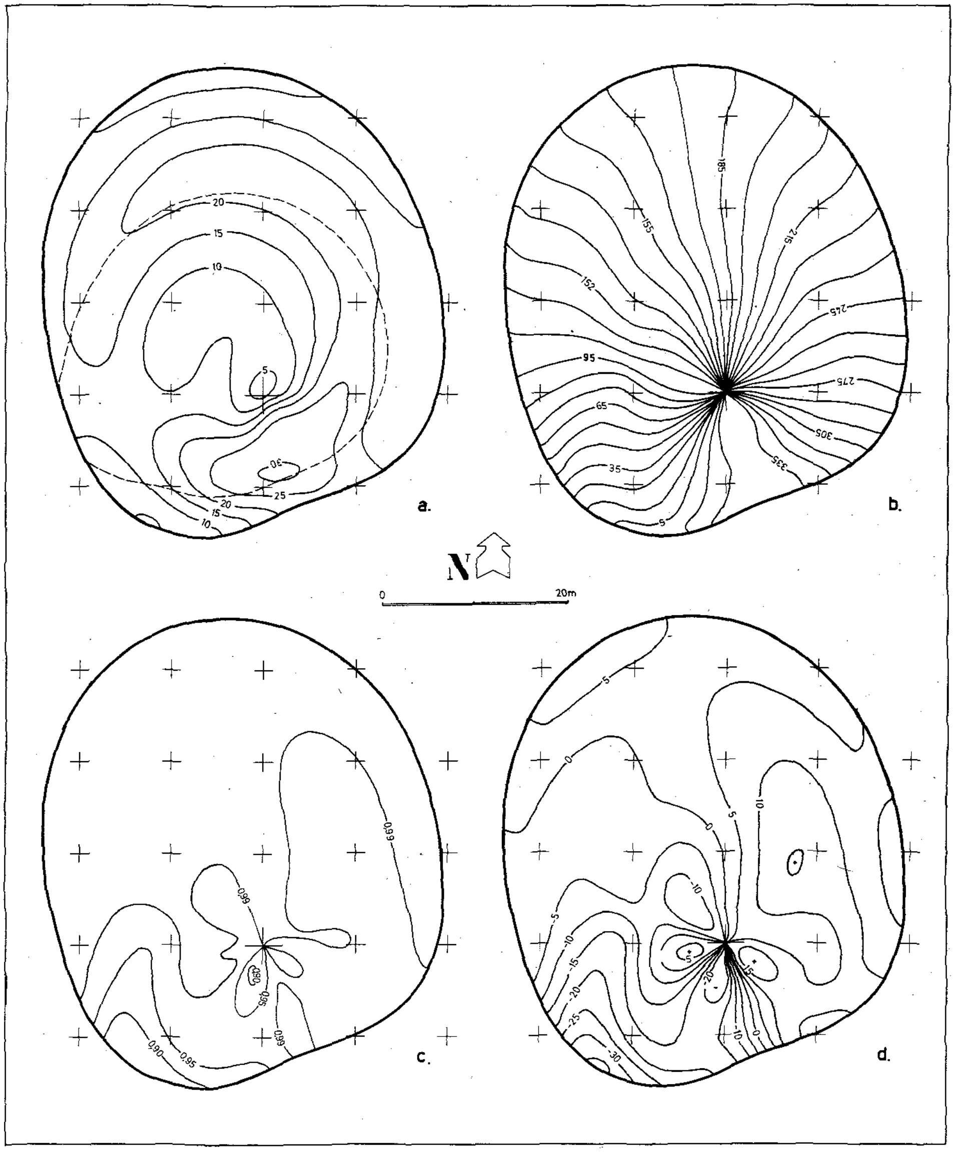
When processing, the information about the doline geometry is transformed into the Fourier coefficients. During further procedure (F. Šušteršič, 1985), it is separated into two packs, containing fundamental shape of the doline, and the noise, respectively. On the base of the former data "undistorted" shape of the doline is recomputed (o.c.). An example is ground plane and some semiprofiles of the doline SK-22 (Fig. 4).

The shape of a geometric figure is described by its derivatives, that is formalized into inclination and aspect angles in geomorphology. Fig. 5/a displays the inclination of the slopes of the same doline, and Fig. 5/b presents their aspects. The broken line in Figs. 5/a and 5/b is the "overflow" contour. The spatial distribution of inclinations within a slope section (see also semiprofiles, Fig. 4) displays a very common pattern: relatively gentle slopes close to the perimeter, evidently greater inclinations further towards the center, and a practically flat area in the middle of the doline. The extreme inclination is south of the bottom point, and will be discussed in the next section. The strip of the minimum inclination west of the bottom is probably a weakly pronounced suture (according to F. Šušteršič, 1987, 80) that is visible also on Fig. 5/b. It is also evident that the aspects tend to approach some preferable directions (and vice versa) rather than to point straight to the center.

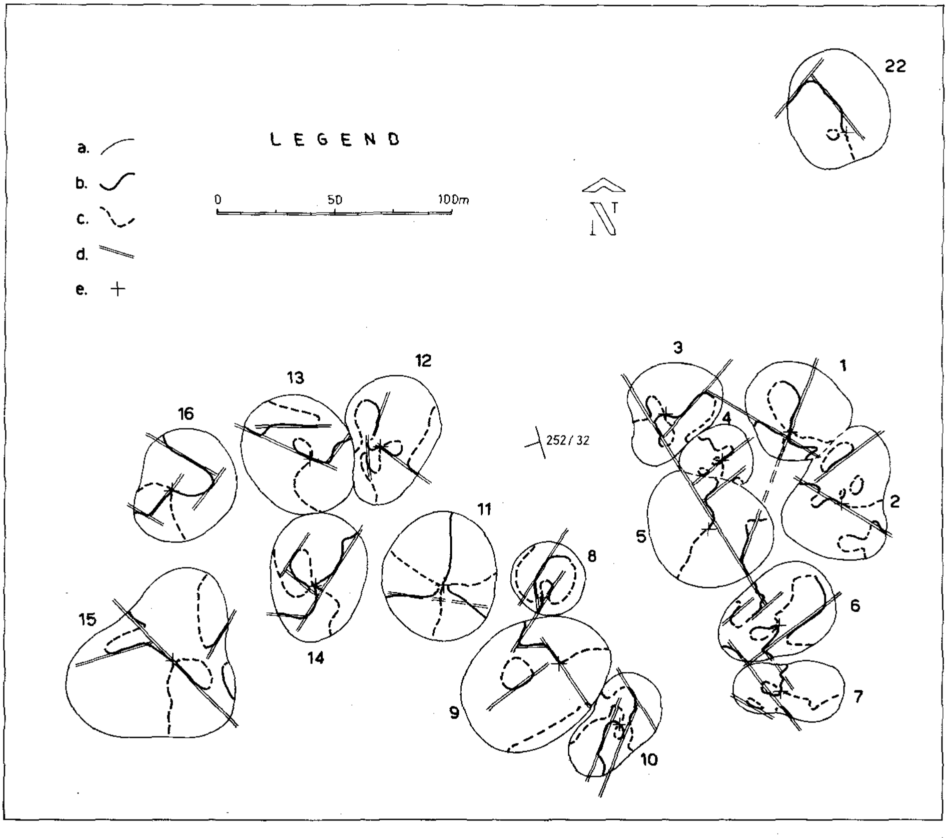
The directional distortion of the slopes provides even more information. At each position the difference between the aspect and straight direction towards the bottom point is computed. Taking cosines of these angles one obtains correlation coefficients between true and ideal shape of the doline (Fig 6/c). At same positions (hatched areas) correlation



Sl. 4: Tloris in nekaj polrezov vrtače SK-022. Korak plastnic znaša 0,5 metra. Črtkana so območja, kjer se padnica pomočja preveč odklanja od smeri proti središču.
Fig. 4: Plan and some semiprofiles of the doline SK-022. Contour lines per 0.5 m. "Nonproper" areas (see text!) are hatched.



Sl 5: Pobočja vrtače SK-022: a/ nakloni pobočij (črtkana črta je "prelivna" plastnica): b/ smeri pobočij; c/ korelacija smeri pobočij s smerjo proti središču; d/ odstopanja od idealne oblike (v stopinjah).
Fig. 5: Slopes of the doline SK-022: a/ slope angles (hatched is "overflow" conture), b/ aspect angles, c/ correlation with the ideal shape, d/ deviations from the ideal shapes (in degrees).



