УДК 551.44+556.3

HYDROGEOLOGICAL APPROACH TO DISTINGUISHING HYPOGENE SPELEOGENESIS

A.B. Klimchouk

Institute of Geological Sciences of NAS of Ukraine, Kyiv, Ukraine,
E-mail: klim@speleogenesis.info

Doctor of geological sciences, leading scientist, Department of hydrogeological problems.

Defined in the most general way, hypogene speleogenesis is the origin of caves in which the cave-forming agency comes from depth, in contrast to epigene (hypergene) speleogenesis in which the cave-forming agency (meteoric recharge and its inherent or soil-derived aggressiveness) originates at the surface. A more specific definition should rely on attributes of the cave-forming agency which are most suitable and efficient for discrimination between epigene and hypogene origin of caves. Relying on the determination of a source of the aggressiveness in distinguishing hypogene speleogenesis is the legitimate approach (usually referred to as geochemical) but it is not a methodologically sound and practically efficient one. The hydrogeological approach and the reference to upwelling groundwater circulation in the definition of hypogene speleogenesis provide a theoretically and methodologically sound basis not only for its identifying, but also for spatial and temporal prognosis.
Key words: hypogene karst, speleogenesis, karst hydrogeology.

ГІДРОГЕОЛОГІЧНИЙ ПІДХІД ДО ВИОКРЕМЛЕННЯ ГІПОГЕННОГО СПЕЛЕОГЕНЕЗУ

О.Б. Климчук

Інститут геологічних наук НАН України, Київ, Україна,
E-mail: klim@speleogenesis.info

Доктор геологічних наук, провідний науковий співробітник відділу гідрогеологічних проблем.

У найбільш загальному вигляді гіпогенний спелеогенез визначається як формування карстових порожнин під впливом агентів, що походять з глибини, на відміну від епігенного спелеогенезу, в якому порожниноформуючі агенти (метеорне живлення та агресивність вод) походять з поверхні. Більш конкретне визначення повинне ґрунтуватися на ознаках агентів і механізмів порожниноформування, що дозволяють найбільш чітко розрізняти епігенне та гіпогенне походження порожнин. Вказівка на «неповерхневе» походження джерела агресивності в такому розрізненні (геохімічний підхід) є правомірним, але методично і практично неефективним підходом. Гідрогеологічний підхід і застосування критерію висхідного водообміну у визначенні гіпогенного спелеогенезу складають теоретично і методологічно обґрунтовану основу не тільки для його ідентифікації, а й для просторово-часового прогнозування.
Ключові слова: гіпогенний карст, спелеогенез, гідрогеологія карсту.

ГИДРОГЕОЛОГИЧЕСКИЙ ПОДХОД К ВЫДЕЛЕНИЮ ГИПОГЕННОГО СПЕЛЕОГЕНЕЗА

А.Б. Климчук

Институт геологических наук НАН Украины, Киев, Украина,
E-mail: klim@speleogenesis.info

Доктор геологических наук, ведущий научный сотрудник отдела гидрогеологических проблем.

В самом общем виде гипогенный спелеогенез определяется как формирование карстовых полостей под воздействием агентов, происходящих из глубины, в отличие от эпигенного спелеогенеза, в котором полостеформирующие агенты (метеорное питание и агрессивность вод) происходят с поверхности. Более конкретное определение должно основываться на признаках агентов и механизмов полостеобразования, позволяющих наиболее четко различать эпигенное и гипогенное происхождение полостей. Указание на «неповерхностное» происхождение источника агрессивности в таком различении (геохимический подход) является правомерным, но методически и практически неэффективным подходом. Гидрогеологический подход и использование критерия восходящего водообмена в определении гипогенного спелеогенеза образуют теоретически и методологически обоснованную основу не только для его идентификации, но и пространственно-временного прогнозирования.
Ключевые слова: гипогенный карст, спелеогенез, гидрогеология карста.

Introduction: Approaches to define hypogene speleogenesis

Advancements in karst and cave science during the past 20-30 years have led to the growing recognition of the possibility, wide occurrence, and practical importance, of conduit porosity development in deep-seated conditions, without direct influence of near-surface factors. Hypogene speleogenesis has become one of the hottest topics in karst and cave science, and the subject draws the increasing attention of other branches of geosciences, as well as of practitioners, particularly in the mineral and hydrocarbon resources exploration and in geological engineering.

However, there are some differences in approaches on how to define hypogene speleogenesis.A.N. Palmer [2000a] defined hypogenic caves as those *formed by water in which the aggressiveness has been produced at depth beneath the surface, independent of surface or soil* CO_2 *or other near surface acid sources*. This approach emphasizes the source of aggressiveness, and it is termed here "geochemical".

With the "hydrogeological" approach, hypogene speleogenesis is defined as the *formation of solution-enlarged permeability structures by water that recharges the cavernous zone from below, driven by hydrostatic pressure or other sources of energy, independent of recharge from the overlying or immediately adjacent surface* [Ford, 2006; Klimchouk, 2007, 2013a]. This definition places an emphasis on the groundwater circulation system (GCS). It directly indicates that hypogene speleogenesis develops by upwelling flow, whereas the geochemical definition does not require this.

Are these approaches contradictory? In my opinion, they are not, although they impose somewhat different perspectives on the subject. Because of this, they determine different sets of speleogenetic environments and different samples of caves to be considered of the hypogene origin. This is a source of confusion and uncertainty that needs to be eliminated.

The aggressiveness of upwelling flow, in most cases, has been produced at depth, independent of near surface processes, and this is what constitutes the large common body of objects, outlined by both definitions. However, in some cases groundwater can keep the original undersaturation (and hence, aggressiveness) from distant recharge areas while moving deep underground along non-soluble aquifers in an artesian system and then ascending in discharge areas through soluble rocks. In such cases, it cannot be said that the aggressiveness has been produced at depth, but the aggressive water does enter the cave-forming zone from below. This situation is especially common of hypogene speleogenesis in evaporites. Moreover, dissolution of evaporates is "*independent of surface or soil* CO_2 *or other near surface acid sources,*" as well as some other dissolution mechanisms such as dissolution in mixed carbonate/sulfate strata (dedolomitization). In other cases, the aggressiveness can be produced at depth as a result of mixing of two non-aggressive waters of contrasting chemistries along the interface while none of the waters is upwelling. Examples are freshwater lenses over saline water in homogenous eogenetic carbonates in island flank-margin environments, or downward infiltration water mixing with phreatic water at the water table.

Based on the geochemical approach, A.N. Palmer [Palmer, 2007] places the artesian transverse cave development in evaporites into the realm of epigene speleogenesis, whereas cave development due to mixing along hydrochemical interfaces in unconfined aquifers is placed into the hypogene category. Within the hydrogeological approach advocated by the present author, the classifying of speleogenesis in these respective environments is the opposite.

