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DOLINE MORPHOGENETIC PROCESSES FROM GLOBAL AND LOCAL VIEWPOINTS

GEOMORFOGENETSKI PROCESI VRTAČ Z GLOBALNEGA IN LOKALNEGA VIDIKA

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Ivan Gams: Geomorfogenetski procesi vrtač z globalnega in lokalnega vidika

Geomorfogenetski procesi korozijskih vrtač so razpoznavni iz omejitev za njihovo globalno in lokalno razprostranjenost: več padavin kot znaša potencialna evapotranspiracija, prepustna odeja prsti, kraška vodna gladina in korozijska fronta (to je stik agresivne in sigotvorne vode) globlje pod površjem, površinski naklon pod 30°, kompaktna kamnina. Vrtače so posledica lokalno pospešene korozije. Njihov začetek je v lokalno bolj pretrti kamnini z večjo specifično (površina/volumen) površino, izpostavljeno koroziji talne vlage. Vpliv zdrobljenosti kamnine je bil potrjen z laboratorijskim poskusom. Poznejša rast kotanje sloni na avtomatizmu, ki izhaja iz večje stične površine prst/kamen kot jo ima začetna ravna površina (zdaj odprtina kotanje). Lijakaste vrtače se ob večanju kotanje običajno spremenijo v skledaste, kjer je preseganje večje. Na obliko vplivajo še prepustnost tal in soliflukcija. V zmernem podnebju je nudil dva milijona let dolgi pleistocen z večjo vlago iz snega in mehaničnim razkrajanjem kamna boljše pogoje za razvoj vrtač kot toplejša neogen in holocen, ko je človek bistveno skrčil primarno gozdno okolje in z njim procese v vrtači. Udornice niso upoštevane.
Ključne besede: vrtača, tipi vrtač, geneza vrtač, globalni kraški procesi, lokalno pospešena korozija, morfoklimatski kraški procesi, Slovenija.

Abstract UDC: 551.435.83:551.44

Ivan Gams: Doline morphogenetic processes from global and local viewpoints

Geomorphogenetical processes of solution dolines are evident from restraints in their global and local distribution: more precipitation than potential evapotranspiration, permeable soil cover, water level and solution front (transition from aggressive to flowstone depositing water) below shallow epikarst, slope inclination below 30°, solid soluble rock. Dolines are an effect of local accelerated solution. In initial phase they are connected with more fractured stone, as the grains have greater specific (surface/volume) surface exposed to soil moisture. Effect of stone fracturing on solution was tested in laboratory. Later growth of basin is based on automatism, as the size of soil/stone interface is increased with deepening of the basin. Funnel-like dolines with growth usually convert in a bowl-like form with greater exceeding. The form is controlled also by water permeability of soil and solifluction. In temperate climate the two million year long Pleistocene offered with more moisture from snow and with intensive fracturing of stone better conditions for doline development than the warmer Neogene and Holocene when man's impact in last centuries essentially redused primary forest environment and thus processes in the basins. Collapse dolines are not taken into account.
Key words: doline, doline types, doline genesis, global karst processes, local accelerated corrosion, morphoclimatic karst processes, Slovenia.

INTRODUCTION

None of the numerous opinions on doline development published up to now (see the survey of them in Maksimovič, 1963, Sweeting, 1972, 44-73, Jennings, 1985, 106-120, Ford & Williams, 1989, 396-399) was unanimously accepted. Modern measurements of the processes in the doline, mostly in its soil, have brought new knowledge on doline ecology (Barany, 1980), but using them for doline genesis is a questionable task as the recent processes under the grass are different from the original one in the forested land where nearly all dolines initiated before the man's impact. The processes in a doline now in the Holocene are different from those in the much longer and colder Quaternary. The favourable lithological or hydrological conditions for doline development in its early phase could be removed till now by the doline growth. Older dolines are more or less inherited forms. In the Dinaric Karst of Slovenia in the river basins the recent solution rate is between 30 and 100 m^3 $CaCO_3/km^2$ (or equivalent lowering of the surface in one million years for 30-100 m, Gams, 1966). If a doline began to develop at the beginning of the two million years long Quaternary, the surface of karst surroundings, together with the basin, has been lowered much more than the recent dolines are deep.

In this paper the discussion on doline development is based mostly on the selected main principles already accepted in the general geomorphology and especially in karst geomorphology, and on two new theoretical and tested factors neglected till now in the science.

GLOBAL PROCESSES

1. According to new measurements (Williams, 1985, Ford & Williams, 1989, 415, White, 1988) the solution of carbonate rocks in the covered karst is most effective in the epikarst, that is in a thin, 10 m or more thick upper zone composed of soil cover with soil moisture, soils in the pockets in crevices, and of rock. In the vicinity of the building at Postojna where the karst school in July 2000 was in session, the trickling water in the little cave Groblje below a 1 - 3 m thick ceiling contained about 100 mg $CaCO_3$/l and was depositing a little dripstone (Gams, 1966, 16-17) The factors for the solution causing dolines have to be in this view searched in this epikarst zone.