Sl. 6: Privlačne (debelo) in odbojne (črtkano) črte ničelnega odklona v vrtačah pri Skalčem Kamnu. Dvojne tanke črte predstavljajo možne nosilne strukture.
Fig. 6: Attractive (bold) and repulsive (broken) zero deviation lines within the measured dolines at Skalčen Kamen. Double thin lines represent possible geological structures.

is lower than 0.90 (absolute deviation approx. 25°). It means that semiprofiles across these areas are not proper (F. Šušteršič, o.c., 81). They may serve just as information, but must be omitted in numerical taxonomical operations.

Deviation angles are both positive and negative, and obviously there do exist lines of zero deviations (Fig. 5/d). Again, they are attractive if the radial component of the neighboring slope vector is directed towards them, and repulsive if the radial component is directed away. Physically, this means that the attractive zero lines reveal the positions of relative mass deficiency, and the repulsive ones a mass surplus. In other words, the attractive zero lines appear where the karstification is faster (possibly tectonically affected areas), and the repulsive zero lines are found where the rock is either more resistive, or accumulation of slope material appears.

These structures do not generally run in a radial direction; most probably they form a trellis-like network. This pattern is very usual with the buried grikes-and-clints surface outside the dolines (Fig. 6). So, it is quite possibile that there is no difference between the processes acting upon the rock surface, beneath the soil veneer within the dolines and outside of them.

But one restriction must be imposed. Due to relatively small number of measured semiprofiles (6), aliasing in tangential direction is very likely, and along the semiprofiles the higher harmonics were abandoned intentially. Consequently, the pattern may be detected in general lines only, and its details would be better revealed when studying the "noise".

Doline SK-22 is formed in mechanically relatively unresistant rock, so that downslope transport has obscured the underlying limestone surface shaping. Nevertheless, a Dinaric structure and one of its normals are quite distinguishable.

DOLINES AT SKALČEN KAMEN

LOCATION

The location Skalčen Kamen is part of the transect Borovnica and Grčarevski vrh. The project is explained in more in detail in F. Šušteršič (1987, Fig 1.). At the location, roughly indicated by Cvijić (o.c.), all the dolines fitting the main strip of the transect vrh were surveyed. It must be noted that only the area west of the "Krožna pot"[10] has been studied up to the present. The only exception is the doline matched "SK-22" which lies the closest to the actual crossing Skalčen Kamen.

The Skalčen Kamen lies in the Ravnik[11], an approximately 1.5 - 3 km wide, and 13.5

[10] In Slovene it means "circular road". The road was built for forestry purposes as the master communication for effective removal of logs. At the location Skalčen Kamen a secondary road branches off it.

[11] Within the delimited area which was used for density calculations there are 62 dolines while 68 dolines were mapped in total.

km long strip of grossly flat terrain between Begunje and Logatec. In its axial direction it is inclined about 30'. According to occurence of typical sediments it is evident that at some time in Pleistocene, a surface stream running in NW direction penetrated the Ravnik. However, it was just an episode in the completely karstic evolution, and its surprisingly straight flanks imply a predominantly tectonic origin. Unfortunately, a complete geomorphic study has not carried out yet.

The Ravnik surface crosses several carbonate formations of the Mezozoic. At the Skalčen Kamen the bedrock is of Malmian age, mainly limestone with an approx. 38 m thick dolomite intercalation. The dip is uniform, 252.3 / 31.6 (21 measurements, spherical variance = 0.0156). Detailed studies of the rock and the structure have presently been undertaken.

At present, the main courses of the sinking river Ljubljanica, between Cerkniško polje, Planinsko polje, and the Vrhnika springs pass about 100 - 150 m below the surface. Traces of some fossil river caves were found, but vertical shafts prevail, typically not deeper than 20 m. At the actual location there are only five shafts, and two rather ambiguous segments of phreatic tubes.

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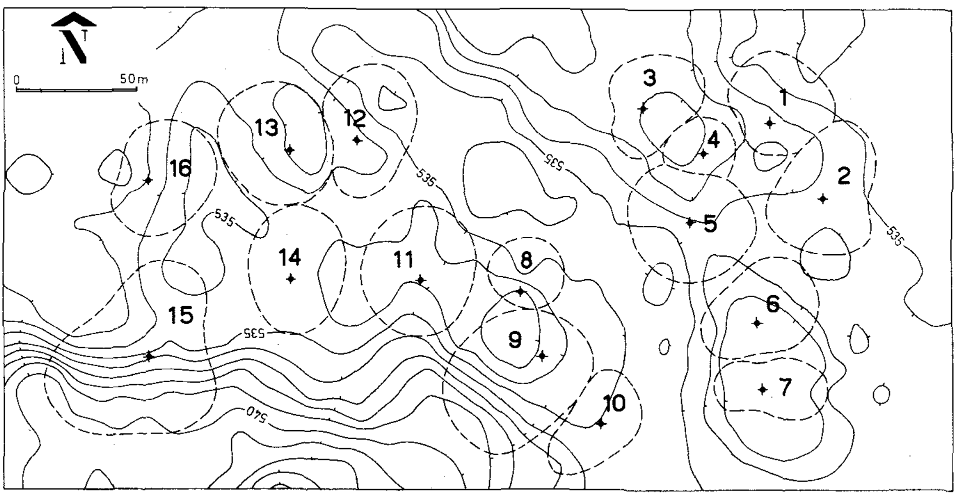
The spatial position of a doline is identified with the grid coordinates (Y, X and Z) of its "bottom point". The central parts of the dolines are generally filled with loose material and relatively flat. Consequently, Easting and Northing coordinates should be taken with



Sl. 7: Računalniška rekonstrukcija "idealnega" reliefa brez vrtač, in njihovi obodi (črtkano)
Fig. 7: Computer reconstruction of the "ideal" relief in the neighbourhood of the measured dolines, and the "lips" of the dolines (broken lines).

relative (about 1 m) tolerance. In order to enable further investigations these positions were marked with metal markers.

The area where all the dolines (62 in total)[11] were registered covers 0.174 km^2, that means the density of 356.1 dolines/km^2. Thus, the influence area of a doline covers 2808 m^2, the radius of the equivalent circle being r = 29.9 m. This density nearly equals the one established on Upper Cretaceous (352.5 per km^2), and differs from the one on Lower Cretaceous (212.2 per km^2) (F. Šušteršič, 1987, 79), in the same transect.

In order to understand the role of the dolines, two patterns are of paramount importance: their planar distribution, i.e the network of lines that they presumably lie on, and their coordination, visualized by the Voronoi diagram. Both the procedures rely upon the relations between points. If the dolines were spaced at greater distances, the question which non-dimesional point should represent the doline, would not be of great importance. However, in conditions when the dimensions of larger dolines exceed the radius of the average influence area it becomes crucial, especially if it is considered that the bottom points do not coincide with the ground plane gravity centres, and both of them with the equivalent cone apices, too. Until the roles of the three are not sufficiently cleared, this interesting question is put aside.

Sixteen dolines lie within the inner strip (Fig. 7) and they permit some insight into their spatial distribution. Among them, only three (SK-11, SK-15, SK-16) stand completely alone. The perimeters of the rest make contact in different ways. Dolines' SK-1 and SK-2, and SK-4 and SK-5 "bowls" cut one another. The intermediate terrain between the SK-6 and SK-7, and SK-3 and SK-4 does not differ from the surface further out from the dolines, but the whole contact lies within a general relief lowering. These two types are well known in literature. Opposingly, the one between the SK-12 od SK-13 which appear literaly intervolved, does not seem to have been encountered before. However, it may be either a single outcome of absolutely local circumstances, or, more seriously, an effect of incorrect definitions. The latter is the object of further study.

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Dolines may be just the spots where local terrain lowering surpasses the general denudation rate, but there is no difference in the actual processes. If it is so, then it is rather risky to view them separately from the surrounding relief.

On the other hand, the mere existence of doline-generated surface processes which reflect in well determined "lip" suffices to accept the working hypothesis that dolines are genetically individuals, lying within a surface of different origin. In that case the "maternal" surface may be extrapolated over the dolines. In order to obtain it 220 spot elevations, mainly on the intermediate terain, and partly on the dolines perimeters were measured. Program Surfer[12] was used to obtain the contour lines (Fig. 7). Due to the lack of experience, all possible default values were retained.