Moving and aggressive groundwater is the principal cave-forming agency. Speleogenesis (karstic) is a coupled mass-transfer / mass transport process, which critically depends on both, the aggressiveness of ground-water and its circulation (movement). This equally applies to epigene and hypogene speleogenesis. Defined in the most general way, hypogene speleogenesis is the origin of caves in which the cave-forming agency comes from depth, in contrast to epigene speleogenesis in which the cave-forming agency (meteoric recharge and its inherent or soil-derived aggressiveness) is originated at the surface.

The question of a more specific definition is not about which of the attributes of groundwater, the aggressiveness or circulation, is more important for speleogenesis. The emphasis on a GCS in the hydrogeological approach does not mean that the importance of the aggressiveness (dissolution) is neglected, as dissolution is inherently implied as the integral part of the definitions of karst and speleogenesis (karstic). The question is about which of these attributes is most suitable and efficient to discriminate between epigene (hypergene) and hypogene speleogenesis.

It should be remembered that a definition of a natural phenomenon not only classifies a set of respective objects by referring to their most essential common attributes, but it also determines to a large extent methodologies to be implied to identify and study the phenomenon. The latter aspect is particularly important for hypogene speleogenesis, as in most cases we deal with relict caves decoupled from the cave-forming environments. The identification of the cave origin relies on our ability to discern characteristics of the cave-forming environments and processes from studying their indirect indications, preserved after the environments had changed and the original processes ceased, and other processes came to a play. It relies, therefore, on which of the attributes of the cave-forming agency are referred to in a definition as the most essential, and on how they are represented in our study objects.

Aggressiveness

Aggressiveness is an attribute of groundwater that corresponds to a chemical potential for mobilization of a dissolved matter from the rock. It results from disequilibrium in the water-rock system that is created by the groundwater circulation.

It has to be noted that it is the aggressiveness that is an attribute of moving groundwater, but not the opposite. This attribute is the transitional one. It can originate and cease in a given segment of the circulation system, and migrate through the latter with changing intensity and pattern of circulation. Also, the nature of the aggressiveness can change during the evolution of a GCS, and dissolution can proceed through different chemical mechanisms, which are much more varied in hypogene speleogenesis that in the epigene speleogenesis. For a given hypogene cave system, different mechanisms may operate either simultaneously or in a sequence, and it is often difficult to impossible to discern which of them has contributed most to speleogenesis. We normally have limited indications at our disposal to judge about the dissolution mechanisms that operated in the formation of now relict caves, or about where the aggressiveness has been produced at the time of speleogenesis (although its origin at depth below the cave-forming zone is commonly implied). Mineralogical indications are useful but they rarely tell us about characteristics of principal stages of speleogenesis *per se*. Isotopic and geochemical traces of water-rock interactions in host rocks can be a strong evidence of hypogene speleogenesis [Dublyansky et al., 2014; Spoetl, Dublyansky, 2014], but they are not always present or preserved.

Another fundamental question is whether principal characteristics of caves (their patterns, morphology, functioning, and distribution) are determined by differences in a source of the aggressiveness. In other words, does using a source of the aggressiveness as the main criteria for defining types of speleogenesis give us a useful tool to discern genetically meaningful sets of speleogenetic objects? The answer is yes perhaps only for the epikarstic porosity. It is apparently "no" for karstic porosity that forms in phreatic conditions or in water table settings.

The corollary from the above discussion is that relying on the determination of a source of the aggressiveness in distinguishing hypogene speleogenesis is a legitimate approach, but that it is not a methodologically sound and practically efficient one.

Groundwater circulation

Circulation (movement) is an inherent attribute of groundwater. Both the spatial distribution and efficiency of dissolution are controlled by intensity and a pattern (vector) of the groundwater circulation. The above-mentioned major characteristics of caves (particularly cave patterns and morphology) are determined not only by where the aggressiveness is produced relative to the surface, but also (and primarily) by how dissolution effects are distributed. The latter is dictated largely by the hydrodynamic characteristics of a GCS. Hence, it is the GCS that has to be a primary consideration for discrimination between the types of speleogenesis.

The primacy of the hydrogeological settings of a karst aquifer in determining the cave patterns has been demonstrated well by A.N. Palmer [Palmer, 1991, 2000a]. The location and distribution of void-conduit systems and characteristics of their patterns are determined by the overall pattern of GCS, the position of soluble rocks within the GFS framework, and the recharge and discharge conditions. Hence, the differences in origin and the development mechanisms of karstic void-conduit systems (types of speleogenesis) are determined largely by hydrodynamic peculiarities of GCS.

At the broadest scale, two types of GCS are recognized according to hydrodynamics: 1) confined (to a varying degree) stratal and fissure-vein systems, and 2) predominantly unconfined near-surface systems. Accordingly, two fundamental types of speleogenesis can be distinguished: 1) *hypogene speleogenesis* in confined systems, by upwelling circulation across soluble rocks within flow systems driven by external or internal recharge sources, distant or separated by insoluble layers, and 2) *epigene (hypergene) speleogenesis* in hydraulically open settings by downward and lateral circulation from overlying or immediately adjacent recharge surfaces. The differences in hydrodynamics between the respective GCS impose major distinctions in the mechanisms of these types of speleogenesis [Klimchouk, 2013; Климчук, 2013].

Hydrodynamic control on speleogenesis

In unconfined near-surface settings, discharge through conduits is controlled by two conditions [Palmer, 1991]: 1) the hydraulic capacity of conduits (hydraulic control) or, 2) the amount of available recharge from the surface (catchment control). During the early stages of speleogenesis, the positive feedback between discharge and the growth of initial conduits causes their highly competitive and selective development. With the accelerated growth of conduits after breakthrough, they quickly reach dimensions at which the fixed head condition at the recharge boundary cannot be supported any longer so that the initial hydraulic control switches to the catchment control. Further development of conduits is characterized by their competition for the surface recharge, which determines the further increasing selectiveness in the process and close genetic relationship between epigene speleogenesis and karst geomorphogenesis. Hence, in epigene speleogenesis the positive feedback between discharge and the growth of conduits strongly operates not only during the early speleogenetic stages [Palmer, 1991; Dreybrodt et al., 2005], but also during the mature stage.