2. The solution process is physically based on the ionic tension on the rock surface in contact with water mesh (film) (Dreybrodt, 1988) and it is thus a function of the specific size of the stone (grain) surface/stone volume what is in the epikarst also size of interface soil moisture/stone. This specific interface is greater if the stone is more finely crashed. For example, if the rock in form of a cube with a 1 m long side is divided into 1000 cubes with side of 1 dm their specific surface is increased six times and augmented is also the soil moisture/rock interface, and in this way also the total solution. The mechanical crumbling of the rock is in this view accelerating the solution process.

The factor of specific rock surface is more important at the beginning phase of a doline, which is normally a subsoil doline and not yet visible on the surface. Especially in a stone quarry and at new buildings where the soil is stripped off, the subsoil dolines are located at the crossing of the cracks in the rock (Gams, 1967) (Fig. 1). Morawetz (1965) in the Istrian Peninsula also found the beginning phase of dolines in the less resistant rock between the two solid limestone beds. Deeper soil in a more crashed rock surface means a longer duration of soil moisture which was also proved as a favourable factor for solution by the international measurements of solution by standard limestone tablets (Gams, 1985, 376).

The assumption about the faster solution in the more fractured rock was tested in the work of the Department of Geography at the Ljubljana university. We exposed five classes of limestone grains with diameter from. 0,1 to 30 mm in shaking and ondulating aggessive water in bottles. Its conductivity (resistivity) was measured once every two hours usually for 24 to 36 hours, and the water calcium and magnesium hardness was controlled by sporadic titrimetrical measurements.

Figure 2 (two diagrams) prove the faster solution of the smaller rock particles (of micritic Cretaceous limestone in both cases) in the rain water col-

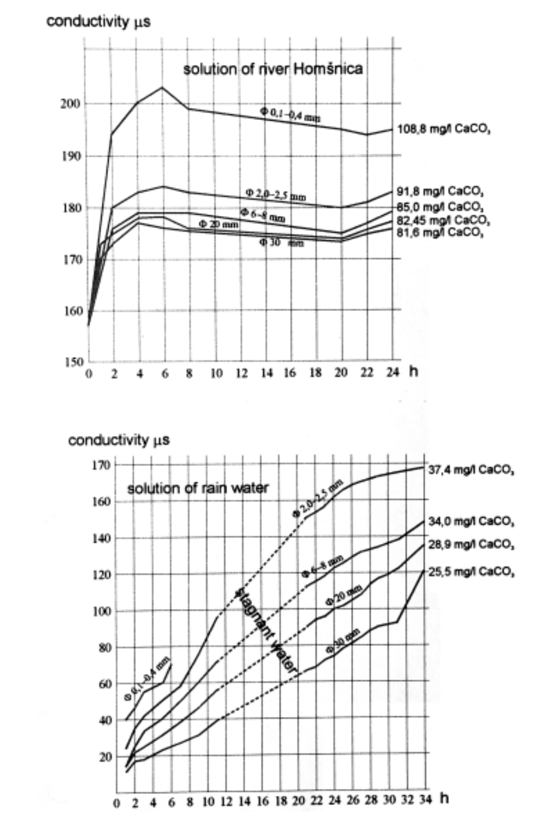

Fig. 2: Solution of Cretaceous micritic limestone fragmented in grain diameters (0,1 - 0,4 mm, 2,0 - 2,5 mm, 6 - 8 mm, 20 mm, 30 mm), tested in laboratory. 1. in the water of the surface river Homšnica, 2. in rain water, both in open system at temperature between 22 - 25 °C (see text).

Sl. 2: Korozija krednega mikritnega apnenca, zdrobljenega na frakcije 0,1 - 0,4 mm, 2,0 - 2,5 mm, 6 - 8 mm, 20 mm, 30 mm, med laboratorijskim poskusom. 1. v rečni vodi Homščnice, 2. v deževnici, oboje v odprtem sistemu pri sobni temperaturi med 22 in 25°.

Fig. 3: Schematic cross sections of dolines (below: 1 - of funnel-like form for three depths at an unchanged diameter, 2 - 4 with parallel slope retreat and increasing with , 2. bowl-like doline, 3 - half circle profile, 4 - in form of cylinder (kettle-like doline). Upper part: Exceeding of the length of slope above the diameter for two relations: 2r = 5d (depths) and 2r = 2,5d. (on page 127)

Sl. 3: Shematski preseki vrtač. Spodaj: 1 - lijakasta, s tremi globinami in nespremenjeno širino, 2- 4: z vzporednim odmikom pobočja in rastočo širino, 2. skledasta vrtača, 3. s polkrožnim presekom, 4. kotlasta vrtača. Zgornji del: preseganje dolžine pobočja nad premerom vrtače za dve razmerji, 2r = 5d (=globine), in 2r = 2,5d (globine) (na strani 127).

