Chapter II.9

GYPSUM KARST IN THE WESTERN UKRAINE
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Introduction

The great gypsum karst of the Western Ukraine, which is associated with Miocene (Badenian) gypsum, provides the world's foremost examples of intrastratal gypsum karst and speleogenesis under artesian conditions. Differential neotectonic movements have resulted in various parts of the territory displaying different types (stages) of intrastratal karst, from deep-seated, through subjacent, to entrenched.

Internal gypsum karstification proceeded mainly under confined hydrogeological conditions. While such development still continues in part of the territory, other parts exhibit entrenched karst settings. Huge relict maze cave systems have been explored here, five of which are currently the longest known gypsum caves in the world. They account for well over half of the total length of gypsum cave that has been explored. This unique concentration of large caves reflects the local coincidence of specific structural prerequisites of speleogenesis (character and extent of fissuring), favourable regional evolution (rapid uplift, and fossilization of maze systems), the presence of overlying limestone aquifers, and a widespread clayey protective cover (which prevented the total infilling and/or destruction of the caves). Surface karst evolved as a consequence of the internal karstification in the gypsum, and the karst landform assemblages differ between the territories that present different types of karst.

Important previous works on the gypsum karst of the region include Ivanov (1956), Ivanov & Dubljansky (1966), Dubljansky & Ivanov (1970) and Dubljansky & Smol'nikov (1969). Abundant new data and their interpretation were developed during the nineteen-eighties and nineteen-nineties, and presented mainly in publications by Andrejchuk and Klimchouk.

1. Geological setting

The Miocene gypsum sequence is widespread along the southwestern edge of the Eastern European Platform, in the transition zone between the platform and the Carpathian foredeep. Gypsum stretches from the northwest to southeast for about 300km as a belt ranging from several kilometres to 40-80km wide (Fig. 1). The present extent of sulphates on the platform is about 20,000km².

Most Miocene rocks along the platform margin overlie eroded Cretaceous strata, which include terrigenous and carbonate sediments, mostly marls and sandstones, together with detrital and argillaceous limestones. The Miocene succession comprises deposits of Badenian and Sarmatian age. The Lower Badenian "member", beneath the gypsum, includes mainly carbonaceous, argillaceous and sandy beds (70-90m thick) adjacent to the foredeep, and these grade into rocks of calcareous bioherm and sandy facies (10-30m thick) towards the platform interior.
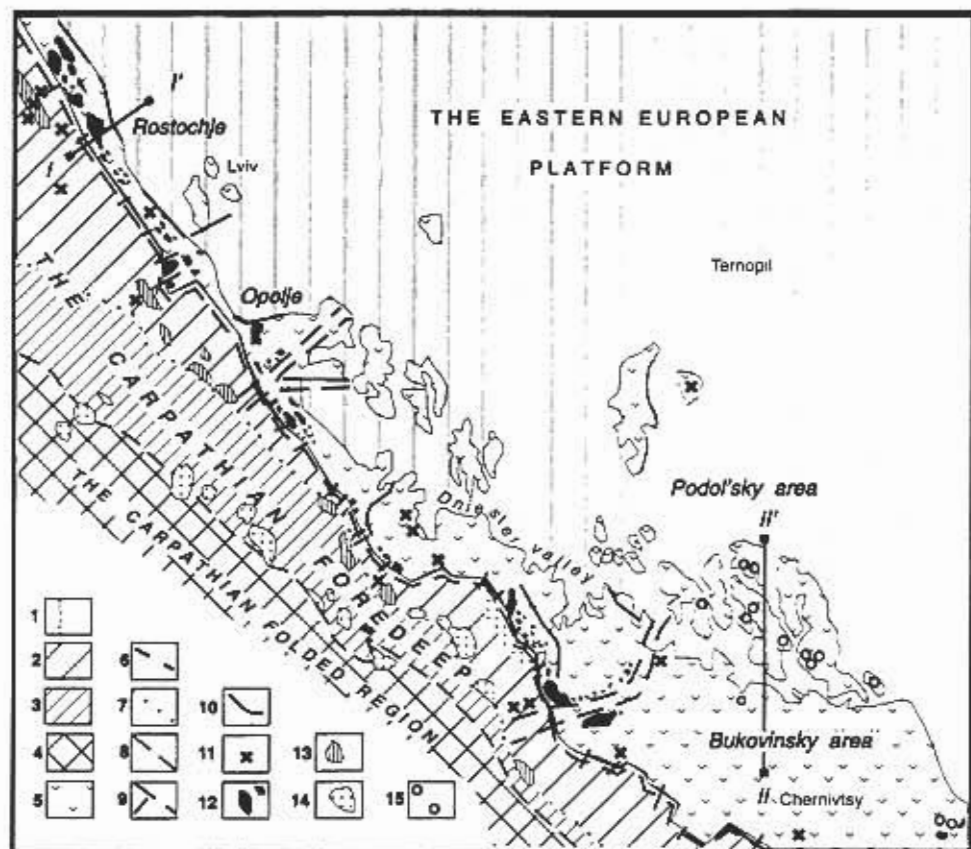
Fig. 2. Location of the gypsum stratum, sulfur deposits, and large caves in the Western Ukraine (modified from Polkunov, 1990). 1 = Eastern-European platform fringe. Carpathian foredeep: 2 = outer zone, 3 = inner zone. 4 = Carpathian folded region; 5 = sulfate rocks on the platform. Tectonic boundaries include: 6 = platform/foredeep, 7 = outer/inner zone of the foredeep, 8 = foredeep/folded region. 9 = other major faults; 10 = flexures. 11 = sulfur mineralization; 12 = sulfur deposits; 13 = gas deposits; 14 = oil deposits; 15 = large maze caves in the gypsum.