Inspection of the figure is very instructive. The terrain which looked random at first

[12] SURFER Access System Ver. 4.15, Copyright (C) Golden Software Inc. 1989.

sight is well organized in the Dinaric and South-North direction. Nearly all the dolines are gathered within the hypothetical terrain lowerings. Their bottom points lie in relative depression, below the computed 535 m contour, but avoid the extreme low positions.

If the surface shaping determines the dolines position this may mean that at some time - presumably in cold ages of Pleistocene - the surface was relatively impermeable, and that dolines were collectors of surface drainage. But, in that case dolines would occupy the very lowest parts, which is not the case.

On the other hand, if the occurence of dolines in a certain area brought about general lowering of neighbouring relief surface, one would expect that this area was shaped in some specific way. But inspection in the field did not reveal this, and well expressed "lips" imply that the surface development within dolines and outside of them go their own, different ways.

Their predominantly lateral, typically tectonically directioned positions possibly imply that the terrain lowering occurs where the parent rock is more fractured, and that dolines appear on the borders of these zones. The differences may be very tiny and might be revealed by minute tectonic analysis which has not been done yet.

The doline-less strip (noticeable also on Fig. 7), dividing the dolines in two groups approximately matches the dolomite layer. Idealized dolines (normative cones) were projected[13] on a vertical plane stretched in the dip direction (Fig. 8). It is evident that the approximate distance between the two groups fits the horizontal width of the dolomite layer reasonably well, but that they do not coincide. At the bottom the volumes of dolines are projected on the same plane, and further filtered by a cosine bell, as wide as the horizontal section of the dolomite layer. The gap between the two groups is expressed much clearer. It would overlap the dolomite stripe better if the surface were 15 m higher, that corresponds to 250 ka denudation (surface lowering), if taking in account its present rate (I. Gams, 1974, 71). Indications exist that the previously mentioned alluvium is approximatively the same age.

PARAMETRIC PRESENTATION

The following tables present some parametres provided by the program VRT[14]. The intention is primarily to give an impression about the dolines dimensions. However, some parameters, especially when inspected along with the other figures, give quite an insight into the formative processes.

In the first column there are doline labels, while in the first line there are parameter codes, explained at the bottom of the table. The units are metric.

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[13] In fact, the bottom points were projected. The length of the normative cone axis (parameter 24) was used as the "depth", and inclination of its surface (parameter 25) was used as inclination of slopes. Fig. 8 is vertically exaggerated 4 times.

[14] The program is written in QBasic 4.5. The ASCII code or compiled version are available with the author or at the Karst Research Institute, ZRC SAZU, 66 230 Postojna, Titov trg 2, Slovenia.

Table 1

	5	6	8	9
SK-001	13.41	29.38	2.84	8.15
SK-002	17.57	33.52	2.94	8.80
SK-003	12.88	27.53	2.74	6.70
SK-004	7.48	17.69	2.20	5.18
SK-005	21.42	28.96	4.77	10.43
SK-006	12.81	29.93	3.06	9.03
SK-007	9.08	27.53	1.66	7.93
SK-008	6.89	23.55	0.56	5.20
SK-009	19.77	45.47	3.98	12.49
SK-010	12.82	26.65	2.60	6.68
SK-011	22.96	31.14	7.46	10.82
SK-012	10.32	32.32	2.04	8.23
SK-013	19.56	32.04	3.48	7.47
SK-014	18.27	32.26	5.53	7.33
SK-015	22.62	47.51	7.15	17.19
SK-016	13.78	28.80	5.16	9.54
SK-022	12.60	36.12	4.20	8.26

(5), (6) - the shortest and the longest radius
(8), (9) - the lowest and the highest elevation of the perimeter

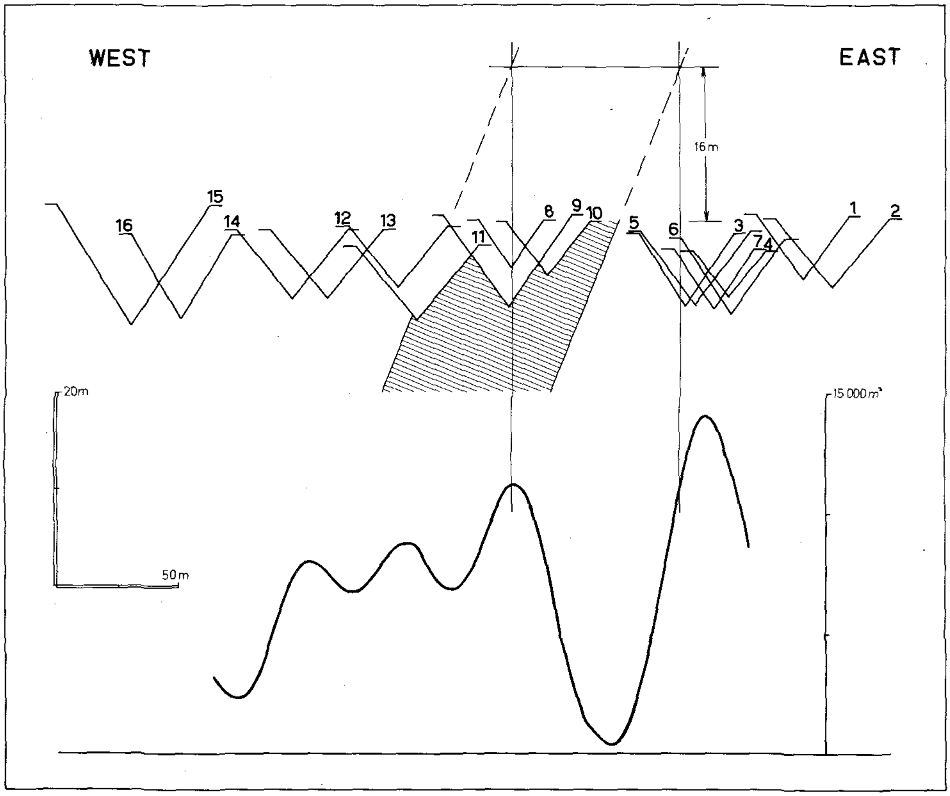
These parameters provide only information about the dolines size order. It is also evident that they are far from geometric regularity.

Table 2

0	10	11	V/A	24	25
SK-001	3351.33	1513.18	2.21	6.64	18.35
SK-002	4532.41	1947.35	2.33	6.98	17.00
SK-003	3146.03	1266.97	2.48	7.45	21.52
SK-004	979.37	632.25	1.55	4.65	21.20
SK-005	5379.75	2105.58	2.55	7.66	17.46
SK-006	4106.44	1544.47	2.66	7.98	20.61
SK-007	2062.63	979.06	2.11	6.32	22.57
SK-008	1290.12	780.76	1.65	4.96	19.60
SK-009	8616.05	2737.43	3.15	9.44	18.62
SK-010	2114.28	1161.52	1.82	5.46	16.24

SK-011	5486.18	2101.92	2.61	7.83	17.95
SK-012	3522.64	1649.21	2.14	6.41	17.83
SK-013	4603.63	1955.86	2.35	7.06	17.15
SK-014	4287.95	1805.59	2.37	7.12	17.54
SK-015	*16026.07*	*3835.63*	*4.18*	*12.53*	*20.26*
SK-016	4714.52	1627.57	2.90	8.69	22.22
SK-022	4414.83	1753.64	2.52	7.55	19.01

(10) - relative volume of the doline, (11) - planimetric area, (V/A) - relative lowering, (24) - length of the axis of the normative cone, (25) - inclination of the normative cone surface ( ).



Sl. 8: Zgoraj: normativni stožci izmerjenih vrtač in dolomitna skladovnica (črtkano), projicirani na navpično ravnino skozi padnico skladov. Štirikratno previšanje. Spodaj: Projekcija zbistrenih prostornin na isto ravnino (glej besedilo!).
Fig. 8: Top: normative cones of masured dolines and the dolomite layer (hatched), projected on a vertical plane running in the dip direction. 4 X vertical exageration. Bottom: Projection of filtered dolines volumes (See text!)