In confined and semi-confined settings, where flow is directed transversely across layers and formations, both recharge and discharge of conduits occurs through adjacent insoluble beds (or segments in fissure-vein systems) with a relatively conservative permeability. Discharge in the whole GCS is controlled by the least permeable elements in the cross-section. Before the onset of speleogenesis, such elements are commonly represented by beds of soluble rocks, and discharge through early conduits in them is controlled by their hydraulic capacity. When transverse conduits reach the breakthrough condition, their further growth does not accelerate dramatically, as it occurs in epigene speleogenesis, because the control over discharge switches to the permeability of adjacent or more distant insoluble beds. The switch to the external conservative control over discharge in hypogene speleogenesis subdues the positive feedback loop and the speleogenetic competitiveness. This difference in speleogenetic mechanisms (epigene and hypogene) is one of the fundamental causes of distinctions in structure and morphology between the respective void-conduit systems. Another fundamental cause is the difference in the vector of groundwater circulation, which is explored below.

Upwelling circulation

The hydrogeological definition of hypogene speleogenesis directly relates it with the upwelling groundwater circulation. Even in relict systems, the past presence of the upwelling circulation can be recognized in most cases from the morphogenetic analysis of caves and paleohydrogeological analysis. The locations, in which upward flow is (or was) dominating, are 1) mappable from hydrogeological data, at least in basinal settings, and 2) predictable from regional hydrogeological analysis (for actual GCS) and paleohydrogeological/paleogeodynamic analysis (for past GCS). Hence, the reference to this attribute in the definition provides a methodologically feasible basis not only for identifying the type of speleogenesis, but also for spatial and temporal prognosis of hypogene speleogenesis.

The immanent link of hypogene speleogenesis with upwelling flow is suggested by vast empirical evidence and justified theoretically. The upward circulation dominates in the lower stories of the geohydrosphere because of the presence of internal recharge sources, the ultimate openness of circulation systems at the upper hydraulic boundary, and overall decrease of pressure toward the surface. During the geostatic and endogenous stages of the basin development the upwelling circulation may encompass the most of the sedimentary cover. The upward branch is also an important component of the circulation in the upper part of the geohydrosphere, in the domain of the hydrostatic (meteoric) regime, where the overall circulation is determined by the balance between the downward and upward branches.

Modern hydrogeology acknowledges an immense importance of the vertical hydraulic communication (leakage) across low-permeability layers separating aquifers in meteoric GCS [Шестопалов, 1981; Mjatiev, 1947; Hantush, Jacob, 1955; Toth, 1995]. Such communication in the meteoric regime is directed downward beneath highlands and upward below topographic depressions. The upward flow below topographic depressions is traced up to depths of 1-1.5 km, and it is generally more intense and localized than the downward flow beneath highlands at compatible depths [Шестопалов, 1981].

The most fundamental reason why hypogene speleogenesis is linked with upward circulation, but not with the downward circulation, lays in the speleogenetic mechanism. As noted above, the overall vertical permeability of the heterogeneous successions is determined by the least permeable intervals. In the areas of upward circulation, initial speleogenesis in soluble beds increases their permeability. This, in turn, steepens the hydraulic gradient across the upper insoluble confining unit and hence, the overall discharge in the system (Fig. 1). This re-activates the positive feedback loop and stimulates further development of transverse conduit. The gradient and discharge further increase with continued erosional entrenchment into to the upper confining unit. In contrast, in the areas of more diffuse downward circulation, hydraulic resistance to flow increases with depth. Moreover, possibilities for

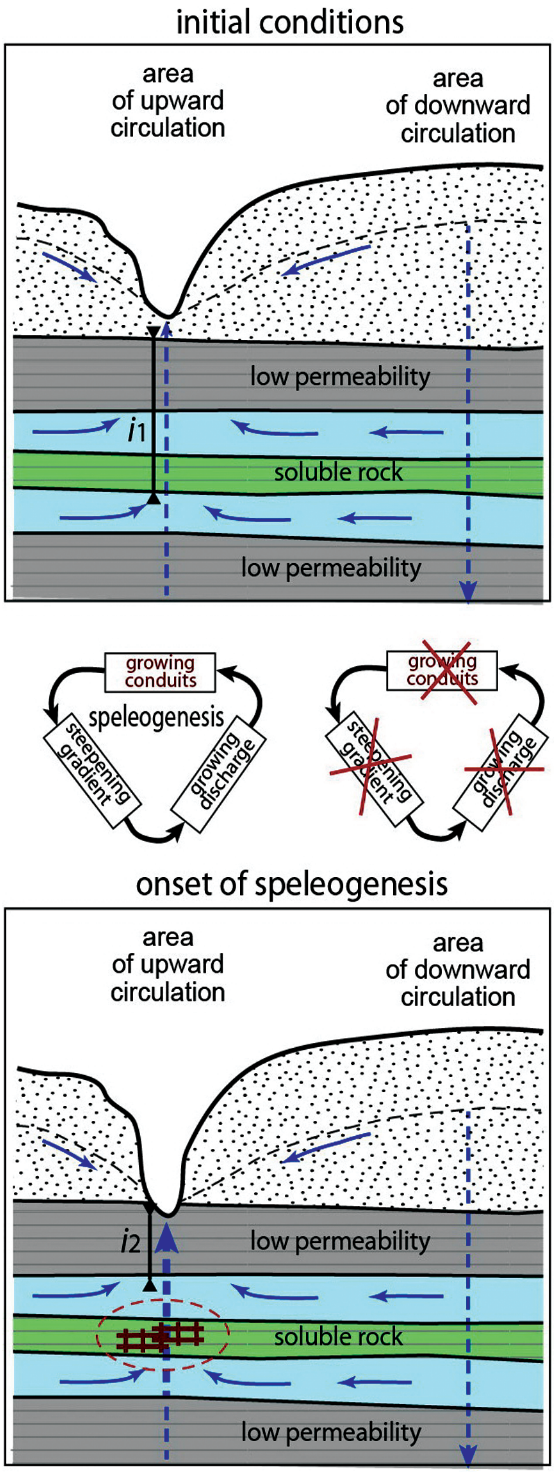

Fig. 1. A conceptual illustration of speleogenetic potentials in the areas of upward and downward circulation in a layered aquifer system:

*i*1 – vertical hydraulic gradient for the lower confined aquifer; *i*2 – vertical hydraulic gradient (much steeper) for the integrated aquifer system after onset of speleogenesis in the separating bed

internal discharge are limited. This prevents an increase in the circulation intensity and inhibits the mechanism of speleogenesis (Fig. 1). Similar arguments can be used for vertical flow in a cross-formational fracture-vein structure that crosses rocks of variable lithologies including soluble ones.

Another important peculiarity of confined (semi-confined) hydrogeological environments is their slow fluid dynamics as compared to unconfined settings, which favors to the natural convection circulation at the conduit (void) scale. Effects of the buoyancy circulation are commonly well expressed in cave morphology [Klimchouk, 2007, 2009]. Dissolution effects of the buoyancy circulation are linked, again, with the upwelling limbs of convection cells but not with the plunging ones.