Photo 1: Subsoil doline with stripped off soil in the quarry at Podutik. The main crushed zone is crossing the less effective one in the middle of the doline.
Foto 1: Podtalna vrtača z izgrebljeno prstjo nad kamnolomom v Podutiku. Glavno poklinsko cono prečka poševna slabše izražena sredi vrtače. (foto I. Gams).

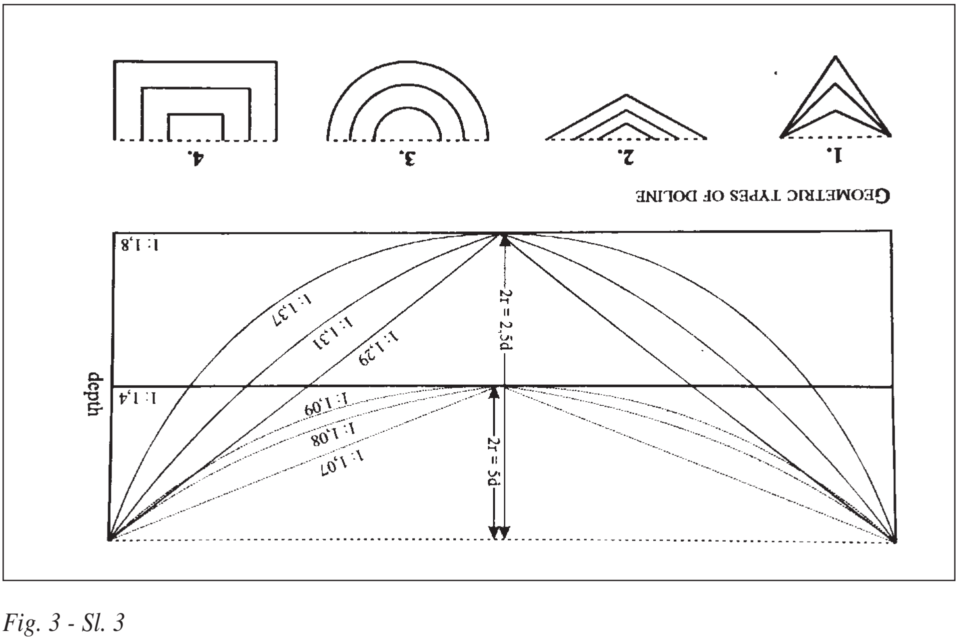

Fig. 3 - Sl. 3

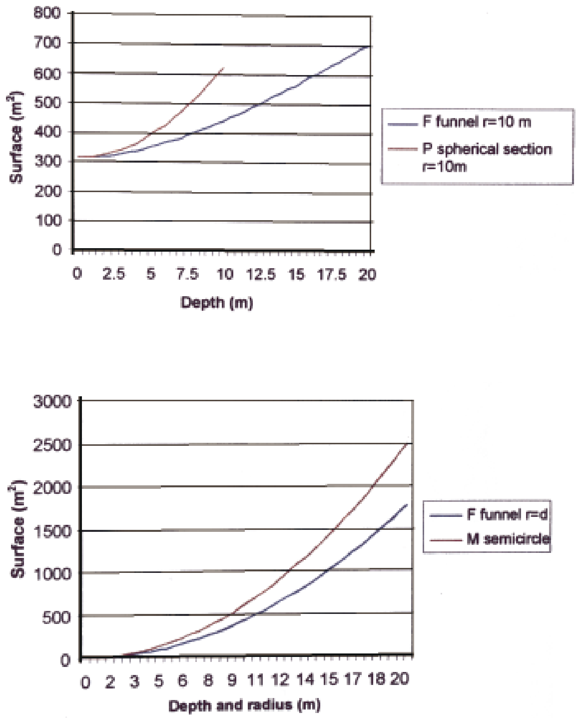

Fig. 4: Relation of doline diametre (r = 10 m) and slope size for increasing doline depth; up: in case of a steady radius = 10 m, for funnel like doline (red line) and circle divison (blue line). Down: for increasing depth and radius for funnel like doline (blue line) and semicircle profile (red line).
Sl. 4: Zgornji diagram: razmerje premera (r = 10 m) vrtače in rastoče globine vrtače za lijakasto vrtačo (rdeča črta), in v primeru krogelnega odseka (modra črta). Na spodnjem diagramu: povečanje površine pri rastoči širini in globini za lijaksto vrtačo (modra črta) in za polkrožno pobočje (rdeča črta).

lected in Ljubljana (second diagram) In the first diagram is shown the experiments with the same kinds of grains and the same procedure but with the river water of the Homšnica which drains acid forest soils on Quaternary deposits.. The decreasing hardness of the Homšnica after 6 hours can be explained by the increased air temperature from 22 to 25 °C in the laboratory. Significant is a similar hardness increase in rain water during water stagnation (12 - 21 hour)!