The gypsiferous sequence (10-40m thick) is variable in structure and texture. In the Podol'sky area, it includes three units, which, in an ascending order, contain crypto- and microcrystalline massive gypsum, bedded microcrystalline gypsum and mega-crystalline gypsum. Gypsum within the upper unit displays large spherulitic structures (Klimchouk, Andrejchuk & Turchinov, 1995). Close to the foredeep, the gypsum is more homogeneous and aphanitic in texture, and the anhydrite content of the sequence increases. There are sporadic thin interbeds of carbonate and clay.

A layer of micritic and cryptocrystalline limestone, ranging from several tens of centimetres to more than 25m in thickness, overlies much of the gypsum. This limestone contains two genetic varieties that differ in carbon isotopic composition. The micritic limestone (locally called
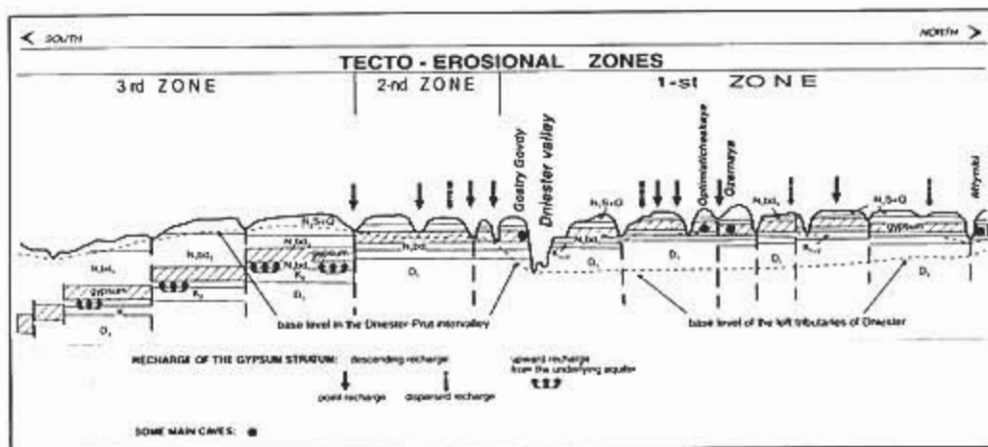
Fig. 2. Geological and hydrogeological settings of gypsum karst development in the Podol'sky and Bukovinsky areas in the south-eastern section of the gypsum belt (line II-II' on Fig. 1 and A-B on Fig.3) (After Klimchouk & Andrejchouk, 1988).

"Ratynsky") has normal "evaporitic" $\delta^{13}C$ values. The other variety, which is crypto- and microcrystalline, was formed epigenetically by replacement of the gypsum during sulphate reduction, and is characterized by "light" carbon, with $\delta^{13}C$ from -32 to -65 ‰. Where the limestone thickness exceeds 1 to 2m, it consists of mainly epigenetic calcite, which locally replaces the gypsum stratum entirely. Together this limestone and the gypsum comprise the Tyrassky Formation.

The Tyrassky Formation is overlain by the Upper Badenian "member", which begins with argillaceous and marly lithotamnion limestones (the Ternopol'sky' beds, 1.5 to 3m thick). Above this is a succession of clays and marls, with its lower part in the Upper Badenian (the Kosovsky Formation), and its upper part in the Lower Sarmatian. The total thickness of clay sediments is 40 to 50m in the Podol'sky area, reaching 80 to 100m towards the foredeep, and thickening to several hundred metres close to the regional growth faults that separate the platform edge from the foredeep.

The Miocene succession is overlain by late-Pliocene and Pleistocene glacio-fluvial sands and loams in the north-west section of the gypsum belt, and by sand and gravel alluvial terrace deposits left by the pre-Dniester river during the late Pliocene and early Pleistocene in the Podol'sky area. Many buried valleys, of early to mid Pleistocene age, are entrenched 30 to 50m into the Kosovsky and Sarmatian clays and, locally, into the upper part of the Tyrassky Formation.