The volumes (10) and the planimetric areas (11) indicate primarly the size order of the dolines. Values of their quotients are predominantly 2.1 to 2.7. It follows that the relative surface lowering within the doline perimeter amounts to about 2.4 m in general (Fig. 9/a). The quotient is larger with the dolines SK-009, SK-015 and SK-016. Consequently, the mass removal has either been lasting longer, or it has been faster. Respective conclusions may be drawn concerning the dolines SK-004, SK-008 and SK-010 where relative lowering was smaller. It is interesting that the dolines of the smallest lowering rate are in touch with the ones with the greatest (especially the group SK-008, SK-009, and SK-010; also the group SK-003, SK-004, and SK-005). One may assume that higher inclination of slopes means faster mass removal, and that an estimate of the doline growth dynamism is given by inclinations of the cone surface (25). The angles range from 16.2° to 22.6°. A simple calculation shows that the volume of a cone increases for the factor 1.43 if its inclination changes within the mentioned range (Fig. 9/b). The plot of the V/A ratio against the inclination angle (Fif. 9/c) reveals very interesting relations. If the former assumption is fair then there exst dolines of large amount of denudation, and of great activity at the same time, too. But therea are no dolines of great activity at present, and large denudation at past (above the bold line). Thus, there exists a well defined time limit since when dolines have begun to appear. In the case of the Skalčen Kamen this conclusion is supported by other geomorphic facts, but this method might be applied also upon other localities where such an evidence is missing!

Table 3

0	20	21	22	23
SK-001	21.95	20.42	302.61	1.07
SK-002	28.10	21.34	18.00	1.32
SK-003	20.50	19.05	36.40	1.08
SK-004	15.29	12.53	79.09	1.22
SK-005	25.99	24.48	303.71	1.06
SK-006	23.91	19.82	60.89	1.21
SK-007	24.13	12.31	273.71	1.96
SK-008	15.81	14.30	289.84	1.11
SK-009	29.89	27.34	56.51	1.09
SK-010	20.77	18.11	36.96	1.15
SK-011	26.72	23.57	4.36	1.13
SK-012	26.74	18.55	7.51	1.44
SK-013	24.72	23.82	321.00	1.04
SK-014	26.85	20.14	6.04	1.33
SK-015	34.52	34.48	44.87	1.00
SK-016	23.60	20.69	24.04	1.14
SK-022	24.05	21.45	2.05	1.12

(20), (21) - lengths of the major and minor axis of the ellipse (22) - direction (azimuth) of the major axis of the ellipse (23) - elongation of the normative ellipse

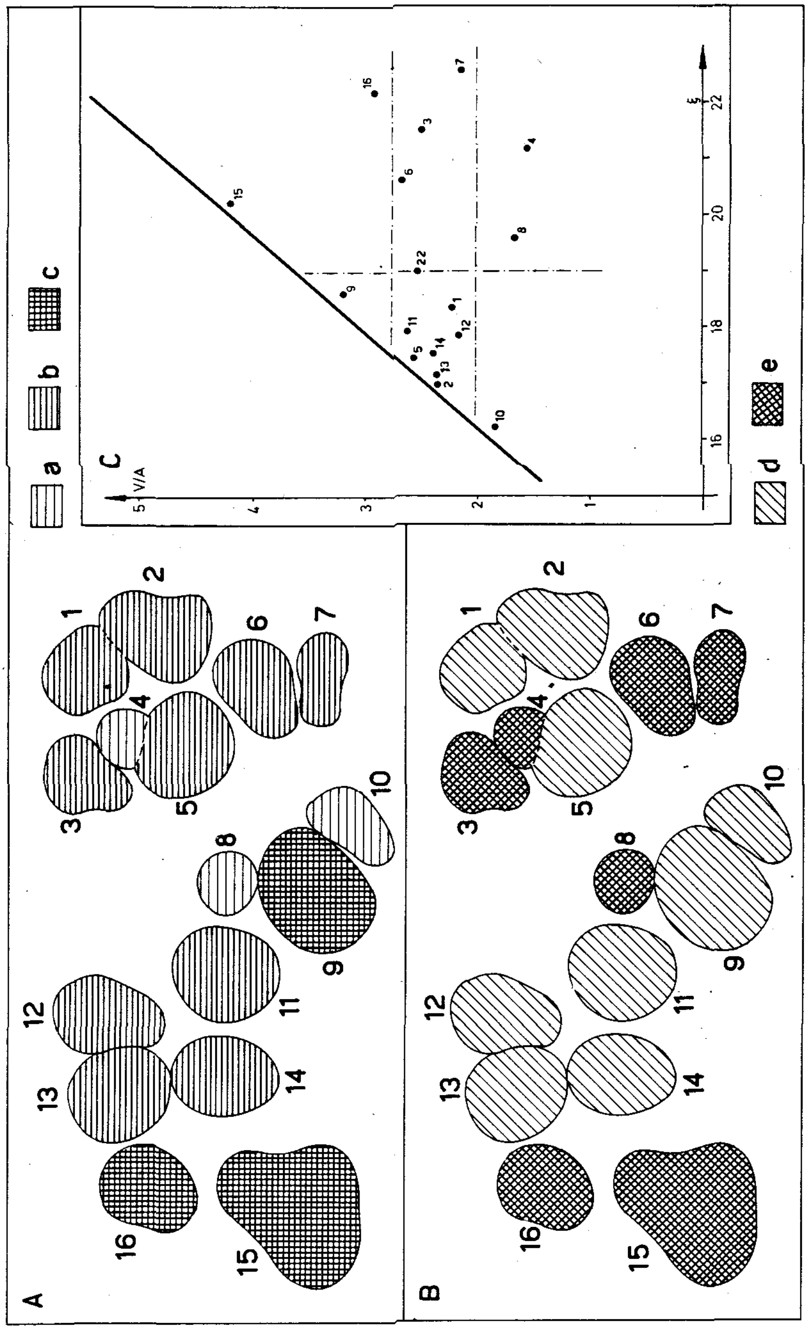


Fig. 9

The ellipses which fit the best the planimetric shapes of the dolines were computed. If the doline is reasonably regular, the axes of the ellipse is a fair estimator of the doline direction. However, if the ground plane of the doline is not regular, and even the idea of the direction loses its meaning, the ellipse longer axis still indicates the planar distribution of the negative mass. A rose diagram (Fig. 10) reveals that the preferred direction is the S-N.