Although the river water had initially a higher carbonate hardness than the rain water, solution of all grain sizes is faster and more efficient than in the rain water. The floating of the smallest grains in rain water soon made the measurements of water hardness impossible.

Both experiments prove faster solution of smaller grains in the time comparable to the duration of rain water detained in the soil when the main solution capacity in contact with carbonate sediment is exhausted.

In Slovenian karst literature a doline is proclaimed to be a collapse doline if a part of its slope is rocky and the basin is great. Below the rocky part of the slope there usually spreads a scree with rubble which is near to the bottom usually covered by thin soil and on the proper bottom by deeper soil below vegetation. According to the role of the fractured rock for the solution speed the stony and steeper part of the slope can be also an effect of locally more solid rock which is more resistant to mechanical weathering and solution, and it can not be a proof for the doline collapse origin. Fracturing the rock into rubble contributes to the widening of the doline diameter. The different resistivity to mechanical weathering makes the upper opening of the doline less circular. This eccentricity was visible also in the form of two "collapse" dolines named Unška koliševka and Risnik 8 (at Divača, fig. 3, 4)), which participants of the karst shool have visited at the afternoon excursion on 27th and 28th June 2000. Both dolines have their northern slope (wall) subvertical built of solid Cretaceous micritic bedded limestone which is more resistant for crumbling. The more gentle southern slopes is mostly covered with rubble. Westwards of Risnik follow some smaller and shallower dolines with northern walls, too. Lithological control of this two dolines derives

Fig. 5: The "collapsed" doline Risnik at the settlement Divača (Kras, Slovenia). The main crushed zone from lower left to higher right side is crossed with the oblique one in the middle of the doline. In less resistant limestone the scree with trees ascends to the highest part of the rim.
Sl. 5: Udorna (?) vrtača Risnik pri Divači. Glavno krušljivo cono sredi doline prečka sekundarna od gornjega levega do spodnjega desnega roba. V bolj krušjivem apnencu sega z drevjem poraslo melišče do vrha. (foto I. Gams)

from colder Pleistocene phases when vegetational subsoil solution was weacker than in Holocene (see on the Pleeistocene age of Divača Karst in Mihevc, 1998). Under the »collapse« doline Risnik at Divača the water channel of Kačna jama was previously supposed only on the basis of rocky slopes. But the new surveying of Kačna jama found no channel under Risnik (Nagode, 1998). The accelerated role of rock crumbling for solution can explain why the volumes of the largest collapse dolines in Slovenia are greater than the known chambers in the Slovenian caves. By the same process the retreat of the wall at the end of a blind valley and a pocket valley can be explained.

3. Once a doline is initiated it continues to grow automatically. This is based on the fact that the size of the slope and of the soil/rock interface exceeds the size of the circular plain between the upper edge (if in form of a circle: πr^2) of the doline. The exceeding rate depends on the doline types and on the doline depths. The excess can be calculated by mathematics if the doline cross-section is simplified (funnel, bowl, kettle-like) and the basin volume simplified in the geometric bodies (funnel, spherical and cylindrical section).

Figure 5 shows a greater exceeding of the soil/rock interface (size) in the case of bowl-like doline (spheric section) than in the case of the funnel-like basin, both types having a steady diameter (10 m), and with increasing depth. Figure 6 shows the exceeding rate of both types of doline in the case of equal growth of radius and depth. This case is much more frequent in nature. Exceeding is faster increasing after a depth of 2 m (and after the diameter surpasses 4 m) (Gams & Krevs, 2000).

The greater exceeding of the soil/rock interface in the bowl-like doline makes the explanation possible, why at the larger dolines (at least in the Slovenian Dinaric karst) the bowl-like types prevail.

Figure 6 shows in the lower part the cross sections of a funnel-like doline with three steps of

Fig. 6: A part of the NW wall in the "collapse doline" Unška koliševka. Upper part of the wall is built of more solid strata than the lower one, where brown color indicates the less resistant beds for crumbling.
Sl. 6: Del severozahodne stene v "udornici" Unška koliševka. Zgornji del gradijo bolj odporni skladi kot so nižji, kjer rjava barva nakazuje proti krušenju manj odporne vložke (foto I. Gams).

deepening (and getting steeper slopes, too) without the widening (no 1). More natural is a simultaneous deepening and widening (no 2), so as also at the semicircular cross-section (no 3) and in case of a kettle-like basin (no 4). The relation of diameter (2d) to depth (d) is schematically shown for two cases in the upper part of the same figure (5): 2r = 5d, and 2r = 2,5d. The exceeding of the ”mantle” (= slopes) in both cases is relatively small for funnel-like and bowl -like dolines. It is greater for the semicircular profile and greatest for the cylindrical profile (kettle-like doline). Once the slope inclination exceeds 30° the creeping of the clastic sediments intensified and the slope is getting stony, loosing the soil/rock interface and intensive solution in it. On a stony slope mechanical weathering begins which accelerates the crumbling of the rock and thus makes for relative faster solution of the rock.