The present distribution of the Miocene formations and the levels of their denudation vary in a regular way from the platform interior towards the foredeep (Andrejchouk, 1988; Klimchouk et al, 1985; Klimchouk & Andrejchouk, 1988). The Tyrassky Formation dips 1 to 3° towards the foredeep and is disrupted by block faults in the transitional zone. To the south-west of the Dniester valley, large tectonic blocks drop down as a series of steps, the thickness of clay overburden increases, and the depth of erosional entrenchment decreases (Fig. 2). This variation, the result of

differential neotectonic movement, played an important role in the hydrogeological evolution of the Miocene aquifer system. They determined the recharge-discharge and flow conditions, and hence helped to guide the development of karst in the gypsum.

2. Hydrogeological setting and karst types

In hydrogeological terms the region represents the south-western portion of the Volyno-Podolsky artesian basin (Shestopalov, 1989). Sarmatian and Kosovsky clays and marls provide an upper confining sequence and the Tyrassky Formation carbonate (above the gypsum) and the Lower Badenian sandy carbonate beds (below the gypsum) are aquifers. The hydrogeological role of the gypsiferous unit has changed with time, from initially being an aquifuge, intervening between two aquifers, to a karstified aquifer with well-developed conduit permeability. Underlying Cretaceous sediments have variable properties across the area. Regional flow is from the platform interior, where clayey formations and the gypsum beds are largely denuded, toward the large and deep Dniester valley and the Carpathian foredeep. The main factors that determine contemporary hydrogeological conditions are the differences in the depths of gypsum occurrences and the extent of erosional entrenchment by the major valleys. Three sub-parallel zones are distinguished, each characterized by a different type of gypsum karst (see Fig.2).

2.1. The first zone: entrenched karst

In the 1st zone the Miocene rocks and underlying formations are deeply entrenched by valleys of the major left bank sub-parallel tributaries of the Dniester, separated by wide inter-valley massifs where the gypsum and clay overburden remain largely intact. The Miocene formations are almost entirely drained and only in the central parts of the inter-valley massifs do the sub-gypsum units contain unconfined underground waters. In some tectonic blocks the water table extends upwards into the lower part of the gypsum (Ozernaya Cave) with multi-year fluctuations that range from 3 to 5m. Huge maze cave systems in the gypsum are relict, having formed under formerly artesian conditions. Modern dissolution is restricted to the lower part of gypsum, where the water table is present, at points of focused vertical percolation (where vertical dissolution pipes develop) and along linear underground streams that are fed via swallow holes that receive periodic surface flow.

Superficial karst landforms on the inter-valley plateaux are represented by relatively scarce large dolines with swallow holes, blind valleys and smaller recent collapse dolines. Dolines are formed mainly by means of the vertical through structure (VTS) mechanism, which is triggered by the development of vertical dissolution pipes. Initial collapse dolines evolve into large cone-shaped forms with swallow holes in their floors, or into blind valleys, if they intercept a sufficiently large amount of surface runoff. Focused point recharge is the main recharge mode of the Miocene aquifer in this zone. Doline density increases locally where the capping clays are removed, as within old, high, river terraces. Discharge takes the form of springs outflowing from the sub-gypsum unit, or from the underlying Cretaceous formations.

These conditions typify an intrastratal entrenched karst, according to the classification intro-

duced in Chapter 1.4. They are characteristic of the area within the interior of the platform, to the north-east and north of the Dniester valley, and for the Podol'sky area in particular. A narrow area on the right bank of the Dniester valley also lies within this zone, but this grades into the 2nd zone deeper into the Dniester-Prut inter-valley.

2.2. The second zone: subjacent karst

To the south-west and south of the Dniester valley the depth of gypsum occurrence increases, and the depth of erosional entrenchment diminishes. The narrow (3 to 15km-wide) 2nd zone is distinguished in the Dniester-Prut inter-valley, where the water table lies within the gypsum or locally within the higher unit. Floors of erosional valleys lie above, or are entrenched into, the gypsum unit, causing diversified karst hydrography to develop, with intermittent streams, swallow holes, and ascending and descending springs. Collapse and subsidence dolines are common, as the water table and localized streams operating within the gypsum intensify breakdown processes by active dissolution and erosional removal of cave fills. Cave systems inherited from the confined stage are accessible only in small fragments, but their wide presence is implied by drilling data and observations in the neighbouring 1st zone, where the gypsum is drained and has been extensively quarried. Relatively small linear through caves are also common, and their origin is attributed to erosion under modern conditions.

In general the groundwater flow in the Miocene aquifer is directed northwards to the Dniester valley, and south-southwestwards to the Prut valley. Flow becomes confined in the latter direction, within the 3rd zone, where the Tyrassky Formation lies at an even greater depth beneath the increasing thickness of clayey overburden. The 2nd zone represents subjacent karst conditions, grading locally into early phases of entrenched karst.