Groundwater regimes

The overall circulation regime of a groundwater system is determined by the nature and magnitude of fluid pressure and by the degree of hydrodynamic confinement of the GCS. Different types of circulation regimes are distinguished in the literature.

In subsiding basins the dominant flow drive in progressively buried strata is compaction due to the increasing load, which causes expulsion of the pore waters from the sediments. This is the geostatic regime, also termed expulsion regime (in the Western literature), or elision or exfiltration regime (in the East European literature). Flow in such systems is directed upward, and on the regional scale – from areas of greatest subsidence to the margins of basins. The expulsion GCS are unlikely to play a role in hypogene speleogenesis.

With still deeper burial and further rise of temperature and lithostatic load, the thermobaric regime develops in which the fluid pressures are caused by the thermal expansion of water or by the release of water by mineral dehydration in a low-permeability environment. The compression regime can be generated by a tectonic strain in the vicinity of collision and uplift areas. In the East European literature these two regimes are commonly combined into the endogenous regime, which also includes localized intrusions of fluids into the sedimentary cover from the lower crust and the upper mantle. The upward migration of endogenous fluids is considered to be the main cause for hydrogeochemical inversions and a phenomenon of the column-like desalinization observed in the lower parts of the sedimentary cover in many basins [Ежов, 1978; Лукин, 2004]. The upward flow overwhelmingly dominates in the endogenous regime. The endogenous GCS, characterized by high temperatures and pressures, are believed to be very potent to support hypogene speleogenesis in a variety of rocks [Dublyansky, 2000; Andreychouk et al., 2009; Klimchouk, 2012].

The free convection regime may develop in some settings, especially in the vicinity of hydrothermal anomalies and in strata comprising evaporites, driven by density differences. The upwelling limbs of convection GCS are capable of supporting hypogene speleogenesis, especially in evaporites.

Following uplift and continental exposure, the hydrostatic regime evolves, driven by topography differences. It is also termed the meteoric regime (in the Western literature) and the infiltration regime (in the East European literature). With the continuing exposure and geomorphic development, meteoric waters increasingly flush out the formation waters from basins so that the hydrostatic regime substitutes the geostatic regime in the upper part of the crust, although the latter may still predominate in deep environments.

Interaction between groundwater systems of different regimes

The meteoric regime is perched on ubiquitously upwelling waters of the geostatic and endogenous regime, commonly over pressured (the fluid pressure exceeds the normal hydrostatic one). Zones of interaction between GCS of different regimes, either crosscutting or lateral, are particularly favorable for hypogene speleogenesis in carbonate rocks because mixing of waters differing in CO_2 or H_2S content or salinity generates aggressiveness. Hypogene speleogenesis is commonly a part of mixed flow systems, where topography-driven flow interacts with the deeper compaction- or density-driven regimes or rising flows of endogenous waters. The nature and the geometry of the transition between the different regimes are controlled by respective fluid potentials and geological heterogeneities, especially sedimentary windows and conductive faults. The vertical boundaries may be blurred, but they are more distinct when they coincide with low-permeability strata of a regional extent. With the onset of uplift and denudation in the course of geological evolution, the deeper strata may migrate upward relative to these boundaries, and the nature and geometry of the transition adjusts to the structure of uplifting strata and changing potentials of the interacting regimes.

Hypogene speleogenesis from the perspectives of regional hydrogeological analysis

As noted above, the association with the upwelling circulation suggests the possibility of discerning regularities of development and distribution of hypogene speleogenesis from the perspectives of the regional hydrogeological analysis.

In basinal settings, the pattern of the meteoric circulation is controlled by a basin's geometry and relief, by geological inhomogeneities that determine permeability distribution, and by interaction with deeper GCS of the geostatic and endogenous regimes, which may pierce through the domain of the hydrostatic regime. In mature artesian basins of the cratonic type, settings favorable for the upward flow and hypogene speleogenesis, are as follows [Климчук, 2013]:

1) marginal areas of discharge of groundwaters of the 2nd hydrogeological story (HG-story);

2) zones of topography-controlled upward circulation within the internal basin area (at the 1st and, in places, at the 2nd HG-stories);

3) crests of anticlinal folds or uplifted tectonic blocs within the internal basin area where the upper regional aquitard is thinned or partially breached;

4) linear-local zones of deep-rooted cross-formational faults conducting upward flow from internal deep sources across the upper HG-stories.

Hydrodynamics in the 3rd and 4th HG-stories in the cratonic basins is dominated by the upward circulation (geostatic or endogenous regimes) strongly controlled by (localized along) cross-formational tectonic structures.

Specific circulation patterns develop in large Cenozoic carbonate platforms (the Florida-type), side-open to the ocean, where upward flow across stratified sequences in the coastal parts, driven by both topography-induced head gradients and density gradients, involves mixing with seawater. At deeper levels, the seawater can be drawn into a platform along permeable horizons and rise in the platform interior due to geothermal heating (the Kohout's scheme), interacting with upper freshwater aquifers.

In young basins where the geostatic regime dominates, hypogene speleogenesis is favored at the marginal discharge areas where circulation systems of different origins and regimes may interact, for instance meteoric systems circulating from the adjacent uplifted massifs, basinal fluids expelled from the basin's interiors, and endogenous fluids rising along deep-rooted faults.

The predictability of the distribution of areas of the upwelling flow in tectonically deformed mountainous regions is significantly lower than in cratonic basins because of the complexity and variability of geological and structural conditions, relief, and a geodynamic history in such regions [Климчук, 2013]. Massifs in the folded regions are characterized by dominance of fracture-vein groundwater systems, although sequences of the upper structural story often host stratal aquifer systems. Upward flow and hypogene speleogenesis in massifs are tightly controlled by faults, especially by those at junctions between large tectonic structures and structural stories, and by the geodynamic evolution. Specific and very favorable settings for hypogene speleogenesis are found in regions of young volcanism and hydrothermal activity.

Hypogene speleogenesis may also occur in deep oceanic settings, especially in regions associated with plate boundaries and hot spots. An outstanding example is represented by extensive fields of large-scale depressions in the Mio-Pliocene carbonate blanket at depth of 1500-2600 m in the volcanic Carnegie Ridge, located within the Galapagos hotspot in the Pacific Ocean, recently documented by high-resolution multibeam bathymetry [Michaud et al., 2005], although interpreted there differently. The host carbonates do not contain shallow facies and have never been subaerially exposed, which excludes any epigene karstification.

The role of confinement

In discussing the origin of maze caves, many of which are believed to form under artesian conditions, A.N. Palmer [Palmer, 1991, 2000b] argued that slow groundwater flow near chemical equilibrium, typical of truly confined aquifers, is least likely to produce maze caves. He further stressed that "*True confinement by itself does not produce maze caves, and any association between confined groundwater flow and maze development is coincidental*" [Palmer, 2000b, p. 79]. The problem of the origin of maze caves is beyond the scope of this paper; it is considered in details by A.N. Palmer [Palmer, 1975, 1991, 2000a, 2000b, 2007, 2011] and A.B. Klimchouk [Klimchouk, 2000, 2007, 2009]. Here it is appropriate to clarify some misconceptions about confinement, with regard to hypogene speleogenesis.

