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Unconfined versus confined speleogenetic settings: variations of solution porosity

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Abstract

Speleogenesis in confined settings generates cave morphologies that differ much from those formed in unconfined settings. Caves developed in unconfined settings are characterised by broadly dendritic patterns of channels due to highly competing development. In contrast, caves originated under confined conditions tend to form two- or three-dimensional mazes with densely packed conduits. This paper illustrates variations of solution (channel) porosity resulted from speleogenesis in unconfined and confined settings by the analysis of morphometric parameters of typical cave patterns. Two samples of typical cave systems formed in the respective settings are compared. The sample that represents unconfined speleogenesis consists of solely limestone caves, whereas gypsum caves of this type tend to be less dendritic. The sample that represents confined speleogenesis consists of both limestone and gypsum maze caves. The comparison shows considerable differences in average values of some parameters between the settings. Passage network density (the ratio of the cave length to the area of the cave field, km/km^2) is one order of magnitude greater in confined settings than in unconfined (average 167.3 km/km^2 versus 16.6 km/km^2). Similarly, an order of magnitude difference is observed in cave porosity (a fraction of the volume of a cave block, occupied by mapped cavities; 5.0 % versus 0.4 %). This illustrates that storage in maturely karstified confined aquifers is generally much greater than in unconfined. The average areal coverage (a fraction of the area of the cave field occupied by passages in a plan view) is about 5 times greater in confined settings than in unconfined (29.7 % versus 6.4 %). This indicates that conduit permeability in confined aquifers is appreciably easier to target with drilling than the widely spaced conduits in unconfined aquifers.

Keywords: Cave morphology, cave patterns, speleogenesis, confined karst aquifers

Intoduction

Speleogenesis in confined settings generates cave morphologies that differ much from those formed in unconfined settings. Speleogenesis in unconfined settings tends to produce broadly spaced dendritic patterns of channels due to highly competing development (Fig. 1A). In contrast, caves originated under confined conditions tend to form two- or three-dimensional mazes with densely packed conduits (Fig. 1B). These caves form as the result of vertical hydraulic communication between "common" insoluble or less soluble porous/fissure aquifers across the soluble bed ("transverse speleogenesis"). There is a specific hydrogeologic mechanism inherent in artesian transverse speleogenesis (restricted input/output) that suppresses the positive flow-dissolution feedback and hence speleogenetic competition in fissure networks which accounts for the development of more pervasive channelling in confined settings. This results in maze patterns where appropriate structural prerequisites exist. This is the fundamental cause for the distinctions between cave morphologies evolving in unconfined and confined aquifers, and for eventual distinctions of karstic permeability, storage characteristics and flow system behaviour between the two types of aquifers (Klimchouk, 2000a, 2003).

This paper aims to illustrate variations of solution (channel) porosity resulted from speleogenesis in unconfined and confined settings. This can be done by the analysis of morphometric parameters of typical cave patterns.

Porosity components in karst aquifers

Four types of elementary porosity components are commonly recognised in karst aquifers (Klimchouk and Ford, 2000; Worthington, Ford and Beddows, 2000; Worthington, 1999): 1) *pores* in the rock matrix (tiny intergranular, intercrystalline, etc voids); 2) *fissures* (planar discontinuities such as bedding planes, joints and faults in which the aperture is negligible in scale when compared to the length and breadth); 3) *conduits* (elongated planar or tubular openings where the aperture is a significant proportion of the length; and 4) *vugs and caverns*, (seemingly isolated voids of irregular shape and with diameters several orders of magnitude greater than those of average matrix pores). Elementary void types originate under different conditions and combine in various proportions to form aquifers. Pores are commonly the result of sedimentation and diagenesis; fissures are generated (or at least hydrologically opened) mainly by the late diagenesis, tectonism and weathering, and conduits and vugs are commonly formed due to speleogenesis. Hydrologically isolated solution vugs are scarce, if they exist at all, so they can be combined with conduits in the hydrogeological consideration. As a result, karst aquifers are considered as triple porosity aquifers.

Worthington (1999) and Worthington, Ford and Beddows (2000) analysed four different carbonate aquifers and demonstrated that most of the aquifer storage is in matrix pores but most of flow is in conduits, with fissures playing an intermediate role. It has been shown that enhancement of *porosity* by dissolution is relatively minor. On the other hand, the enhancement of *permeability* has been considerable, because dissolution has created dendritic networks of interconnected channels that are able to convey 94% or more of the flow in the aquifer.