2.3. The third zone: deep-seated and subjacent karst

The 3rd zone stretches along the boundary between the platform and the foredeep. Within this zone the Miocene aquifer formations lie at considerable depths beneath the Kosovsky clays, which are cut only by shallow erosional valleys, so that flow is confined.

Recharge conditions differ between a narrow north-west and a wider south-east section of the gypsum belt. In the north-west, recharge occurs within the adjacent unconfined area (where both the clays and the gypsum are denuded), by infiltration directly into the sub-gypsum beds. In the south-east of the gypsum belt recharge occurs from the neighbouring area of subjacent gypsum karst (the 2nd zone), via karst systems.

On the opposite flank of the confined flow area, along the foredeep margin, regional faulting has brought the Miocene aquifer into lateral contact with an even thicker Kosovsky clayey sequence, so that further flow in this direction is prevented and upward discharge occurs locally, focused upon areas where the confining properties of the Kosovsky clays are weakened by stratigraphical or tectonic discontinuities, or incised erosional valleys. The latter situation is common in the north-west part of the gypsum belt, where discharge is commonly focused along buried valleys, and in the south-east section, where discharge converges towards the major modern Prut valley.

Lower Badenian sandy-carbonaceous sediments that lie immediately below the gypsum provide the major aquifer. Erroneously the gypsum unit was long considered as being an aquifuge separating the sub-gypsum and supra-gypsum aquifers; numerous indications of karstification in the gypsum were incorrectly interpreted. However, it has recently been shown (Klimchouk, 1990, 1992, 1997a) that extensive karst systems develop in the gypsum due to the effects of upward cross-formational hydraulic communication between the early aquifers, with the gypsum providing the hydraulic connection (see section 3.2 below). Such systems, which are modern analogues of relict maze caves that are known in the 1st zone, develop preferentially in areas of potentiometric lows, where an overall discharge from the artesian aquifer system occurs. Analysis of data on the many cavities intercepted in the gypsum by exploratory drilling in different deposits, suggests that their morphology and structure are similar to those of explored relict caves (Klimchouk, 1997a,b).

Gypsum karstification within the 3rd zone is not manifested to the surface across most of those areas where the clayey overburden thickness exceeds 45 to 60m; this represents an zone of deep-seated karst. However, in areas where the natural groundwater circulation has been affected by an anthropogenic impact (such as opencast quarrying or groundwater abstraction) and karst processes have consequently been intensified in the gypsum, collapse and subsidence dolines may develop at the surface, being induced by karstification in the gypsum at still greater depths (see Chapter I.10). Moreover, there are "azonal" areas within the 3rd zone, related particularly to the most uplifted tectonic blocks, where the gypsum lies at relatively shallow depths and major valleys have incised into it, breaching artesian confinement (as in the Krivsky and Mamalyzhsky blocks in the Bukovinsky sub-region; Andrejchuk, 1988). Locally this results in drainage of the upper part of the gypsum unit, and widespread development of collapse and subsidence phenomena. Thus, such cases correspond to subjacent karst conditions.

3. Caves and their genesis

3.1. General characteristic

Fourteen large caves are known in the region, with development exceeding 1km. Eleven are north of the Dniester valley, within the Podol'sky sub-region, and nine of these caves lie within a narrow belt sub-parallel to the Dniester valley. Two caves (Mlynki and Ugryn') are outside this belt, some 15 to 20km to the north. All of these caves are within the 1st zone, as is one more cave, Gostry Govdy, on the right bank of Dniester. Two other large caves, Zolushka and Bukovinka, are situated in the Bukovinsky sub-region, near Prut river, in the area of artesian flow within the Miocene aquifer system (3rd zone), but within the "azonal" area comprising the most uplifted blocks, where the upper part of the gypsum has been entrenched and drained. Because of this, water table conditions prevail in the gypsum unit within this area. In the area of Zolushka Cave, additional water table lowering has been caused by groundwater abstraction related to quarrying (see Chapter I.10).

All the large gypsum caves in the region are mazes developed along of vertical and steeply inclined fissures and arranged into laterally extensive networks. Aggregating passages form lateral

Table

Parameters of large caves and cave fields

Cave name	Extent (m)	Specific volume ($m^3 \, m^{-1}$)	Passage density, ($km \, km^{-2}$)	Coefficient of karstification, (% area)	Coefficient of karstification, (% volume)
The Podol'sky sub-region					
1 Optimisticheskaja	200,000+	2.6	298	38	4
2 Ozernaja	117.000	6	173	51	6
3 Mlynki	25,000	3.3	123	24	3
4 Kristalnaja	22,000	5	161	28	7
5 Slavka	9,100	3.8	118	24	3
6 Verteba	7,820	6	206	61	12
7 Atlantida	2,525	4.5	168	30	4
8 Ugryn	2,120	3.8	193	36	7
9 Jubilejnaja	1,500	2.3	277	37	4
10 Komsomolskaja	1,244	2.1	124	17	3
11 Dzhurinskaja	1,135	2.3	126	18	2
The Bukovinsky sub-region					
12 Zolushka	92,000	8	208	71	6
13 Bukovinka	2,408	2.5	321	57	4
14 Gostry Govdy	2,000	1.6	272	27	4
Totals	477,852	–	–	–	–
Averages	–	3.8	198	37	5

two- to four-storey systems that occupy areas of up to $0.8 km^2$. Significant morphological parameters of the caves are summarized in the Table, and some typical cave patterns are illustrated by Fig.3.