J.E. Mylroie and J.R. Mylroie [Mylroie, Mylroie, 2009] provide a lengthy discussion on whether confined flow is necessary to produce hypogene caves. They argue that the morphological features believed to be characteristic of hypogenic caves in the hydrogeological connotation of this term [Klimchouk, 2007, 2009] are not solely the result of confined hypogenic conditions, but also occur in eogenetic karst aquifers, in environments that have never been confined, and have never undergone burial or been moved out of the influence of meteoric diagenesis.

The present author agrees that true confinement by itself does not produce maze caves. It has to be noted that the term 'confined aquifer' is not used in modern hydrogeology in a sense of a true hydraulic isolation, so that "true confinement" simply does not exist. Although a certain degree of leakage was long accepted to occur even through aquicludes, it was during the last 40-50 years that the great role of transverse hydraulic communication across separating beds in basins has been fully acknowledged. The "classical" artesian paradigm, with its notions of confined flow through largely isolated aquifers, was replaced with the basin hydraulics paradigm, with its notions of a multiple aquifer system and significant cross-formational (across aquitards) communication between aquifers. The adoption of this paradigm to karst studies has eliminated the ground for the above-mentioned concern and opened a new perspective to the problem of speleogenesis in artesian settings [Klimchouk, 2000, 2007]. The above cited works show that the association between confined groundwater flow and hypogene cave development is not coincidental, and that artesian transverse speleogenesis is one of the most common variants of hypogene speleogenesis.

The question whether confinement by itself is a necessary condition for hypogene speleogenesis is somewhat misleading. The term "confined" refers to a hydrodynamic condition wherein groundwater is under pressure in a bed or stratum confined above and below by units of distinctly lower permeability. The potentiometric surface in such aquifers lies above the bottom of the overlying confining unit, and this allows water to move up through available preferential paths. Hence, at least a certain degree of hydrogeological confinement is a necessary condition for the forced ascending groundwater circulation to occur. It is the upwelling circulation, but not confinement by itself, which is considered in the hydrogeological approach to be the main condition for hypogene speleogenesis, although confinement is certainly the common characteristic of flow in saturated heterogeneous media.

Another misconception [Mylroie, Mylroie, 2009] is that confinement always implies that a carbonate sequence must be once buried and moved to the mesogenetic realm. In fact, confinement does not necessarily imply considerable burial, but it does imply the layered heterogeneity. Confined (pressurized) flow may occur in sequences of eogenetic limestones, as they commonly demonstrate distinct layered heterogeneity formed due to variations in depositional and post depositional processes. For instance, D.A. Budd and H.L. Vacher [Budd, Vacher 2004] show that matrix permeability of young carbonates in the Upper Floridan Aquifer range over three orders of magnitude between different lithofacies. K.J. Cunningham et al. [Cunningham et al., 2006] developed a high-resolution cyclostratigraphic model for the Plio-Pleistocene carbonate Biscayne Aquifer, Florida, and demonstrated pronounced regular variations in porosity structure and permeability between lithofacies, arranged in cyclic successions of three types. Permeability of the aquifer is heterogeneous, with values differing up to two orders of magnitude between the lithofacies.

It is known [Girinsky, 1947] that where a vertical head gradient exists between aquifers in a layered sequence, and if hydraulic conductivities in adjacent beds differs by at least two orders of magnitude, flow in high conductivity beds is predominantly lateral, but flow in the separating beds is predominantly vertical. The above data on heterogeneity of eogenetic carbonate sequences suggest that they may host confined (leaky) aquifer systems with a characteristic pattern of interaction that may include rising transverse flow components.

Although hypogene speleogenesis develops mainly in confined conditions, it is not limited to them. When hypogenic caves are shifted to the shallower, unconfined situation due to uplift and denudation but their further development continues to be driven by upwelling flow from deeper systems, this is still hypogene speleogenesis, although now partly unconfined. Unconfined hypogene development can be regarded as an extinction phase of hypogene speleogenesis in most cases. However, the cave development fed by the upwelling recharge to the bottom of an unconfined aquifer in eogenetic carbonates can also be considered to be hypogenic.

Hypogene speleogenesis in eogenetic carbonates in islands

Cave development in eogenetic carbonates in coastal/island settings is described by the flank margin model [Mylroie, Carew, 1995]. Caves form as the result of mixing of freshwater and seawater at the bottom and especially at the distal margins of a floating freshwater lens. Because the aggressiveness is produced at depth within the bedrock mass, these caves are considered to be hypogenic within the geochemical approach [Mylroie, Carew, 1995; Palmer, 2007]. As the standard model considers a floating Dupuit-Ghyben-Herzberg freshwater lens and cave development in unconfined phreatic conditions, the flank-margin caves were not regarded as hypogenic according to the hydrogeological approach.

J.E. Mylroie and J.R. Mylroie [Mylroie, Mylroie, 2009] provided a number of illustrations showing a great deal of similarity between flank-margin caves and confined hypogenic caves formed by upwelling flow. They argue that the characteristic morphological features of flank-margin caves form due to slow flow conditions in the mixing zone that allow natural convection to extensively operate, and that the upwelling limbs of natural convection cells play a pronounced role in shaping the passage morphology. This is indeed a feasible explanation for the above-mentioned similarity. Flow in confined aquifers is also commonly slow, and the great role of natural convection circulation in shaping hypogene caves has been demonstrated and underscored [Klimchouk, 2000, 2007, 2009]. It has to be noted that the upwelling flow is a part of the buoyancy circulation in any case.

A question remains for the of flank-margin caves, however, as to whether their morphogenesis is solely due to the natural convection circulation, self-developed along the freshwater/marine water interface in a homogenous rock, or whether it originates by the upward leakage (recharge) of a freshwater aquifer from a layer of high hydraulic conductivity (a confined aquifer) below, across a separating layer of relatively low conductivity (an aquitard)? In such case, the caves would be classified to be properly hypogenic according to the hydrogeological approach. One could expect the presence not only of certain characteristic wall and ceiling bedrock features in such caves, but also the entire "*morphological suite of rising flow*" [Klimchouk, 2007, 2009], including feeders. This suite, but not separate features, was considered to be truly diagnostic for hypogene caves, as it unambiguously indicates upwelling circulation of the cave-forming fluid across the soluble rock unit; the main criteria referred to by the hydrogeological definition.