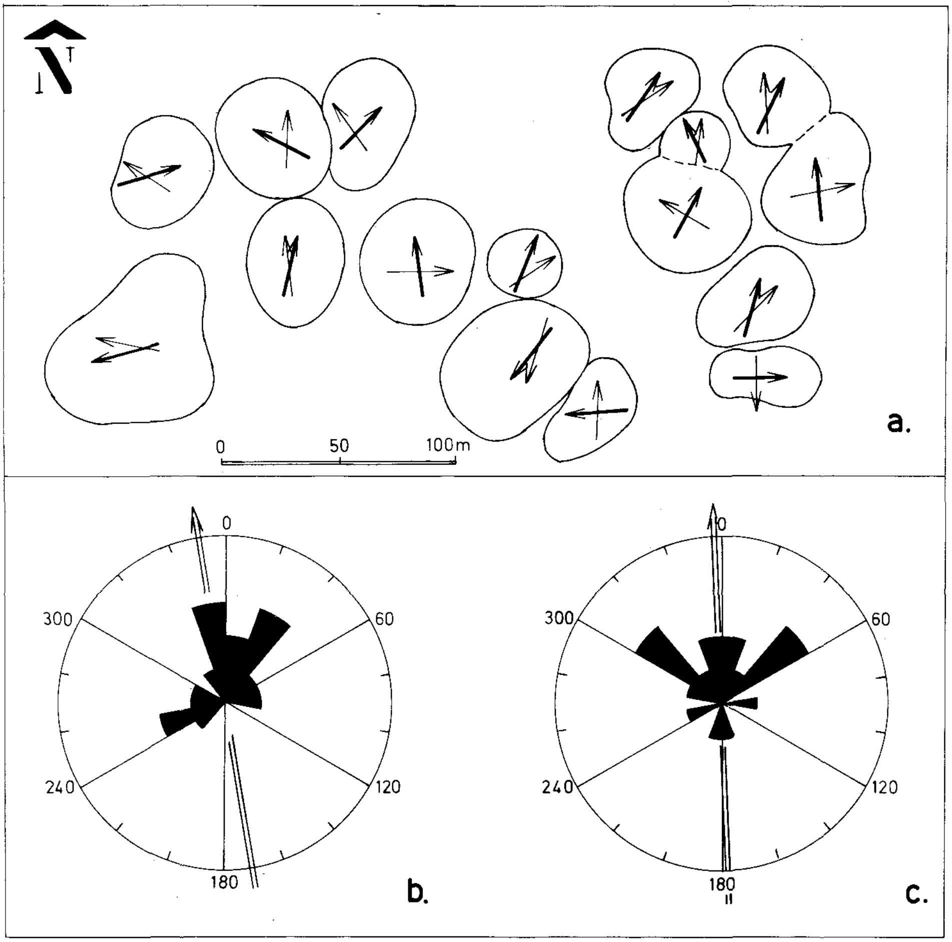
Table 4

0	15	16	17	28	30	29
SK-001	8.53	25.85	0.2192	12.99	357.50	0.1753
SK-002	2.25	355.42	0.0509	10.28	258.41	0.2445
SK-003	4.54	53.85	0.1276	10.10	56.27	0.1564
SK-004	3.08	336.34	0.1225	9.70	318.03	0.2724
SK-005	1.22	240.75	0.0266	7.31	301.35	0.1480
SK-006	5.26	16.59	0.1339	10.92	43.39	0.1695
SK-007	4.43	89.29	0.1417	12.49	178.80	0.4224
SK-008	8.09	22.60	0.2897	10.45	55.04	0.2024
SK-009	12.72	232.80	0.2431	8.31	198.64	0.1429
SK-010	1.56	265.33	0.0456	4.43	2.39	0.1299
SK-011	3.44	351.98	0.0751	6.63	89.92	0.1719
SK-012	7.05	44.42	0.1737	11.52	324.13	0.3067
SK-013	5.15	296.38	0.1164	7.81	2.03	0.1667
SK-014	5.24	12.86	0.1234	13.94	354.06	0.2150
SK-015	6.24	256.55	0.1007	10.83	282.28	0.0948
SK-016	5.83	76.09	0.1446	2.70	333.52	0.1720
SK-022	10.42	344.63	0.2489	11.35	22.59	0.1704

(15) - shift of the gravity center, (16) - azimuth of the shift of the gravity center, (17) - normalized shift of the gravity center, (28) - shift of the apex, (30) - direction of the apex position, (29) - normalized shift of the apex

Sl. 9: Denudacija znotraj vrtač:
A: dejanski iznos = prostornina / ploščina. a/ < 2m, b/ 2m < 2.75m, c/ 2.75m <.
B: intenzivnost odnašanja = naklon plašča normativnega stožca (E). d/ < 19°, e/ < 18°.
C: Soodvisnost iznosa in intenzivnosti denudacije. Debela črta je približna meja "prepovedanega" (glej besedilo!) območja.
Fig. 9: Denudation within dolines: A: actual amount = volume divided by planimetric area. a/ < 2 m, b/ 2 m < 2.75 m, c/ 2.75m. B: intensity = inclination of the normative cone (E). d/ < 19°, e < 18°. C: Plot of the denudation against the intensity. Bold line is approximative limit of the "forbidden" area (See text!).

It is evident that the ground plane gravity centres, as well as the positions of the normative cone apexes, are shifted quite far from the bottom points. Though the directions seem scattered (Fig. 10), the directional statistics reveal coherent results. The average direction of the gravity centres shift is 351.6° (circular variance = 0.5358), and the apexes position 357.7° (circular variance = 0.5153). Differences, as well as scattering are due to



Sl. 10: a: Smeri odmikov težišč tlorisov (debelejša puščica) in vrhov normativnih stožcev (tanjša puščica). b: Rožni diagram smeri odmikov težišč tlorisov. c: Rožni diagram odmikov vrhov normativnih stožcev. Dvojni tanki črti s puščico sta povprečni smeri.
Fig. 10 a: Direction of shifts of the planar gravity centres (bold arrow) and the normative cone apices (thin arrow). b: Rose diagram of shifts of the planar gravity centres. c: Rose diagram of the normative cone apices (thin arrow). Double thin lines with pointer represent average directions.

uneven neigbouring terrain, but the general trend northwards is not negligible. In other words, this means that the deepest position of the doline lies towards the southern part of the ground plane. This may be the result of greater production of slope material on southward oriented slopes, and the creep of it towards south. Provided that the whole area has been predominantly forrested during the historical time, it is very likely that the displacement of the deepest position in the doline is due to Pleistocene subarctic conditions.

GEOMETRY

The first impression of the dolines one obtains when observing the map concerns their planar shape. As stressed in my previous work (F. Šušteršič, 1984, 1987), and also evident from A. Bondesan (& al., 1992, Figs. 14, 15), they are not as regular as many simple morphometric methods presume. Some of those irregularities are due to the roughness of the neighbouring terrain, and they do not imply irregularities of the "bowls" themselves. The others are probably due to the greater dynamism of the whole doline which does not permit the "bowl" to achieve the regular shape.

The research of the considered dolines further supports my previous observations (o.c.) that the "bowls" of the dolines are not symmetrical enough to permit classification which includes "a priori" symmetry. Consequently, the classical subdivision (Cvijić, 1893, D. C. Ford, Williams, P. W., 1989, 397) may serve as the first step of recognition only, and the semiprofiles remain the stepping stone to a more realistic classification and numeric taxonomy.

As a rule, within the perimeter, detailed morphometry revealed that the dolines geometry consists of three concentric areas.

- In the center there is a flat area, generally covered by soil. More rarely the soil is missing, and the center of the doline is occuppied by an inverted cone of loose boulders. Very exceptionally there appear the openings of vertical shafts[16]. The outer limit of this zone may usually be recognized by eye. On some infrequent occasions the border between the massive soil accumulation in the center, and relatively thin veneer of the soil on the solid slopes is virtually undistinguishable, and only detailed surveying or penetration would provide the proper information. If the soil deposit is somewhat more extensive, its surface is generally slightly inclined southwards.
- Then follows the ring of most inclined, and also the toughest slopes. They are the least weathered part in the whole doline. The surface may even be solid rock. More generally, it is reminiscent of the surface on hillslopes outside the dolines. It must be stressed that the inclination is not constant and the inflection point of the doline slopes is always within this zone.
- In the outer belt slopes are gentler, usually inclined at about a half of the maximum. They are evidently less stable than the ones within the itermediate belt. Somewhere clints

[15] The direction SE-NW is the direction of the main dinaric shear movements, while the N-S direction is the direction of the extension fissures of the same system.

[16] This was observed in quite an extent by Jennigs (J. N., 1975), without drawing further consequences.

stick out of the veneer of colluvium. The vertical extent of this zone does not exceed about 3 m, but it varies from doline to doline, even from place to place within a single doline. Its outer border is the perimeter of the doline, which it is marked by an abrupt change of the slope. In the case study the dolines had not been modified by human activity.

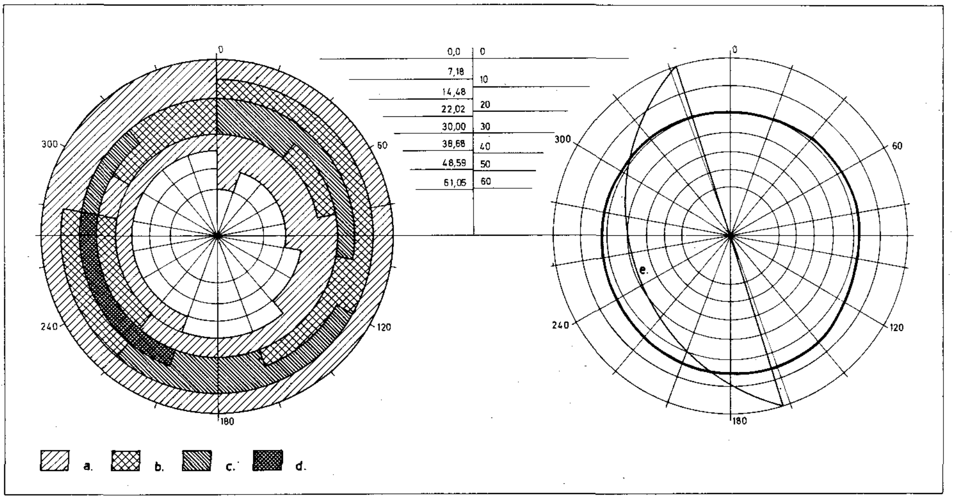
In the doline SK-022, the three zones are well evident from semiprofiles directioned 111.3° and 201.3° (Fig. 4). The inner belt is characterized by constant, linear increase of the slope angle. Thus, the slope is parabolic, which is a direct consequence of equilibration of the colluvium. The maximum slope is achieved in the intermediate belt, where slope angle changes according to the bell-like pattern. In the outer belt the slope angle tends to an approximate constant value. The slopes tend to be conical, which is an equilibrium reaction of an undercut, less stable layer. Other semiprofiles present more complex shapes, probably due to the reason that the "bottom point" has been shifted quite away from the center.