The funnel-like doline is according to the classic karstology (Cvijić, 1893) connected with the central aquifer and its role in water and mass transport. Along with the widening and deepening of the basin the transformation into a basin with more circular contour lines is going on. This process is based on the notion of specific soil/rock surface and on the faster solution of a local stony elevation which is attacked by solution on both sides and on a larger specific surface than in the depression in between. The same effect is making smooth the soil/rock interface in subsoil karst (Gams, 1976).

The greatest exceeding of the slopes (mantle) above circumference is in case of the kettle- like form. In a doline with vertical slopes the soil/rock interface remaines the same during the time of deepening and so a shallow chasm can develop. But there is less biological activity in the soil and a weaker solution below the soil and vegetation cover.

4. Global climatic restraint of the doline distribution.

The schematic global zonal precipitation, temperature, evapotranspiration, depth of the solution front in the endokarst, and zone of dense dolines are shown in the diagram (Fig. 7) (Gams, 1992). The collapse doline which occur in all climates are here not taken in account. The arid climate with greater evapotranspiration than precipitation and with a solution front near to the surface is without closed karst basins. Dolines are absent too in the polar zone with long frozen soil and without soil moisture. This was tested also by means of limestone tablets on the 2514 m high Kredarica in Slovenija (Gams, 1976). In the humid tropical climate with higher precipitation than potential evapotranspiration, surpassing 2 m, are the oblong enclosed basins called cockpits. They are star-like and attributed to the streams flowing after heavy rain (Sweeting, 1972, 46, Jennings, 1985, 106 -120, Ford & Williams, 1989, 415) and not circular as the dolines in the temperate zone. (Fig. 8). The doline are most typical in that part of the temperate zone where the precipitation considerable surpasses the potential evapotranspiration.

On both sides of the global climatic “doline” zones the dolines are more and more limited to the higher elevations. The global occurrence of dolines is scarcely known even in the temperate zone. In the north-eastern mountainous border of the Mediterranean basin, in the Istria Peninsula dolines are dense down to 50 m altitude on the western coast, but to the SE in the Dinaric Karst they began to appear higher and higher on the coastal mountains (Šerko, 1947), map of dolines and kettles (kotliči). In Greece, Turkey and Lebanon they are developed but only on the highest mountain plateaus.