Optimisticheskaja Cave is the longest gypsum cave, and the second longest cave of any type, known in the world, with more than 200km of surveyed passages. The region holds the five longest known gypsum caves in the world, accounting for well over half of the total known length of gypsum caves. By area and volume the largest caves are Ozernaja ($330,000 m^2$ and $665,000 m^3$) and Zolushka ($305,000 m^2$ and $712,000 m^3$), followed by Optimisticheskaja Cave ($240,000 m^2$ and $500,000 m^3$).

The absolute parameters of cave systems and their fields are subject of change, depending upon exploration efforts; they grow constantly during the course of speleological exploration. Specific parameters are more informative. Specific volume (the volume/length ratio) characterizes "voluminousness" of cave passages in a certain cave system. For the caves of the region this feature range from 1.6 (Gostry Govdy Cave) to 8.0 (Zolushka Cave) $m^3 \, m^{-1}$; the average for the region is of $3.84 \, m^3 \, m^{-1}$.

Passage network density is characterized conveniently by use of the ratio of cave length to the unit area of a cave field (km km-2). This parameter varies for the region from 118 (Slavka Cave) to 321 (Bukovinka Cave) km km-2, with the average value of 198 km km-2.

The availability of detailed morphometrical data on caves and the host rock bodies allows the calculation of coefficients of karstification of the gypsum stratum both in terms of area and volume. The former parameter varies from 17% (Komsomol'skaja Cave) to 71% (Zolushka Cave). High
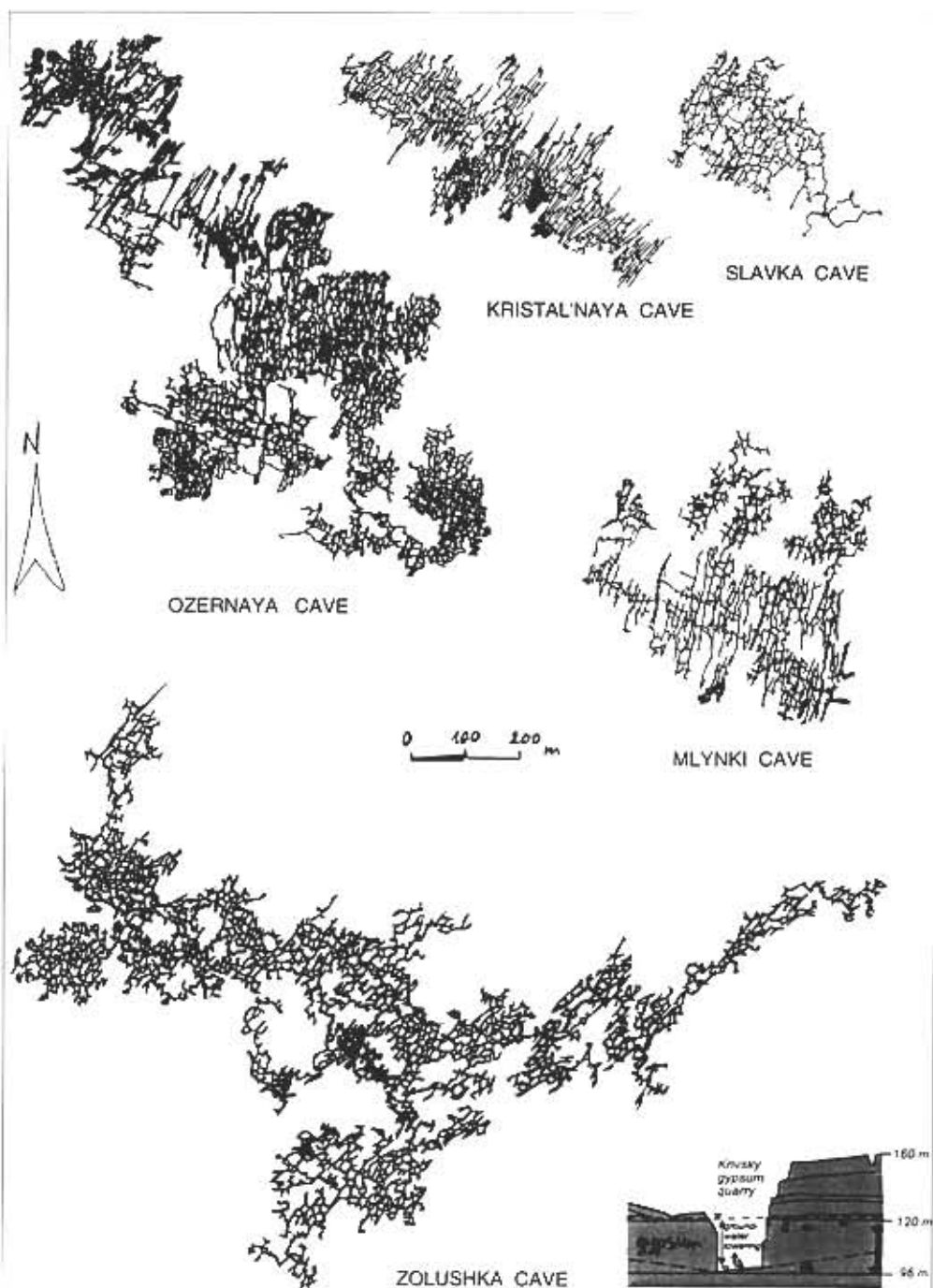
Fig. 3. Maps of some of the major gypsum caves in the Western Ukraine.