Conduit porosity can be characterised by deriving respective figures from survey data of well-explored caves. In the above-cited works, such an analysis was performed for ten well-mapped cave systems, all developed in unconfined aquifers. It has been found that cave porosity (the fraction of the bedrock that is occupied by an explored cave) varies between 0.004 - 0.48 %, with the average value being of 0.16 %. The areal coverage of a cave (a fraction of the area of the cave field occupied by passages in a plan view) varies between 0.37 - 7.5 %, with an average value of 2.46 %. Similar estimates were determined earlier (Klimchouk, 1992; 2000b) for 14 artesian gypsum maze caves in the Western Ukraine that provided much greater values: cave porosity variations within 2.0 - 12.0 % (average 4.5) and areal coverage of caves within 17.5 - 48.4 % (average 29.5). These conflicting values could have been interpreted as resulted from differences in speleogenetic mechanisms operating on cave patterns formed in unconfined and confined settings. However, the artesian caves were all from one region and represented speleogenesis in gypsum. Therefore, it could be argued that the greater porosity characteristics were specific to gypsum or due to regional structural peculiarities rather than due to the difference between unconfined and confined speleogenetic mechanisms.

In this paper we expand morphometric analysis to compare typical caves formed in unconfined aquifers with those formed in confined settings in both gypsum and limestones, and in different regions.

Some methodological aspects of morphometric analysis of caves

For the purposes of speleogenetic analysis and hydrogeological and engineering characterisation of karstified rocks, some specific parameters can be used, derived from basic measures of a cave, cave field and the rock block. *Specific volume* (the cave volume/length ratio, which is an average cross-sectional area of the cave) characterises typical size of passages in the cave system. *Passage network density* is characterised conveniently by the ratio of the cave length to the area of the cave field (km/km^2). *Areal coverage* is the area of the cave itself divided by the area of the cave field expressed as a percentage. It refers to plan-view cave porosity density, which is equivalent to the probability of a drill hole encountering the cave. *Cave porosity* is a fraction of the volume of a cave block, occupied by mapped cavities. It is the volume of the cave divided by the volume of cave block expressed as a percentage.

Cave explorers routinely determine the cave length by reduction of survey data. The cave area (the area occupied by passages and chambers) is less frequently reported but it can be measured from cave maps. The volume of caves (the combined volume of all passages and chambers) is rarely reported. To accurately determine volume, it is necessary to sum up volumes of individual elements of the cave, determined from the original survey measurements of length, width and height. If this was not done routinely throughout all the mapping history of a complex cave (an exception rather than rule), then the volume of the cave can only be roughly evaluated by multiplying the cave area by the average passage height and applying a coefficient accounting for typical shape of the passage cross-section. More adequate estimates are obtained by summing up values determined separately for morphologically distinct cave series.

The parameters that characterise conduit pattern and porosity (the passage density, the areal coverage and cave porosity) depend upon the area of cave field and the volume of rock considered. The area of the cave field is commonly determined by drawing the minimum rectangle that encloses represents the plan array of mapped passages (Fig. 1). The volume of rock is determined by multiplying the cave field area by the vertical amplitude of a 3-D array of passages. The "rectangular" method is used in order to streamline measurements and make them unambiguous and repeatable. However, it leads to underestimation of the areal coverage and cave porosity due to inadequate exaggeration of the area of a cave field and rock volume taken into consideration. A degree of exaggeration depends on "compactness" of the plan arrangement of passages and the presence of branches that occasionally protrude away from the bulk area of, the conditions that may change considerably in the course of exploration of a given cave system.