Though the three belts remain recognizeable in any direction, the slope angles generally change according to the direction of the slope. The doline SK-022 was scanned in 1 m intervals, and the aspect and the slope angles were computed. The results of the rough count of scores are presented in the following table:

Table 5

	0	5	10	15	20	25	30	35	40
0 - 19.9	5	18	8	6	9	11	-	-	
20 - 39.9	1	16	15	12	13	2	-	-	
40 - 59.9	-	9	23	14	7	-	-	-	
60 - 79.9	-	6	47	8	-	-	-	-	
80 - 99.9	-	12	55	7	-	-	-	-	
100 - 119.9	-	25	46	42	-	-	-	-	
120 - 139.9	1	37	50	60	4	-	-	-	
140 - 159.9	1	38	59	49	31	-	-	-	
160 - 179.9	1	58	58	44	44	-	-	-	
180 - 199.9	1	28	59	42	46	-	-	-	
200 - 219.9	1	8	49	41	44	-	-	-	
220 - 239.9	2	4	17	60	36	-	-	-	
240 - 259.9	1	2	4	57	27	-	-	-	
260 - 279.9	-	1	1	38	17	4	-	-	
280 - 299.9	-	-	1	30	10	10	-	-	
300 - 319.9	-	-	1	13	13	9	-	-	
320 - 339.9	-	-	-	3	23	36	3	-	
340 - 359.9	-	5	6	8	7	24	9	-	

Vertical classification: aspect angle
Horizontal classification: slope angle



Sl. 11: Levo: Frekvence smeri pobočij v vrtačah SK-001 do SK-016: a: 0 % - 1 %; b: 1 % - 2 %; c: 2 % - 3 %; d: 3 % <. Desno: Vpad skladov matične kamnine (lok) in smer najstrmejših pobočij (debela črta) - stereografska projekcija. Opomba: Slika prikazuje dejansko usmerjenost pobočij. Če želimo poudariti njihov položaj znotraj vrtač, moramo sliko zasukati na glavo.

Fig. 11 Left: Frequencies of the slope directions within the dolines SK-001 to SK-016: a/ 0% - 1%, b/ 1% - 2%, c/ 2% - 3%, d/ 3% <. Right: Dip of the parent rock (arch) and the line (bold) of the greatest inclination of slopes (stereographic projection). Note: The figure is oriented according to actual aspects of slopes. If intending to visualize their position within the dolines the figures must be turned up-side-down.

However, this arrangement is rather misleading because the areas of the spherical rectangles differ between parallel belts. In order to obtain fair statistics, the widths of the slope classes were changed to obtain equal areas. Additionaly, the data was changed to parts per mille:

Table 6

	0.00	7.18	14.48	22.02	30.00	38.68
0 - 19.9	9	9	6	9	-	
20 - 39.9	5	12	10	7	-	
40 - 59.9	1	17	14	1	-	
60 - 79.9	-	30	5	-	-	
80 - 99.9	1	35	7	-	-	
100 - 119.9	2	36	27	-	-	
120 - 139.9	2	45	39	-	-	
140 - 159.9	1	51	50	-	-	
160 - 179.9	1	60	51	4	-	
180 - 199.9	2	47	41	11	-	
200 - 219.9	2	27	42	10	-	
220 - 239.9	2	7	58	1	-	
240 - 259.9	1	2	44	4	-	
260 - 279.9	-	1	25	9	-	
280 - 299.9	-	1	19	9	-	
300 - 319.9	-	1	10	10	-	
320 - 339.9	-	-	6	30	1	
340 - 359.9	1	5	5	19	5	

Somewhat more comprehensive, but in essence the same picture displays the sumaric table for all the rest of the dolines at the Skalčen Kamen.

Table 7

	0.0	7.2	14.5	22.0	30.0	38.7	48.6	61.0
0 - 19.9	2.2	12.3	22.6	21.9	4.6	0.1	0.2	
20 - 39.9	2.7	14.0	21.6	20.0	1.8	0.2	-	
40 - 59.9	2.1	16.8	24.3	18.5	1.2	-	-	
60 - 79.9	4.0	18.5	27.9	11.7	2.4	0.9	-	
80 - 99.9	2.6	14.4	21.7	8.1	1.9	0.4	-	
100 - 119.9	2.2	15.8	14.6	9.1	2.0	-	-	
120 - 139.9	4.5	23.3	14.5	7.8	0.4	-	-	
140 - 159.9	4.8	25.6	17.1	3.2	-	-	-	
160 - 179.9	4.6	26.1	23.8	3.0	-	-	-	
180 - 199.9	5.5	24.3	26.4	6.8	-	-	-	
200 - 219.9	5.5	26.3	30.3	8.6	0.1	-	-	
220 - 239.9	4.1	16.7	32.3	10.1	0.3	-	-	
240 - 259.9	2.1	15.0	35.2	11.6	0.8	-	-	
260 - 279.9	2.4	12.1	33.1	12.2	1.6	-	-	
280 - 299.9	1.0	9.1	24.1	9.9	1.4	-	-	
300 - 319.9	1.4	6.5	21.1	10.2	1.4	-	-	
320 - 339.9	2.6	7.0	16.2	11.7	2.5	-	-	
340 - 359.9	2.1	8.3	17.9	14.5	3.5	-	-	
Total	56.4	292.3	424.9	199.0	25.7	1.5	0.3	

The slopes oriented southwards are the gentlest and the slopes oriented northwards are the steepest. However, the dip angle of parent rock influences the slope formation too and the former tables present the interplay of both (Fig. 11).

Combined with the previously discussed shift directions of the ground plane gravity centres and the normative cone apices towards the north, this is another hint that dolines had achieved most of their present form in cold periods of the pleistocene. At this times, exposition of slopes, and consequently, freeze and thaw oscilations were the most important factors controlling the slope formation. That the slopes feature forms of paralell slope retreat is so selfexplanatory.

Not ignoring an important detail: neither runnels or other traces of water streaming on the slopes, nor alluvial sedimentation at their feet were found. The only linear entrenchments, detected by computer analysis and hardly observable by naked eye are sutures, i.e. relative lowerings of tectonically crushed zones (F. Šušteršič, 1987, F. Šušteršič, 1988).

It is clear that the extent of the central portion depends exclusively of the accumulation of the products of the slope processes, and thus it is only temporary. Then, what is below? According to Cvijić's drawing (o.c.), and its numerous replicas, there should be a zone of weathered rock gradually passing to a number of small channels in solid rock. Anglo-saxon students would prefer the idea of a swallet, continuing to one tube or two tubes. P. W. Williams (1985, 465, Fig. 2) presented a somewhat different picture which is a compromise between the former two ideas.

Systematic examination of many dolines, especially in progressing faces of quarries, revealed that at least in this part of Slovenia, neither concept is fair. As dolines, cut by quarries (Fig. 12), as the relatively infrequent examples of completely empty dolines, display the same structure. The bottom of the "bowl" is of solid rock nearly to the actual center, where there appears an abrupt break into a vertical shaft. Sometimes, the edge is smoothed to some extent, but it is absolute clear that the transition is not gradual (Fig. 13). The diameters of the shafts are from 5 m 10m, while their depth is not known. No quarry face is high enough to cut the whole shaft. At the moment, the deepest accessible one is about 60m - but the apparent bottom is a boulder choke!