values are also characteristic for the fields of Verteba Cave (61%), Bukovinka Cave (57%) and Ozernaya Cave (51%). The average value is of 37%. The coefficient of volume karstification varies from 2-3% (Dzhurinskaja, Mlynki, Slavka and Komsomol'skaya caves) to 12% (Verteba Cave), with an average value of 5%.

3.2. Cave genesis: hydrodynamic pattern and evolution

Recent studies (Klimchouk, 1990, 1992, 1994) suggest that maze caves in this region developed (and are presently still developing in the 3rd zone) under confined conditions, due to effects related to upward cross-formational groundwater circulation between the pre-existing sub-gypsum and supra-gypsum aquifers. Such flow patterns are characteristic of potentiometric low areas, related to topographic lows (valleys) that commonly coincide with zones of enhanced fluid conductivity created within the capping clays by tectonic or stratigraphical discontinuities (Fig.4). Overall discharge from artesian aquifer systems occurs in such areas. Mechanisms of cave system development in such situations are discussed in detail in Chapter 1.5, where it is shown that maze patterns will result if appropriate structural conditions exist.

Across the entire studied region, confined hydrogeological settings (with limited discharge and sluggish flow) prevailed during most of the Pliocene, when slow speleogenetic initiation probably occurred. By the late Pliocene to early Pleistocene the old shallow and wide pre-Dniester valley had formed, as evidenced by the extent of the alluvium of 7th and 6th terraces preserved to the north-east of the modern valley. This initial erosional entrenchment into the confining clays created better conditions for discharge, and encouraged establishment of groundwater flow and cross-formational communication within the artesian system. The "great cave belt" of the Podols'ky region lies totally within the limits of this ancient pre-Dniester valley. Its north-eastern boundary approximates to the limits of the old alluvial deposits that are preserved within the modern inter-valley massifs. The two maze caves that lie north of this alluvial limit are related to a separate buried valley that has been traced in that area.

Towards the end of the early Pleistocene and through middle Pleistocene time, active uplifts in the Podol'sky sub-region resulted in further incision of the Dniester, but within a much narrower valley, only slightly wider than the modern one. Also, the left bank tributaries of the Dniester incised rapidly, dividing the area north of the Dniester into large, elongated, sub-parallel massifs. This led to a substantial acceleration of groundwater circulation within the Miocene artesian system and eventual breaching of its artesian confinement; marking a stage of subjacent karst. With further deepening of the surface drainage during late Pleistocene times, conditions of entrenched karst were established, and cave systems in the gypsum became relict.