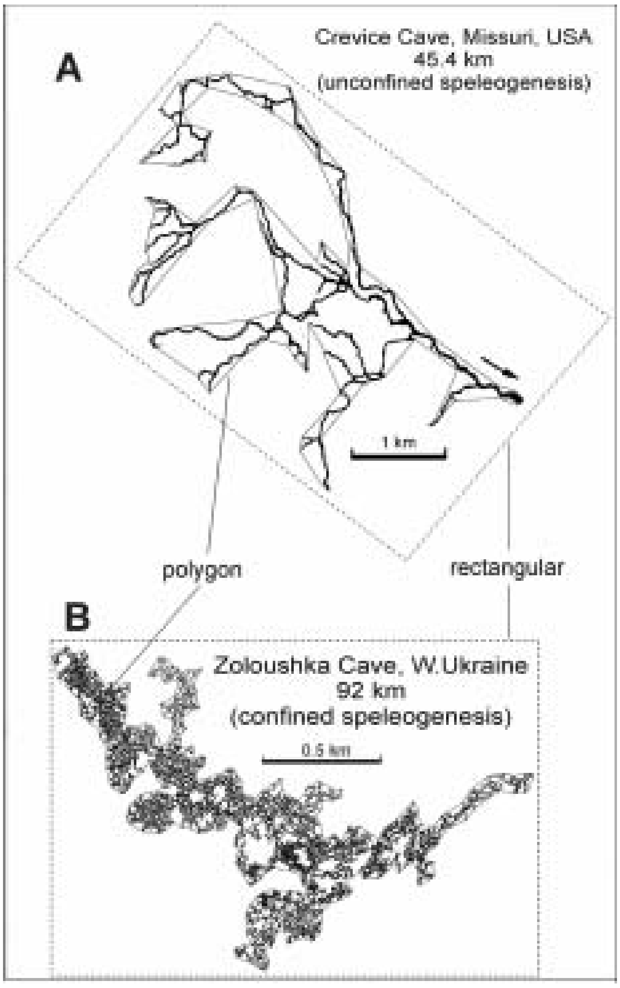

Fig. 1. Typical patterns of caves formed in unconfined (A - dendritic pattern) and confined (B - network maze pattern) settings. The figure also illustrates two methods of delineation of cave fields: by drawing the rectangle or polygon that encloses the plan array of mapped passages.

An alternative method advocated here is drawing the polygon that reasonably closely embraces the plan array of a cave (Fig. 1). It may seem to give ambiguous results due to subjectivity of the polygon shape. However, in practice this subjectivity results in variation of the resultant areal coverage and cave porosity values only within 10-15%, much less than, for instance, variation due to drawing the rectangle around the plan arrays of passages mapped in the same cave system for different years. For various patterns, parameters determined by the rectangular method are underestimated 2 to 5 times as compared to estimates derived using the polygon method. The latter seems to be more justified for comparison of cave patterns with hydrogeological and speleogenetic purposes.

Caves used for morphometric analysis

For the purpose of comparison between conduit pattern and porosity characteristics in unconfined and confined settings, it was necessary to choose comprehensively explored and well-documented large caves that are unambiguously typical for respective settings. Availability of basic cave measurements and maps that would correspond to the respective exploration status, exerted further limits on the choice.

The set of unconfined caves was based on data published by Worthington (1999) and Worthington, Ford and Beddows (2000). To recalculate the areal coverage and cave porosity using the polygon method for the cave field area, and to determine the passage density that was not given in the cited works, it was necessary to refer to maps and basic cave data. Of the ten caves characterised in these works, only three caves were used for the analysis for which the author was able to collect the needed materials (Blue Spring Cave, Mammoth Cave and Friars Hole System). The Krasnaja Cave, the best example of an unconfined cave from Crimea, Ukraine, supplemented these caves. Gypsum caves formed in unconfined settings were not used for the analysis, as their patterns tend to be generally less dendritic than that of limestone caves. Most caves in gypsum consist of single or crudely branching conduits.

Gypsum maze caves of the Western Ukraine represent the bulk of the caves formed under confined conditions for which all parameters were determined earlier (Klimchouk, 1992, 2000b). Another gypsum cave within this set is the Estremera labyrinth from Madrid area, Spain. Limestone caves of presumably artesian transverse genesis (Klimchouk, 2003), used for this analysis, include Wind and Jewel Caves from South Dakota, Botovskaya Cave from Siberia (Russia), Fuchslabyrinth (Germany), Moestroff (Luxemburg) caves and Knock Fell Caverns (UK).