On the walls of the open shafts flowstone is quite usual. Shaping of their walls is typical for the pits, eroded by free falling water or by water films on the walls. In short, they are examples of the "ortovacua", defined by W. Maucci (1951/52). It appears that they match the "domepits" (W. B. White, 1988, Ford, D. C., Williams, P.W., 1989, 304, Fig. 7.38) in anglo-saxon literature.

The filling is predominantly loamy material, with loess or periglacial gravel mixed together. In many cases movement into the central shaft below is evident (Fig. 14) (also P. Habič, 1987). The sections in quarries, as well as minute study of dolines slopes reveal that in the vicinity there exist filled parallel shafts which are completely passive and do not perform any mass movement, much less any influence on the formation of the doline.

SOME DISCUSSION

If Cvijić's most cited object is not a doline, then another holotype must be determined. As mentioned before, the doline matched SK-022 was by no doubt implicitively referred to by Cvijić, within the group example of dolines at Skalčen Kamen. Besides, it features well the forms and processes, encountered in all the dolines of the area, and more general, it is also a good representative of millions of dolines in the Dinaric karst on the Balkans peninsula. Therefore, it is proposed that this should serve as the holotype of Cvijić's dolines, while the structure reproduced in his two books must be abandoned. The attribute "Cvijić's" is important because there is quite an evidence that the dolines, studied predominantly by the Anglo-saxon researchers (J.N. Jennings, 1975 is partly an exception) are not of the same kind.

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Consequently, the role of the dolines in the karst surface must be reconsidered. This topic was extensively discussed by S. Bahun (1969); for our purpose his ideas might be simplified into three options:

1. Dolines are integral part of the karst surface. Due to local conditions lowering has been more extensive at some spots, but the processes are absolutely the same.

2. Dolines are specific phenomena of transition of the surface drainage into the underground one. Thus they are not just local lowerings, but they still play a role in the surface karstification.

3. Dolines are reproductions of the underground karst voids on the surface. The very act of intercourse is not a collapse, but denudation of the surface which is permanently opening the underlying caverns to surface. Having appeared on the surface these "negative masses" may have their own way of development, controlled by superficial processes.

It is evident that Cvijić has chosen the first option. However, a fundamental objection arises automatically. If the weak-points on the surface are geological structures, which are linear as a rule, then, why are dolines so very circular, even if ranged along tectonical lines, and clearly displaying these structures even in their internal form.

The second option is the one how Cvijić was predominantly understood. A number of the Anglo-saxon authors (M. Day: 1976, 1983, Ph. R. Kemmerly: 1976, 1982, 1986, P. W. Williams: 1985) support it more than enough. Even some rare examples from the karst of Slovenia might be best explained in this way.

The third option appears to fit best the dolines at Skalčen Kamen and its wider neighbourhood. Bahun (o.c.) did not pay great attention to the initial caverns, while C. D'Ambrosi (1960) explictively derived dolines from the Maucci's (1952) "ortovacua", i.e. vertical shafts. This best fits my observations of the dolines. It appears that some other researchers, especialy (J. N. Jennings, 1975, G. Benvenutti & U. Sauro, 1977, and A. Bondesan, M. Meneghel, and U. Sauro, 1992) deal with the same matter, though not being completely aware of all the consequences.

However, any further work depends greatly on our knowledge about the vertical shafts. At the moment, the classification of the vertical shafts is only rudimentary, and their origin has not been completely solved. It appears that only the domepits are prone to evolve into dolines, but the explanations of their origin diverge. In my experience, the explanation proposed by W. Maucci (o.c.), and further supported by A. Frumkin (1984, 1986) best fits the reality of the Classical karst.

The present shape of the dolines at the Skalčen Kamen is predominantly due to the Pleistocene gelifraction, and consequently, parallel slope retreat. Nevertheless, it does not mean that they are only passive concavities in the karst surface. Within them quite different rates of mass removal have been detected. Surprisingly, this process seems to be time constrained, though not simultaneous in all the population. Rather than the loamy filling in the central part of the dolines, the mass removal affects the coarse material deeper in the central shaft. In the section of the doline Renčelica near Sežana (P. Habič, 1987) it is clearly visible that the pleistocene gravel is sinking in the center of the doline (Fig. 15). A similar process has been established in some collapse dolines (F. Šušteršič, 1973), even if actually not connected with active caves.

It does not seem that the present dolines are any kind of catchment area. However, if the mass removal is so fast that the slopes can not cope with it, they will become steeper and steeper and the critical angle between vetical and superficial drainage is surpassed. In that case the second option of the doline interpretation becomes valid. In Pliestocene, when prmafrost appeared, this process might be quite widespread. However, the swallets formed in these conditions typically differ from the central shafts (dome pits).

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Many dilemmas remain. Perhaps, the guideline for the future is the citation from W. B. White (1988, 20): "Dolines and pits have traditionally been discussed separately, ... they are closely related to the same processes of vertical solution and transport".

KLASIČNE VRTAČE KLASIČNEGA KRASA

Povzetek

Korenine

Del svojega Karsta (1893, 1895) je J. Cvijić posvetil zaprtim kraškim globelim srednjih izmer - vrtačam. Sto let nadalnjih raziskav je znanje o vrtačah bolj razširilo kot poenotilo. Zdi se, da raziskovalci uporabljamo isti besednjak, a ne govorimo vedno o istih naravnih pojavih. V takih primerih se samoumevno obračamo k koreninam in skušamo dognati, kaj so imeli v mislih pionirji, ki so postavili definicije.

Cvijić (o.c.) se sklicuje na opazovanja po celotnem ozemlju nekdanje Jugoslavije, vendar nudi en sam oprijemljiv primer vrtače. To je presekana globel v boku useka na železniški postaji Logatec. Slika tega prereza (J. Cvijić, 1893, 43; 1895, 63) je postala ena najbolj ponatiskovanih v vsej geomorfološki literaturi (Sl. 1). Današnje stanje tega prereza (Sl. 2) je zaradi širitve postaje precej drugačno, vsekakor pa je jasno, da ne gre za centralni presek vrtače, temveč za prečni prerez linearnega znižanja površja vzdolž zdrobljene cone (Sl. 3, krožec).

Napačno izbran primer je Cvijića in naslednike zapeljal k dedukciji, ki je daleč od realnosti. Vrtačo je razumel kot znižanje reliefa na tektonsko bolj poškodovanem mestu, pod njo pa je pričakoval množico drobnih kanalov v zdrobljeni kamnini. Ker v rabi izraza "ponor" ni dosleden, dojemajo predvsem anglosaški raziskovalci vrtačo (doline) kot stično točko med krajevnim površinskim in kraškim odvodnjavanjem (M. Day, M., 1976, 1983; Ph. R. Kemmerly, 1976, 1982, 1986; P. W. Williams, 1985). Njihova opazovanja takšno gledanje podpirajo - ne da pa se ga vskladiti z opazovanji vrtač na klasičnem krasu Slovenije oz. Dinarskega krasa. Da bi razčistil dilemo, sem podrobno obdelal 17 vrtač na lokaciji Skalčen Kamen 6 km jugovzhodno od Logatca, kjer Cvijić omenja lepe primere vrtač. Za v bodoče predlagam kot "holotip" vrtačo z delovno oznako SK-22.

Metoda

V nadalnjem so predstavljeni predvsem rezultati morfometrije. Znotraj preseka, definiranega v F. Šušteršič (1987), sem po metodah, opisanih v F. Šušteršič (1985 in 1989) izmeril in obdelal vrtače na lokaciji Skalčen Kamen. S pomočjo računalniškega programa VRT je bilo izračunanih 30 parametrov, med njimi:

(5), (6) - Najkrajši in najdaljši tlorisni polmer vrtače glede na najnižjo točko.
(8), (9) - Največja in najmanjša višinska razlika med obodom in najnižjo točko.
(10) - Prostornina vrtače (zaprte globeli).
(11) - Ploščina znotraj oboda.
(15) - Premik težišča tlorisa glede na najglobljo točko.
(16) - Azimut premika težišča.
(17) - Normirani premik težišča (parameter 16 deljen s kvadratnim korenom tlorisne ploščine, deljene s pi).
(20), (21) - Najdaljša in najkraša os elipse, ki ima enako ploščino in enak vztrajnostni moment kot tloris vrtače (normativna elipsa).
(22) - Smer daljše osi normativne elipse.
(23) - Razmerje med daljšo in krajšo osjo normativne elipse.
(24) - Dolžina osi normativnega stožca. Vrtači je prirejen stožec z enako prostornino in tlorisno ploščino, presekan z ravnino, ki se najbolj prilega obodu. Ta parameter nadomešča intuitivno "globino".
(25) - Naklon plašča normativnega stožca. Ta parameter nadomešča intuitivni "povprečni" naklon pobočij.
(28) - Premik konice stožca glede na najglobljo točko vrtače.
(29) - Normirani premik konice. Podobno kot pri parametru (17).
(30) - Smer položaja konice glede na najglobljo točko.
(V/A) - Relativni iznos denudacije znoraj oboda vrtače.