In the area to the south-south-west of the Dniester valley, overall uplift rates during most of the Pleistocene were much slower, and there was a relative subsidence of some tectonic blocks adjacent to the foredeep. This imposed slow rates of speleogenetic development, which became active only during the late Pleistocene in some of the more uplifted blocks, such as those of Krivsky and Mamalyzhsky that were entrenched by the Prut valley (Zolushka and Bukovinka caves). In the north-western part of the gypsum belt karstification was intensified during the
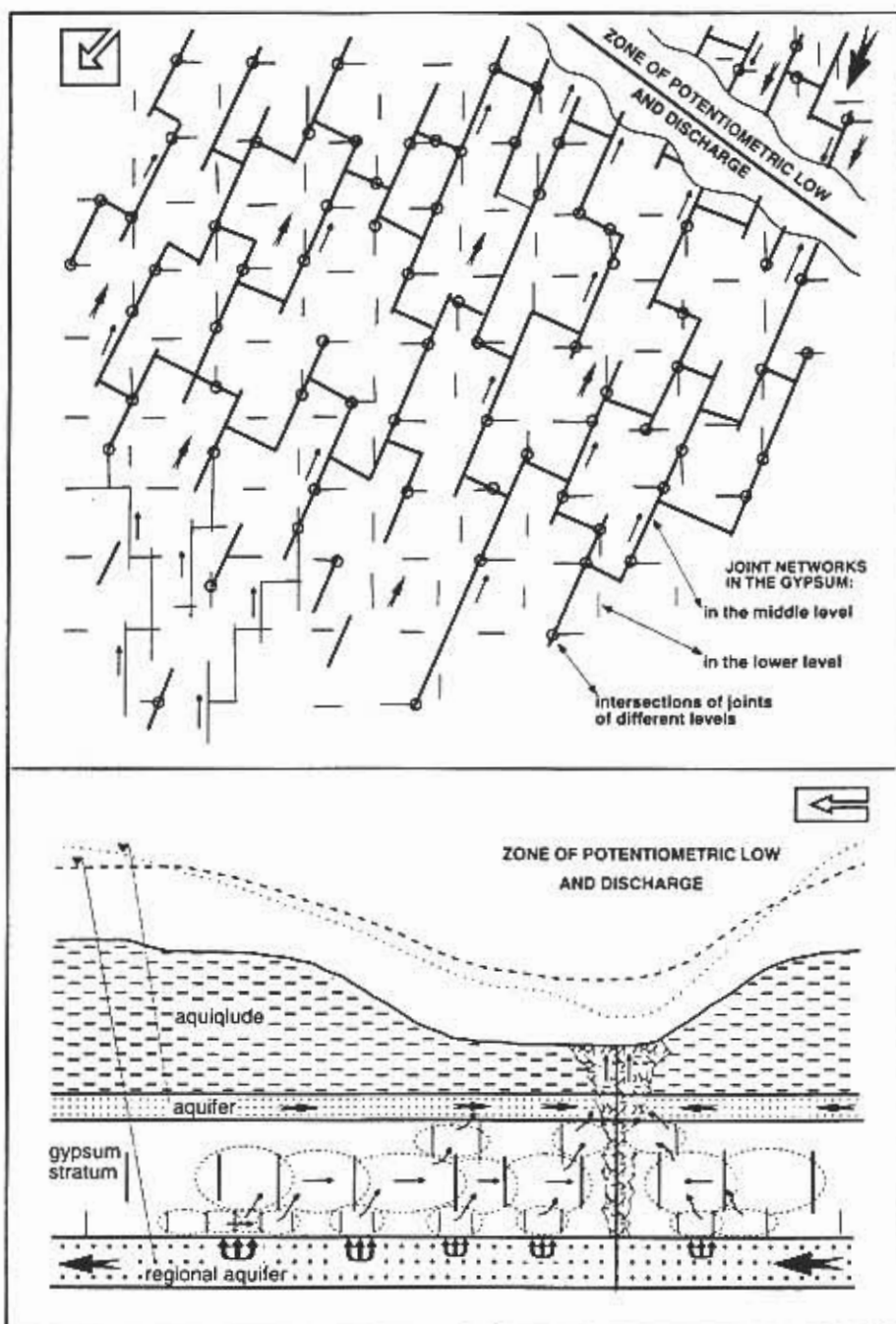
Fig. 4. The initial stage of upward development of multi-storey maze caves under artesian conditions in the Western Ukraine.

middle Pleistocene, being related to valleys that were incised to the top of the Tyrassky Formation but subsequently buried when the local neotectonic movement trend changed from uplift to subsidence. Karst and speleogenetic processes have been reactivated more recently in response to Holocene uplift (which has encompassed the whole region), and also as a reflection of the increasing effect of anthropogenetic impacts (see Chapter I.10).

The hydrodynamic and hydrochemical conditions of cave development during the mature and active stage of artesian speleogenesis can be illustrated by examples from the north-west of the gypsum belt (Jazovsky and Nikolaevsky deposits). Groundwaters entering the gypsum from below (from the sub-gypsum sandy-carbonate aquifer) have a TDS content ranging from 0.4 to 0.6 g L^{-1}, and are very aggressive with respect to gypsum, being able to dissolve it at rates ranging from -2.48 to -25.57mm a^{-1}. Water chemistry and dissolution rates in cavities within the gypsum vary substantially, depending upon the cave system configuration (the actual flow path within the gypsum) and flow velocity. The TDS content ranges from 1.3 to 2.1 g L^{-1}, and dissolution rates range from -0.16 to -3.46 mm a^{-1} (see also Chapter I.3).

Under cross-formational circulation conditions in an artesian system, all available fissures in the gypsum, which hold similar positions within analogous flow paths, will enlarge at comparable rates. This behaviour generally favours the development of maze cave morphologies, but the actual conduit arrangement in any situation will depend upon the initial local fissure pattern.