TABLE 1

Characterisation of conduit patterns and porosity in unconfined versus confined aquifers

Cave	Length, km	Area of cave, m^{2}x10^6	Volume of cave, m^{3}x10^6	Area of cave field km^2	Volume of rock, m^{3}x10^6	Specific volume, m^3/m	Passage density, km/km^2	Cave porosity, %	Areal coverage, %
"Common" caves – speleogenesis in unconfined settings									
Blue Spring Cave, Indiana, USA, Carboniferous limestones	32.0	0.146	0.5	2.65	119.34	15.6	12.07	0.42 (0.08)	5.5 (1.1)
Mammoth Cave, KY, USA, Carboniferous limestones	550.0	1.386	8.0	36.78	3310.2	14.5	14.95	0.24 (0.09)	3.77 (1.4)
Friars Hole System, WV, USA, Carboniferous limestones	70.0	0.3	2.7	4.37	349.92	38.6	16.00	0.77 (0.28)	6.86 (2.5)
Krasnaya Cave, Crimea, Ukraine, Jurassic limestones	17.3	0.064	0.27	0.74	37.0	15.5	23.23	0.15	8.55
Maze caves – speleogenesis in confined settings									
Jewel Cave, South Dakota, USA, Carboniferous limestones	148.01	0.67	1.49	3.01	135.63	10.00.0	49.11	1.10	22.20
Wind Cave, South Dakota, USA, Carboniferous limestones	143.2	0.43	1.13	1.36	61.0	7.9	105.68	1.86	31.73
Knock Fell Caverns, N.Pennines, UK, Carboniferous limestones	4.0	0.006	0.012	0.02	0.12	3.0	170.94	10.26	25.64
Fuchslabyrinth Cave, Germany, Triassic limestones (Muschelkalk)	6.4	0.0058	0.007	0.03	0.15	1.1	217.61	4.80	19.55
Moestroff Cave, Luxembourg, Triassic limestones (Muschelkalk)	4.0	0.004	0.0035	0.01	0.05	0.9	406.09	7.14	40.61
Botovskaya Cave, Siberia, Russia, Lower Ordovician limestones	23.0	0.067	0.104	0.11	1.37	4.5	201.75	7.62	58.51
Estremera Cave, Madrid, Spain, Neogene gypsum	3.5	0.008	0.064	0.06	0.71	18.3	59.32	9.04	13.56
Optimistychna Cave, W.Ukraine, Neogene gypsum	188.0	0.26	0.52	1.48	26.03	2.8	127.03	2.00	17.57
Ozerna Cave, W.Ukraine, Neogene gypsum	111.0	0.33	0.665	0.74	13.2	6.0	150.00	5.04	44.59
Mlynki Cave, W.Ukraine, Neogene gypsum	24.0	0.047	0.08	0.17	2.38	3.3	141.18	3.36	27.65
Kristalna Cave, W.Ukraine, Neogene gypsum	22.0	0.038	0.11	0.13	1.82	5.0	169.23	6.04	29.23
Slavka Cave, W.Ukraine, Neogene gypsum	9.0	0.019	0.034	0.07	0.98	3.7	139.14	3.47	29.05
Verteba Cave, W.Ukraine, Neogene gypsum	7.8	0.023	0.047	0.07	0.66	6.0	117.82	12.00	34.74
Atlantida Cave, W.Ukraine, Neogene gypsum	2.52	0.0045	0.0114	0.02	0.29	4.5	168.00	4.00	30.00
Ugryn Cave, W.Ukraine, Neogene gypsum	2.12	0.004	0.008	0.01	0.14	3.8	176.67	5.71	33.33
Jubilejna Cave, W.Ukraine, Neogene gypsum	1.5	0.002	0.0035	0.01	0.08	2.3	277.78	4.00	37.04
Komsomol’ska Cave, W.Ukraine, Neogene gypsum	1.24	0.0017	0.0026	0.01	0.07	2.1	177.14	3.00	24.29

Dzhurinska Cave, W.Ukraine, Neogene gypsum	1.13	0.0016	0.0027	0.01	0.12	2.4	125.56	2.00	17.78
Zoloushka Cave, W.Ukraine, Neogene gypsum	89.5	0.305	0.712	0.63	18.93	8.0	142.06	3.76	48.41
Bukovinka Cave, W.Ukraine, Neogene gypsum	2.4	0.0043	0.006	0.02	0.14	2.5	120.00	4.44	21.50
Gostry Govdy Cave, W.Ukraine, Neogene gypsum	2.0	0.0013	0.0033	0.01	0.07	1.7	270.27	4.00	17.57

Notes:

1. In the columns "Cave porosity" and "Areal coverage" values in brackets for the first three caves are those obtained by Worthington (1999) using "rectangular" method for delineation of cave fields.