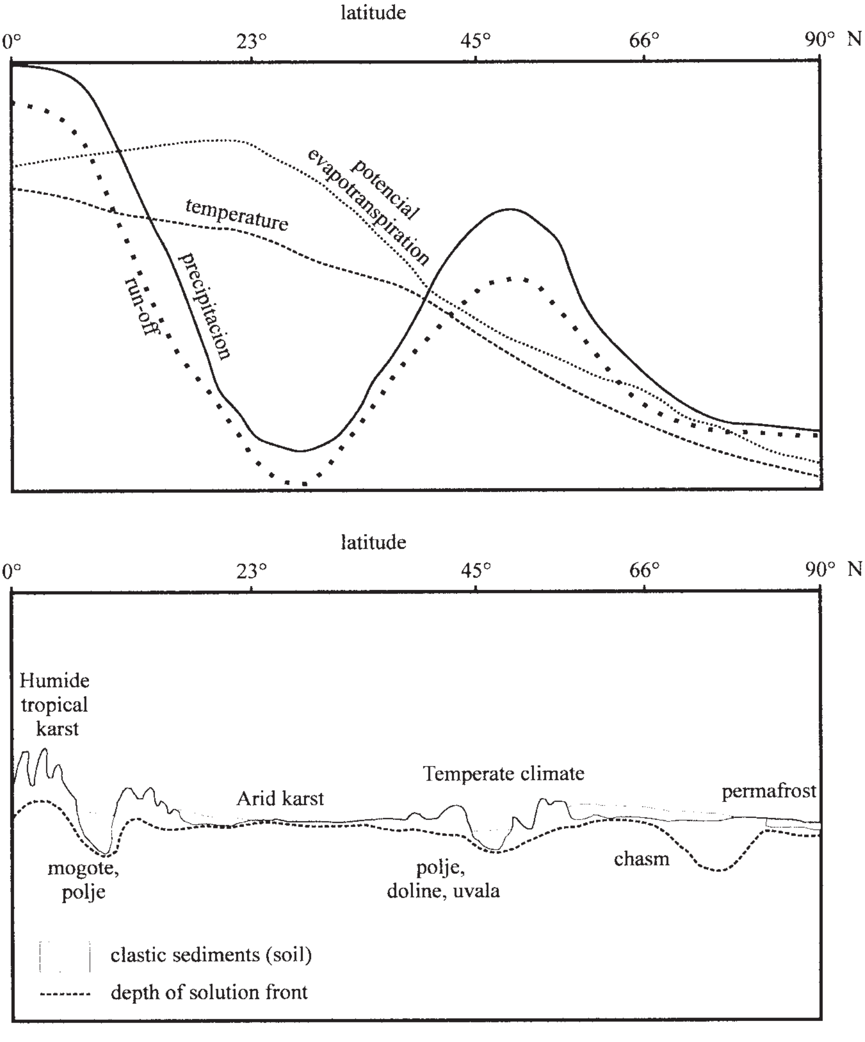

Fig. 7: Global schematic zonation of the conditions for doline development Upper diagram: climatic conditions, in lower diagram depth of solution front and closed basins - dolines and poljes.
Sl. 7: Globalna shematska pasovitost pogojev za razvoj vrtač. V zgornjem diagramu klimatski pogoji, v spodnjem globina korozijske fronte (do stika s sigotvornostjo prenikajoče vode) in zaprte kotanje - vrtače in kraška polja.

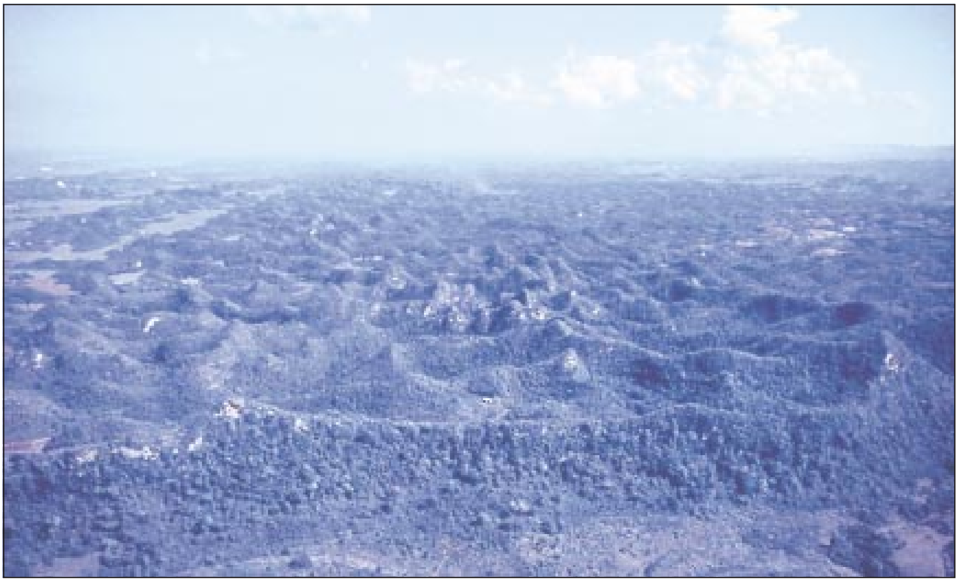

Fig. 8: Cockpits in karst of Puerto Rico.
Sl. 8: Tropske vrtače cockpits na Puerto Ricu (foto H. Monroe).

Fig. 9: Snow in the basins on northern slope of the Bohinj Mountains under Mt. Vogel, Julian Alps, at the altitude 1500 - 1700 in June.
Sl. 9: Sneg v kotanjah v Bohinjskih gorah pod Voglom junija meseca v višini 1500 - 1700 m (foto I. Gams).

LOCAL CONDITIONS FOR DOLINE DEVELOPMENT

Local accelerated solution and begin of doline

Inside the zone where the precipitation surpasses the evapotranspiration, and outside the zone with permafrost, solution dolines occur due to the local accelerated solution. This is an effect of different factors (Gams, 1965). One of the most important is a greater run-off of the rain and snow melting water (Fig. 9 and 10). On a rocky surface and in a snowy climate the deepening of the depression and generation of kettle-like dolines (stone doline, kotliči in the Slovenian - Kunaver, 1982) due to the snow local accumulated by wind deposits, is a consequence of this process. The deeper the basin, the more snow is accumulated inside, the longer the phase of moisture of wet snow in contact with rock, and the greater the local solution. In the covered Slovenian Dinaric kast of middle altitude the precipitations in great dolines are a little higher (acc. to measuring in June 1970, the two deep dolines near Logatec in Slovenia got on the bottom 8 and 16 % more precipitation than the rain gauge outside and evaporation on the bottom was essentially reduced. In spring even in the forest land snow lasted longer in the bigger dolines (Gams, 1972, p. 25 - 27). Soil in the stony depression or in moraine in high Alpine karst considerable increases the solution on the

Photo 10: Dense (polygonal) dolines on the top of the mountain Treskavica (Hercegovina) in the altitude 1900 - 2000 m. Before the man's impact tree line reached this altitude (s. rest of trees left).
Foto 10: Goste (poligonalne) vrtače na vrhu hercegovske gore Treskavice v n.v. 1900 - 2000, do koder je pred posegom človeka segala zgornja drevesna meja (foto I. Gams).