The above question reveals a weakness in the standard flank-margin speleogenetic model, which is based on an assumption that the rock sequence is homogenous (Fig. 2, A). The references cited in the previous section show that this assumption is not always valid. Moreover, there is a large body of publications that demonstrate significant inhomogeneities, both layered and discordant, and hence the presence of leaky aquifer systems in coastal regions. A simple conceptual setting is presented in Fig. 2, B, where an aquifer system is depicted consisting of an upper unconfined aquifer and the underlying confined aquifer, while the aquifers are separated by a aquitard that allows leakage. An aquitard can be heterogeneous in its lateral extent, allowing more significant leakage in certain areas where the vertical conductivity is enhanced due to the presence of fractures or other discontinuities. The obvious result of this circulation pattern would be the formation of truly hypogene caves driven by the leakage of freshwater from the lower aquifer. The aggressiveness would be produced due to mixing of the leaking freshwater with the marine water at the base of the unconfined aquifer, and natural convection effects would be very pronounced due to spatially fixed, steady and efficient supply of freshwater from below.

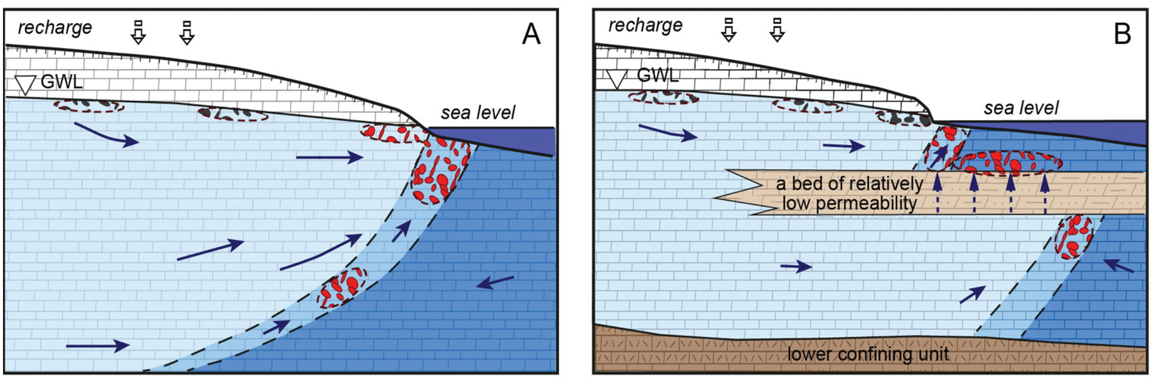

Fig. 2. Speleogenesis in coastal areas:

A – the standard flank-margin model for homogenous rocks (redrawn after J.E. Mylroye, J.L. Carew [Mylroye, Carew, 1995]); B – an expanded model with elements of layered heterogeneity (the hydrogeological setting is borrowed from P.M. Barlow [Barlow, 2003]). Legend: 1 – groundwaters: a – fresh, b – brackish, c – saline (marine); 2 – flow directions; 3 – ascending leakage across the aquitard; 4 – epikarst; 5 – fractures or other conductive discontinuities across the aquitard; 6 – speleogenesis by mixing of vadose and phreatic freshwaters along the water table; 7 – speleogenesis by mixing of freshwater and marine water. Note that the speleogenesis by mixing of freshwater and marine water in cartoon B would be hypogenicspeleogenesis according to the hydrogeological definition

It is therefore suggested that the flank-margin model should be expanded to account for a multiple aquifer settings. From the perspective of the hydrogeological approach, both epigene speleogenesis and hypogene speleogenesis may develop in coastal carbonates depending on a degree of the layered heterogeneity.

Conclusion

Defined in the most general way, hypogene speleogenesis is the origin of caves in which the cave-forming agency comes from depth, in contrast to epigene speleogenesis in which the cave-forming agency (meteoric recharge and its inherent or soil-derived aggressiveness) originates at the surface. A more specific definition should rely on attributes of the cave-forming agency that are most suitable and efficient for discrimination between epigene and hypogene origins of caves.

Relying on the determination of a source of the aggressiveness in classifying hypogene speleogenesis is the legitimate approach but it is not a methodologically sound and practically efficient one. The hydrogeological approach and the reference to upwelling groundwater circulation in the definition of hypogene speleogenesis provide a theoretically and methodologically sound basis not only for identifying the type of speleogenesis, but also for spatial and temporal prognosis of hypogene speleogenesis.

Hypogene speleogenesis develops where upwelling groundwater circulation and disequilibrium conditions causing dissolution are supported during a sufficiently long time. It is localized predominantly in discharge zones and/or zones of interaction of groundwater circulation systems of different nature, depth and scales, and it is controlled by peculiarities of the hydrogeological structure, geodynamic evolution and geomorphic development of regions.

In basinal settings, the localization of areas of the upwelling circulation across soluble rocks, and hence of hypogene speleogenesis, is determined by the influence on hydrodynamics of the basins topography and configuration, tectonic disruptions, internal uplifts, and lithofacial windows, as well as of endogenous (geodynamic) factors. The role of tectonic faults as cross-formational fluid-conducting structures strongly increases in the lower stories of cratonic artesian basins and in massifs of orogenic regions. The development of hypogenic void-conduit systems is commonly multiphase, determined by major phases of the geodynamic history of the regions.

The patterns and morphology of hypogene caves are determined by the structure of initial porosity, pressurized mode and the upwelling vector of groundwater circulation, specific features of the speleogenetic mechanisms in the conditions of the external conservative control over discharge, as well as by peculiarities of the evolution of a given groundwater circulation system. When hypogenic caves are shifted to the shallow subsurface, their morphology may experience considerable modification by dissolution at the water table and by subaerial mechanisms.

Acknowledgements

This work was partially supported by the Ukrainian Ministry of Education and Science Grant 0110U002248.

References

1. *Гиринский Н.К.* Некоторые вопросы динамики подземных вод. В кн.: *Гидрогеология и инженерная геология*. № 9. Москва: Госгеолтехиздат, 1947. С. 3-100.

Girinsky N.K., 1947. Some questions of groundwater dynamics. In: *Gidrogeologiya i inzhenernaya geologiya*, № 9. Moscow: Gosgeolizdat, p. 3-100 (in Russian).

2. *Ежов Ю.А.* О химической инверсии в подземной гидросфере. *Сов. геология*. 1978. № 312. С. 132-136.

Ezhov Yu.A., 1978. On chemical inversion in the underground hydrosphere. *Sovetskaya Geologiya*, № 312, p. 132-136 (in Russian).

3. *Климчук А.В.* Гипогенный спелеогенез, его гидрогеологическое значение и роль в эволюции карста. Симферополь: ДИАЙПИ, 2013, 180 с.