2. Calculations were performed using basic cave measurements and maps obtained or derived from the following sources: Blue Spring Cave, Mammoth Cave and Friars Hole System: Worthington (1999), Worthington, Ford and Beddows (2000); Jewel Cave and Wind Cave: Mark Ohms, personal communication (2000); Knock Fell Caverns: Elliot (1994); Fuchslabyrinth Cave: Müller, Nething and Rathgeber (1994); Moestroff Cave: Massen (1997); Botovskaya Cave: Filippov (2000); Estremera Cave: Almendros and Anton Burgos (1983).

TABLE 2

Average characteristics of conduit patterns for unconfined and confined settings

Parameter	**Settings**			
	Unconfined	Confined		
		Whole set	Gypsum caves	Limestone caves
Passage density	16.6	167.3	157.4	191.9
Areal coverage	6.4	29.7	28.4	33.0
Cave porosity	0.4	5.0	4.8	5.5

The basic cave data and results of calculations are presented in the Table 1. Note that basic cave measurements are given for parts of caves, for which maps and data were available for analysis, so that they may differ from cave statistics reported from recent explorations. Average values for various groups of caves are presented in Table 2.

Discussion and conclusions

The results summarised in Table 2 clearly demonstrate that there are considerable differences in average characteristics of cave patterns and porosity between confined and unconfined settings. Passage network density is one order of magnitude greater in confined settings than in unconfined (average 167.3 km/km^2 versus 16.6 km/km^2). Similarly, an order of magnitude difference is observed in cave porosity: 5.0 % versus 0.4 %. This illustrates that storage in maturely karstified confined aquifers is generally much greater than in unconfined. Average areal coverage of cave is about 5 times greater in confined settings than in unconfined (29.7 % versus 6.4 %). This indicates that conduit permeability in confined aquifers is appreciably easier to target with drilling than the widely spaced conduits in unconfined aquifers.

The fundamental cause for the difference between conduit porosity evolving in unconfined and confined aquifers is demonstrated to be a specific hydrogeologic mechanism inherent in artesian transverse speleogenesis (restricted input/output), which suppresses the positive flow-dissolution feedback and speleogenetic competition in fissure networks (Klimchouk, 2003). This mechanism accounts for the development of more pervasive channelling in confined settingsand the development of maze patterns where appropriate structural prerequisites exist. In contrast, the positive flow-dissolution feedback and competition between alternative flowpaths dominates in unconfined settings to form broadly spaced dendritic cave patterns.

Table 2 shows no appreciable difference of parameters between gypsum and limestone caves formed in confined settings. However, , there are noticeable differences between parameters of particular caves even form the same region (Table 1). For example, compare , the characteristics of Jewel and Wind caves, both occurring within the slopes of the structural dome of the Black Hills, or characteristics of gypsum mazes in the Western Ukraine.

There are two explanations for such differences. First, one of the implications of the artesian transverse speleogenetic model (Klimchouk, 2003) is that virtually all hydrogeologically active fissures will be exploited in speleogenesis. The density of passages in the resultant network depends on the structural prerequisites. Variations in characteristics of fissure networks, resulted from peculiar geological/tectonic position, can account for the above differences. It should be stressed that even though maze caves are the typical result of artesian transverse speleogenesis, they may not form in the respective setting if the structural prerequisites are not favourable. For instance, on the other extreme of structurally-dependent artesian cave patterns are single fissure-like passages blind-terminated at both ends, or few intersected fissure passages, encountered by mines in many regions such as in the Prichernomorsky artesian basin of Ukraine (Klimchouk, 2003). These are not true maze caves although they are the typical results of artecian transverse speleogenesis.

The second reason lies in different speleogenetic history on the late artesian and post-artesian stages. Some caves or their parts may experience more intense growth than others during transition from confined to unconfined settings, if they are favourably positioned relative to main breaches (discharge points or zones). On the post-artesian stage, much of the volume in some caves can be added due to horizontal notching during stillstands of the water table, the effect being most pronounced in gypsum (note values for Zoloushka and Ozerna caves in the Western Ukraine).

This study supports the conclusion drawn in Klimchouk (2003) that any generalisation of hydrogeology of karst aquifers, as well as approaches to practical hydrogeological issues in karst regions, should take into account the different nature and characteristics of conduit porosity and permeability that evolve in confined and unconfined settings.

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