surface (in Julian Alps, Gams, 1966). In the colder Pleistocene was evidentely the favourable climate for doline development (Gams, 1997). Also Šušteršič (1994, 155) attributes the recent doline forms mostly to the Pleistocene slope processes. In the last, Würmian glaciation in the Slovenian Dinaric Karst the animal species typical for the cold steppe lived down to the recent coast of the Trieste Bay. Such a climate provoked a stronger depth develoment of the doline and the shafts. At the same time the cold climate with frequent frosts and vigorous mechanical weathering of the rock at lower altitudes contributed to the transformation of the kettle-forms to the bowl-formed dolines. Having in mind the dolines as inherited from many hundred thousand of years or so we have to assume that a kettle-like collapsed doline due to mechanical weathering of the steep slopes with time diverts into a bowl-like doline. The walls retained their strong inclination in the case where higher strata are more resistant than those below them.

No evidence on the existence of dolines in the Dinaric Karst before the Pleistocene is known. There and in tropical wet climates we can suppose there to exists only rare cockpits with streams flowing to the central ponors and generating the basins, and not real dolines of temperate type. Surface drainage there can be attributed to the less permeable soil. In Xichow region of Yunnan (South China) the soil contains 65 % to 99 % of clay granules (with a radius less than 0,005 mm) (Chen Xiaoping, 1998, p.132). In the Dinaric coastal karst the content of clay particles (less than 0,002 mm) in the horizon B is only 45 to 75 % (Urushibara, 1976, p.127). Thick clay soil on the doline bottom in a humid tropical climate hinders the deepening and in a temperate climate it only widens the bottom giving to the doline a bowl-like form. Due to the denudation of the soil from the doline slope in the forest of NW Dinaric karst the clay content in the bottom soil is less than in the surrounding (Lovrenčak, 1977), as the clay is more resistant to denudation. At present nearly parallel slope retreat prevails and the mean correlation between depth and diameter in Craigmore plateaus in Canterburry, New Zealand is 0.87 (Jennings, 1975).

Local restraints of doline development

In the mentioned favourable climatic zones the density of dolines is dependent on slope gradient. All researchers have found the decreasing density with greater slope angle (between them Maksimovič, 1963, Maksimovič & Gorbunova, 1958 in Perm region, Ford & Williams1989). Kranjc (1972, p.156) found in the Kočevsko polje in the Dinaric karst of Slovenia the slope inclination 30° as the upper limit of doline distribution. At an angle 30° the accumulated clastic sediments without vegetation cover get markedly unstable by processes called in general geomorphology creeping, denudation, solifluction and so on, which are according to the general textbooks on geomorphology active on all slopes of the world but not yet recognized or not yet studied in the dolines. The classical sketch of a doline (Cvijić, 1893) shows the central drainage aquifer on the nearest point of the closed basin, where the transport of water and mineral particles, soil, leaves, humus, litter, rubble and so on is concentrated. In the Dinaric Karst of Slovenia doline density depends on the resistivity against mechanical weathering of the stone. Dolines are dense in the solid and bedded Jurasssic oolithic limestone and in the compact strata of the Cretaceous micritic limestone. The tectonically broken and in epikarst weathered Triassic dolomite in the north-eastern border of the Dinaric Karst is nearly without dolines. They occur there on the flat ground mostly.

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GEOMORFOGENETSKI PROCESI VRTAČ Z GLOBALNEGA IN LOKALNEGA VIDIKA

Povzetek

Nastajanje korozijskih vrtač je še vedno sporno. Meritve procesov v travniških vrtačah v holocenski klimi niso dobra osnova za ugotavljanje procesov in pogojev nastanka teh najbolj pogostih srednje velikih kotanj, saj segajo začetki vrtač v hladnejše dele 2 milijona let dolgega pleistocena in v kvartarno gozdno okolje vobče, ki ga je doslej človek spremenil v travniškega. Spričo nenehnega korozijskega zniževanja kraškega površja moramo večje kotanje z nadpovprečno globino, ki je 5 - 20 m, smatrati za podedovane oblike, v katerih so začetni ugodni pogoji za razvoj navadno že odstranjeni.

Ob takem stanju se kaže pri razlagi nastanka nasloniti na splošne kraško-morfološke principe, ki so naslednji.

Vzroke za nastanke vrtač je treba iskati v vrhnji, epikraški coni, kjer se na stiku prst/kamen odvija najintenzivnejša korozija padavinske vode v vsem kraškem masivu.

Korozija karbonatnih kamnin je posledica ionskih napetosti na površju karbonatne kamnine ob stiku z agresivno talno vlago (vodo), zato je korozijska intenzivnost odvisna od velikosti specifične površine kamen/voda. Bolj zdrobljena kamnina ima večjo specifično površino (n.pr. zdrobitev kocke 1 × 1 m na tisoč kock z desetkrat krajšo stranico šest kratno poveča specifično površino).