Pri obdelavi je upoštevan samo "dolgovalovni paket", kar omogoča izločenje drobnih motenj v oblikovanosti vrtače. Tako dobimo "nemotene oblike" polrezov (Sl. 4). Geometrijo vrtače podajajo iznos (Sl. 5/a) in smer (Sl. 5/b) naklona pobočij. Pobočja se odklanjo od idealne smeri proti najglobljí točki, zato so kosinusi kotnih razlik cenilka skladnosti oblike realne vrtače z idealno (Sl. 5/c). Odkloni so pozitivni in negativni, zato obstojijo črte ničelnih odklonov, ki so privlačne ali odbojne (Sl. 5/d). Privlačne ničelne črte so mesta realativnega znižanja znotraj idealnega pobočja vrtače. Skupinski vzorec privlačnih ničelnih črt v vseh izmerjenih vrtačah (Sl. 6) spominja na škraplje v okolici, kar da misliti, da je podpovršinsko zakrasevanje zunaj vrtač in na pobočjih "sklede" v bistvu enako.

Vrtače pri Skalčnem Kamnu

Lokacija Skalčen kamen leži v osrednjem delu Begunjsko-Logaškega Ravnika. V širši okolici znaša povprečna gostota vrtač 356.1 na km^2. Vplivno območje posamezne vrtače pokriva 2808 m^2, kar da polmer r = 29.9 m. Njihovo prostorsko razporeditev na ožjem območju kaže Sl. 7. Na osnovi 220 merskih točk med njimi je bilo izračunano hipotetično površje, kamor so vrtače "vložene" (ista slika). Splošna organizacija površja "brez vrtač" je sorazmerno zelo pravilna, kaže pa značilne dirnarske smeri. Nobena vrtača ne leži v dnu izračunanih globeli, kar kaže, da niso odtoki krajevno zbrane deževnice.

Razviden je tudi pas brez vrtač, ki se približno krije z dolomitno skladovnico. Na navpično ravnino, ki poteka skozi padnico skladov, sem projiciral normativne stožce vrtač (Sl. 8, zgoraj) in njihove prostornine (spodaj). Približna širina dolomitnega pasu se ujema s širino pasu brez vrtač. Skladanje bi bilo popolno, če bi bilo površje 15 m višje, kar odgovarja 250 ka denudacije (po I. Gamsu, 1974, 71).

Prej našteti parametri so v več tabelah (1 do 4, glej angleško besedilo!) razporejeni v smiselne skupine, kar omogoča zanimive primerjave. Kvocienti med prostorninami in ploščinami so pretežno 2.1 to 2.7. Torej znaša relativno znižanje znotraj oboda v povprečju 2.4 m (Sl. 9/a). Kjer je večji, je bilo odnašanje mase hitrejše, ali pa je trajalo dlje. Večji naklon normativnega stožca (Sl. 9/b) lahko pomeni intenzivnejše odnašanje. Na sl. 9/c so nanešeni kvocienti V/A in naklonski koti. Torej obstojajo vrtače z visokim iznosom denudacije in veliko trenutno aktivnostjo, ni pa vrtač kjer bi bila denudacija velika v preteklosti, danes pa bi bila intenzivnost odnašanja nizka (nad krepko črto). Torej obstoji časovna meja, pred katero se vrtače niso pojavljale.

Iz povprečnih smeri odmikov težišča tlorisa (351.6°, cirkularna varianca = 0.5358) (Sl. 10/a) in konic normativnega stožca (357.7° (cirkularna varianca = 0.5153) (Sl. 10/b) je očitno, da so najgloblje točke vrtač bliže južnemu kot severnemu robu. Po vsej verjetnosti je to posledica pleistocenskih pobočnih procesov, ki so bili učinkovitejši na prisojnih, severnih pobočjih.

Meritve vrtač pri Skalčnem kamnu potrjujejo prejšnje ugotovitve (F. Šušteršič, 1984, 1987), da sestavljajo osnovni vzorec pobočij trije koncetrični pasovi, katerih nakloni seveda zavisijo tudi od osončenosti. V sredini je skoraj ravno območje ilovnatega polnila. Sledijo sorazmerno strma pobočja praktično v živi skali. Zunanji pas je položnejši - krije se z bolj preperelim, površini bližjim predelom matične kamnine. Ti pasovi so jasno razvidni s polrezov vrtače SK-022 (Sl. 4).

Sledeče tabele (5 - 7) prikazujejo statistiko naklonov pobočij v vseh vrtačah in posebej v vrtači SK-22. Potrjena je prejšnja ugotovitev, da na iznose naklonov močno vpliva osončenost, očiten pa je tudi vpliv vpada skladov (Sl. 11). Ponovno lahko ugotovimo, da kažejo pobočja izključno sledi pleistocenskih pobočnih procesov, nikakor pa ne fluvialnih.

Po vsej podobi se pod vrtačami nahajajo navpični jaški, zapolnjeni z ilovico in pleistocenskim materialom, kar kažejo tudi preseki v kamnolomih (Sl. 12). "Skleda" vrtače prehaja v jaške z jasnim pregibom, lahko pa te prehode minimalno zaobli (Sl. 13) v notranjost polzeči material (Sl. 14). Odkopavanja kažejo, da stene teh jaškov mnogokrat prekriva siga. Njihova globina ni znana - najglobljі (izpran) v Leskovi dolini je globok prek 60 m, v kamnolomih pa običajno sežjo preko višine celega čela. Kaže, da odgovarjajo "ortovakuolam", kot jih definiral W. Maucci (1951/52) in ki jih Anglosaksonci imenujejo "domepits".

Nekaj razprave

Ker smo odvrgli Cvijićevo tolmačenje vrtač in definirali nov holotip, moramo pretresti tudi vlogo vrtač v kraškem površju. Kaže, da je tematiko najbolje razčlenil S. Bahun (1969). Med različnimi možnostmi, ki jh ponuja, realnosti Skalčnega Kamna najbolj odgovarja tista, ki ima vrtače za preslikave kraških votlin na površje. Samo dejanje preslikave ni podor, temveč zniževanje površja, ki postopoma načenja prostore v globini. Po odprtju uberejo lastno razvojnoo pot, kjer se uveljavljajo površinski procesi.

Bahun (o.c.) ni bil posebej pozoren na izvor prvotnih votlin in je prezrl, da je C. D'Ambrosi (1960) vrtače eksplictino izpeljal iz Mauccijevih (o.c.) "ortovakuol", torej brezen. Ta kombinacija se najbolje sklada z mojimi opazovanji (o.c.), delno pa tudi z J. N. Jenningsom (1975), G. Benvenuttijem in U. Saurom (1977) in A. Bondesanom, M. Meneghelom in U. Saurom (1992). Globlje spoznanje vrtač v veliki meri zavisi od razumevanja navpičnih brezen. Kaže, da se v vrtače razvije samo en tip, tisti, ki sta ga doslej proučevala W. Maucci (o.c.) in A. Frumkin (1984, 1986).

Sedanja oblika vrtač je v veliki meri delo pleistocenskih pobočnih procesov. Ne znotraj vrtač, ne v okolici ni sledov fluvialnega oblikovanja. Ker se zdi slednje za vrtače Tennesseeja dokazano dovolj prepričljivo (Ph. Kemmerly, 1986), gre po vsej verjetnosti za dvoje različnih pojavov, ki ju obravnavamo pod istim imenom. Vodilo nadalnjim raziskavam naj bo W. B. Whitova (1988, 20) misel: "Iz navade vrtač in brezen ne obravnavamo skupaj ... toda .. oboje je tesno povezano z istimi procesi navpičnega raztapljanja in transporta."

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