Klimchouk A.B., 2013c. Hypogene speleogenesis, its hydrogeological significance and the role in evolution of karst. Simferopol: DIAIPI, p. 180 (in Russian).

4. *Лукин А.Е.* Глубинная гидрогеологическая инверсия как глобальное синергетическое явление: теоретические и прикладные аспекты. Ст. 1. Феноменология и природа глубинной гидрогеологической инверсии. *Геол. журн.* 2004. № 4 (310). С. 53-70.

Lukin A.E., 2004. Deep hydrogeological inversion as a global synergetic phenomenon: theoretical and applied aspects. Communication 1. Phenomenology and the nature of the deep hydrogeological inversion. *Geologicheskiy Zhurnal*, 4 (310), p. 53-70 (in Russian).

5. *Мятиев А.Н.* Напорный комплекс подземных вод и скважин. *Изв. АН СССР. Отд. техн. наук*. 1947. № 9. С. 33-47.

Mjatiev A.N., 1947. Confined complex of underground waters and wells. *Izvestija AN SSSR. Otd. tekhnich. nauk*, № 9, p. 33-47 (in Russian).

6. *Шестопалов В.М.* Естественные ресурсы подземных вод платформенных артезианских бассейнов Украины. Киев: Наукова думка, 1981. 196 с.

Shestopalov V.M., 1981. Natural resources of groundwaters in platform artesian basins of Ukraine. Kiev: Naukova Dumka, 196 p. (in Russian).

7. *Barlow P.M.* Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. US Geological Survey, Reston, Virginia, 2003. 113 p.

Barlow P.M., 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. US Geological Survey, Reston, Virginia, 113 p. (in English).

8. *Budd D.A., Vacher H.L.* Matrix permeability of the confined Floridan Aquifer, Florida, USA. *Hydrogeology Journal.* 2004. № 12. P. 531-549.

Budd D.A., Vacher H.L., 2004. Matrix permeability of the confined Floridan Aquifer, Florida, USA. *Hydrogeology Journal,* № 12, p. 531-549 (in English).

9. *Cunningham K.J., Renken R.A., Wacker M.A., Zygnerski M.R., Robinson E., Shapiro A.M., Wingard G.L.* Application of carbonate cyclostratigraphy and borehole geophysics to delineate porosity and preferential flow in the karst limestone of the Biscayne Aquifer, SE Florida. In: R.S. Harmon and C.W. Wicks (Eds.). Perspectives on Karst Geomorphology, Hydrology and Geochemistry, GSA Special Paper 404, Boulder, Colorado, 2006. P. 191-208.

Cunningham K.J., Renken R.A., Wacker M.A., Zygnerski M.R., Robinson E., Shapiro A.M., Wingard G.L., 2006. Application of carbonate cyclostratigraphy and borehole geophysics to delineate porosity and preferential flow in the karst limestone of the Biscayne Aquifer, SE Florida. In: R.S. Harmon and C.W. Wicks (Eds.). Perspectives on Karst Geomorphology, Hydrology and Geochemistry, GSA Special Paper 404, Boulder, Colorado, p. 191-208 (in English).

10. *Dreybrodt W., Gabrovsek F., Romanov D.* Processes of Speleogenesis: A Modeling Approach. ZRC Publishing, Ljubljana, 2005. 376 p.

Dreybrodt W., Gabrovsek F., Romanov D., 2005. Processes of Speleogenesis: A Modeling Approach. ZRC Publishing, Ljubljana, 376 p. (in English).

11. *Dublyansky Y.V.* Hydrothermal speleogenesis—Its settings and peculiar features. In: A. Klimchouk, D. Ford, A. Palmer, W. Dreybrodt (Eds.). Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, 2000. P. 293-297.

Dublyansky Y.V., 2000. Hydrothermal speleogenesis—Its settings and peculiar features. In: A. Klimchouk, D. Ford, A. Palmer, W. Dreybrodt (Eds.). Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, p. 293-297 (in English).

12. *Dublyansky Y.V., Klimchouk A.B., Spљtl C., Timokhina E.I., Amelichev G.N.* Isotope wallrock alteration associated with hypogene karst of the Crimean Piedmont, Ukraine. *Chemical Geology*. 2014. Vol. 377. P. 31-44.

Dublyansky Y.V., Klimchouk A.B., Spљtl C., Timokhina E.I., Amelichev G.N., 2014. Isotope wallrock alteration associated with hypogene karst of the Crimean Piedmont, Ukraine. *Chemical Geology*, vol. 377, p. 31-44 (in English).

13. *Andreychouk, V., Dublyansky, Y., Ezhov, Y., Lisenin, G.* Karst in the Earth's Crust: Its Distribution and Principal Types. University of Silezia – Ukrainian Institute of Speleology and Karstology, Sosnovec-Simferopol, 2009. 72 p.

Andreychouk, V., Dublyansky, Y., Ezhov, Y., Lisenin, G., 2009. Karst in the Earth's Crust: Its Distribution and Principal Types. University of Silezia – Ukrainian Institute of Speleology and Karstology, Sosnovec-Simferopol, 72 p. (in English).

14. *Ford D.C.* Karst geomorphology, caves and cave deposits: A review of North American contributions during the past half century. In: R.S. Harmon and C.W. Wicks (Eds.). Perspectives on Karst Geomorphology, Hydrology and Geochemistry, GSA Special Paper 404, Boulder, Colorado, 2006. P. 1-14.

Ford D.C., 2006. Karst geomorphology, caves and cave deposits: A review of North American contributions during the past half century. In: R.S. Harmon and C.W. Wicks (Eds.). Perspectives on Karst Geomorphology, Hydrology and Geochemistry, GSA Special Paper 404, Boulder, Colorado, p. 1-14 (in English).

15. *Hantush M.S,. Jacob C.E.,* Nonsteady radial flow in an infinite leaky aquifer. Transactions, Amer. Geoph. Union 36, 1955. P. 95-100.

Hantush M.S,. Jacob C.E., 1955. Nonsteady radial flow in an infinite leaky aquifer. Transactions, Amer. Geoph. Union 36, p. 95-100 (in English).

16. *Klimchouk A.B.* Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective. National Cave and Karst Research Institute, Special Paper № 1, Carlsbad, New Mexico. 2007. 106 p.

Klimchouk A.B., 2007. Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective. National Cave and Karst Research Institute, Special Paper № 1, Carlsbad, New Mexico, 106 p. (in English).

17. *Klimchouk A.B,* Morphogenesis of hypogenic caves. *Geomorphology*. 2009. Vol. 106. P. 100-117.

Klimchouk A.B., 2009. Morphogenesis of hypogenic caves. *Geomorphology*, vol. 106, p. 100-117 (in English).

18. *Klimchouk A.* Speleogenesis, Hypogenic. In: D.C. Culver and B.W. White (Eds.). Encyclopedia of Caves, 2nd edition. Elsevier, Chennai, 2012. P. 748-765.