Učinek povečane specifične površine na korozijo smo preverjali v fizičnogeografskem laboratoriju v Oddelku za geografijo univerze v Ljubljani (slika 2). Pet granulacij krednega mikritnega apnenca v razponu med 0,1 in 30 mm je bilo v posodah na aparatu za valovanje, 24 - 36 ur izpostavljenih potočni vodi Homšnice in, v drugem primeru, deževnici, zajeti v Ljubljani. Sprotna meritev mineralizacije je bila opravljena z meritvami električne prevodnosti, redkeje titrimetrično z običajnimi reagenti. V obeh primerih je bila korozija drobnejših frakcij močnejša in hitrejša. Korozija

padavinske vode kraško površje v bolj zdrobljeni kamnini lokalno torej hitreje poglablja, v začetni fazi še pod odejo prsti, kjer nastanejo podtalne vrtače (slika 1). V vrtačah z delno skalnatim pobočjem, kjer intenzivnejše mehanično preperevanje ustvarja melišča, na dnu pokrita s prstjo in vegetacijo, zato lahko nastajajo večje kotanje kot znašajo prostornine največjih votlin v znanih jamah.

Skladno s poglabljanjem vrtače površina njenih pobočij vedno bolj presega površino ravnine znotraj zgornjega oboda kotanje, kar samodejno pospešuje rast vrtače. Preseganje lahko izračunamo, ako shematiziramo prečne preseke (lijakasta, skledasta, kotlasta vrtača) v geometrijska telesa (stožec, krogelni odsek, polkrogelni odsek - sl. 3). Preseganje (slika 4) pobočij v lijakasti vrtači je manjše kot pri skledasti (s polkrožnim profilom). V tej luči je razumljivo, da lijakaste vrtače z rastjo prehajajo v skledaste.

Samodejno poglabljanje vrtače zavrejo strmi deli pobočja, kjer se zaradi spiranja klastičnih sedimentov na ogoličenih skalnatih delih zmanjša korozija in poveča mehanično krušenje.. Naklon pobočij v zmerni klimi je zato navadno manjši od posipnega kota za grušč (30 - 33°). Taka nagnjenost površja je pri nas zato tudi zgornja meja pojavljanja vrtač. Večji nakloni v pobočju vrtače se pojavljajo v lokalno bolj kompaktnih skladih s slabšim krušenjem, kjer se manj uveljavlja princip hitrejše korozije zaradi specifične površine Tudi v primeru bolj kompaktnih skladov nad manj kompaktnimi lahko nastanejo stene, značilne za udornice (slika 5, 6).

V vlažni toplejši klimi vododržna debela finozrata preperina na dnu zavre poglabljanje. V bolj glinasti in manj prepustni zemlji v vlažnih tropih zato lahko iščemo vzrok za odsotnost vrtačastih oblik, kot so znane iz zmerno tople klime. Tamkajšnje kotanje, znane kot cockpit, so posledica obdobnih potočkov po pobočju, ki ponirajo v dnu.

Po svetu se vrtače javljajo v dveh klimatskih pasovih, to je vlažno tropskem in vlažnem zmernem podnebju, torej tam, kjer padavine občutno presegajo potencialno evapotranspiracijo. Ni jih v aridni klimi in v območju permafrosta. V območju vrtač je korozijska fronta globlje pod površjem (slika 7), kar je pogoj za nastanek kotanj. V zmernem pasu so gostejše in večje na vzpetinah, kjer je padavin navadno več in temperature nižje, z njo pa manj tudi evapotranspiracije. Gostota vrtač pada z rastjo naklona kraškega površja. Močno prestavljanje klastičnih sedimentov torej zavira rast vrtač. V Sloveniji so vrtače, skladno s povedanim, najbolj goste v najbolj kompaktnih apnencih, zlasti oolitnih jurskih in mikritnih krednih apnencih, medtem kot so na bolj krušljivem triasnem dolomitu omejene na uravnave z debelejšo prstjo.

Rast vrtač je učinek lokalno pospešene korozije, kjer skraja izstopa učinek specifične površine, to je bolj zdrobljene kamnine, nato preseganje stične površine skala/prst, v skalnatem površju v snežni klimi pa tudi zaradi lokalno povečanega vodnega odtoka padavinske vode. V visokogorstvu pade toliko več sneg, kolikor bolj je kotanja globoka. V tipični taki obliki vrače, v kotliču, to je v obliki, v kateri obseg pobočij najbolj presega vrhnjo odprtino, je agresivne vode več kot v okolici in vlaga na dno in stene deluje dalj časa v letu.

Zaradi večjega mehančnega krušenja skale, manj prepustne preperine in več zimskih padavin v obliki snega in manjše evapotranspiracije, so bili v hladnejšem pleistocenu ugodnejši pogoji za razvoj vrtač kot v holocenu ali pliocenu. Večino vrtač na nižinskem pokritem krasu, razen resničnih udornic, je iz teh razlogov v holocenu smatrati za fosilne tvorbe.