Klimchouk A., 2012. Speleogenesis, Hypogenic. In: D.C. Culver and B.W. White (Eds.). Encyclopedia of Caves, 2nd edition. Elsevier, Chennai, p. 748-765 (in English).

19. *Klimchouk A.B.* Hypogene speleogenesis. In: A. Frumkin, (Ed.). Treatise on Geomorphology, vol. 6 Karst Geomorphology. Academic Press, San Diego, California, 2013a. P. 220–240.

Klimchouk A.B., 2013a. Hypogene speleogenesis. In: A. Frumkin, (Ed.). Treatise on Geomorphology, vol. 6 Karst Geomorphology. Academic Press, San Diego, California, p. 220–240 (in English).

20. *Klimchouk A.B.* Hydrogeological approach to distinguishing hypogene speleogenesis settings. In Intern. Symp. on Hierarchical Flow Systems in Karst Regions, Symposium Program and Abstracts, Budapest, 2013b. P. 95.

Klimchouk A.B., 2013b. Hydrogeological approach to distinguishing hypogene speleogenesis settings. In Intern. Symp. on Hierarchical Flow Systems in Karst Regions, Symposium Program and Abstracts, Budapest, p. 95 (in English).

21. *Michaud F., Chabert A., Collot J-Y., SallarЋs V., Flueh E.R., Charvis Ph., Graindorge D., Gustcher M.-A., Bialas J.* Fields of multi-kilometer scale sub-circular depressions in the Carnegie Ridge sedimentary blanket: Effect of underwater carbonate dissolution? *Marine Geology.* 2005. Vol. 216, № 4. P. 205-219.

Michaud F., Chabert A., Collot J-Y., SallarЋs V., Flueh E.R., Charvis Ph., Graindorge D., Gustcher M.-A., Bialas J., 2005. Fields of multi-kilometer scale sub-circular depressions in the Carnegie Ridge sedimentary blanket: Effect of underwater carbonate dissolution? *Marine Geology*, vol. 216, № 4, p. 205-219 (in English).

22. *Mylroie J.E., Carew J.L.* Karst development on carbonate islands. In: D.A. Budd, P.M. Harris and A. Saller (Eds.). Unconformities and Porosity in Carbonate Strata. American Association of Petroleum Geologists, 1995. P. 55-76.

Mylroie J.E., Carew J.L., 1995. Karst development on carbonate islands. In: D.A. Budd, P.M. Harris and A. Saller (Eds.). Unconformities and Porosity in Carbonate Strata. American Association of Petroleum Geologists, p. 55-76 (in English).

23. *Mylroie J.E., Mylroie J.R.* Diagnostic features of hypogenic karst: is confined flow nececessary? In: K.W. Stafford, L. Land and G. Veni (Eds.). NCKRI Symposium 1 Advances in Hypogene Karst Studies. National Cave and Karst Research Institute, Carlsbad, New Mexico, 2009. P. 12-26.

Mylroie J.E., Mylroie J.R., 2009. Diagnostic features of hypogenic karst: is confined flow nececessary? In: K.W. Stafford, L. Land and G. Veni (Eds.). NCKRI Symposium 1 Advances in Hypogene Karst Studies. National Cave and Karst Research Institute, Carlsbad, New Mexico, p. 12-26 (in English).

24. *Palmer A.N.* The origin of maze caves. *NSS Bulletin*. 1975. Vol. 37, № 3. P. 56-76.

Palmer A.N., 1975. The origin of maze caves. *NSS Bulletin*, vol. 37, № 3, p. 56-76 (in English).

25. *Palmer A.N.* Origin and morphology of limestone caves. *Geological Society of America Bulletin*. 1991. Vol. 103, № 1. P. 1-21.

Palmer A.N., 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin*, vol. 103, № 1, p. 1-21 (in English).

26. *Palmer A.N.* Hydrogeologic control of cave patterns. In: A Klimchouk, D Ford, A Palmer, W Dreybrodt (Eds.). Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, 2000a. P. 77-90.

Palmer A.N., 2000a. Hydrogeologic control of cave patterns. In: A Klimchouk, D Ford, A Palmer, W Dreybrodt (Eds.). Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, p. 77-90 (in English).

27. *Palmer A.N*. Maze origin by diffuse recharge through overlying formations In: A. Klimchouk, D. Ford, A. Palmer, W. Dreybrodt (Eds.). Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, 2000b. P. 387-390.

Palmer A.N., 2000b. Maze origin by diffuse recharge through overlying formations In: A. Klimchouk, D. Ford, A. Palmer, W. Dreybrodt (Eds.). Speleogenesis: Evolution of Karst Aquifers. National Speleological Society, Huntsville, p. 387-390 (in English).

28. *Palmer A.N.* Distinction between epigenic and hypogenic maze caves. *Geomorphology.* 2011. Vol. 134, № 1. P. 9-22.

Palmer A.N., 2011. Distinction between epigenic and hypogenic maze caves. *Geomorphology*, vol. 134, № 1, p. 9-22 (in English).

29. *Palmer A.N.* Cave Geology. Cave Books, Dayton, Ohio, 2007. 454 p.

Palmer A.N., 2007. Cave Geology. Cave Books, Dayton, Ohio, 454 p. (in English).

30. *Spoetl C., Dublyansky Y.V.* Fingerprinting water-rock interaction in hypogene speleogenesis: potential and limitations of isotopic depth-profiling. In: A. Klimchouk, I. Sasowsky, J. Mylroie, S.A. Engel, A.S. Engel (Eds.). Hypogene Cave Morphologies. Selected papers and abstracts of the symposium held February 2 through 7, 2014, San Salvador Island, Bahamas. Karst Waters Institute Special Publication 18, Karst Waters Institute, Leesburg, Virginia, 2014. P. 103.

Spoetl C., Dublyansky Y.V., 2014. Fingerprinting water-rock interaction in hypogene speleogenesis: potential and limitations of isotopic depth-profiling. In: A. Klimchouk, I. Sasowsky, J. Mylroie, S.A. Engel, A.S. Engel (Eds.). Hypogene Cave Morphologies. Selected papers and abstracts of the symposium held February 2 through 7, 2014, San Salvador Island, Bahamas. Karst Waters Institute Special Publication 18, Karst Waters Institute, Leesburg, Virginia, p. 103 (in English).

31. *T—th J.* Groundwater as a geologic agent: An overview of the cases, processes and manifestations. *Hydrogeology Journal*. 1999. № 7. P. 1-14.

T—th J., 1999. Groundwater as a geologic agent: An overview of the cases, processes and manifestations. *Hydrogeology Journal,* № 7, p. 1-14 (in English).

Received
April 2, 2015