3.3. Structural prerequisites of speleogenesis

The maze and multi-storey structure of caves in this region is preconditioned, in the prevailing hydrodynamic environment of speleogenesis, by the extent and specific characteristics of the fissure patterns in the gypsum. Vertical fissures are arranged in largely independent networks confined within individual horizons of the gypsiferous unit, each of which is characterized by different rock textures and structures. This feature, together with some topological peculiarities of the fissure patterns, indicates that the fissures are lithogenetic rather than tectonic in origin (Klimchouk, Andrejchouk & Turchinov, 1995; see also Chapter I.1). Fissure patterns at each level have their own characteristic frequency, orientation distribution and degree of lateral connectivity, and elements of these are inherited by the passages that comprise each level of a cave system. This is the fundamental reason for different structures being displayed by passage networks at different levels. The extent and the nature of the vertical connectivity between storeys of fissures (passages) varies substantially between areas (tectonic blocks). The general background of vertical cross-formational groundwater circulation in these artesian systems is that a considerable lateral component of the cave development is caused by 1) the presence of laterally extensive interconnected fissure networks in some horizons and, 2) by the lack of coincidence of permeability structure between the sub-gypsum and supra-gypsum aquifers and between different horizons in the gypsum unit.

All of the caves include some morphological elements within the lower part of the gypsum stratum, which provided upward recharge of developing cave systems from the underlying aquifer. In most cases the fissures in the lowermost horizon do not form extensive laterally connected

networks, so that recharge of a continuous network at the next higher storey ("master storey") occurred through the separate fissures of localized small networks (Ozernaja, Slavka, Dzhurinskaja, Zolushka and some areas of Optimisticjeskaja caves). Such "feeder" conduits are commonly numerous and uniformly distributed across an area, providing relatively dispersed inflows of aggressive water to the conduit network of the master storey and supporting uniform dissolutional widening of all passages. In some other cases (such as Atlantida Cave) lateral flow and the development of master passages occurred chiefly along the base of the gypsum unit, with vertical "ascending" domepits and small networks formed locally at the upper storey. In all cases, multi-storey conduit systems developed (with some elements terminated at the base of the overlying sequence), with the ultimate function of conducting groundwater upwards between the sub-gypsum and supra-gypsum aquifers.

3.4. Meso-morphology of caves

The shapes and sizes of the passages, and of the smaller-scale forms produced within the passages, depend upon geological and hydrodynamic factors, the most important of which are the following:

1) shape and size of initial fissures;
2) distinctive structural and textural features of the gypsum within a given horizon;
3) position and function of a given morphological element in a karst circulation system;
4) distinctive features of the local hydrogeological evolution.

Because of the locally varying role of these factors, passage morphology can differ significantly between different parts of a single cave and, especially, between the separate cave levels. Vertical structural/textural differentiation of the gypsum unit (into three distinct sub-horizons across most of the Podol'sky sub-region) is believed to have resulted largely from late diagenetic recrystallization of the rock (Klimchouk, Andrejchuk & Turchinov, 1995). Such differentiation is the main cause of the development of distinct lithogenetic fissure (and, hence, passage) patterns, each confined to a specific horizon. Also, the different functional position of passage levels in cave systems of "ascending" type contribute further to the morphological distinction between levels. Thus, at least the first three of the factors listed above combine to influence the development of different passage morphologies located at different levels.

The reverse situation is even more consistently true: passages developed at the same level within a particular cave area (passages occupying the same geological position, and providing the same hydrological function in a system) are characterized by consistent morphological parameters, as all four of the factors listed above act with uniform weight.

Passages typically have a cleft-like shape, with a flat or gothic-arched ceiling. Also common are relatively wide (2 to 4m) passages with symmetrical horizontal notches and inwardly inclined facets in the walls, or with two or more levels of notching. The ceilings of these passages can also be flat or gothic-arched (see Fig.6 in Chapter 1.5). Such morphological features are the result of dissolution driven by natural convection, under either artesian or water table conditions (see Chapter 1.5 for details).

Dissolutional cupolas and domepits are widespread, having developed upwards from a master passage for up to 12m above ceiling level. They can be "blind", or open upwards into a passage at the next higher level. Some terminate at the base of the overlying limestone bed. Such domepits may be extended laterally in their upper parts, if a higher level fissure was intercepted. It is likely that cupolas and domepits, as well as another common feature, ceiling half-tubes, are also formed largely by dissolution driven by natural convection,. The development of ceiling half-tubes is achieved by buoyant currents of relatively fresh water that will always tend to occupy the highest available position in a passage containing bulk water that is more highly saturated (see Klimchouk, 1997c, and Chapter 1.5 for details). Such half-tubes can commonly be traced continuously from the "feeder" conduits at lower level, through master passages, to domepits that open to the next higher level or reach the upper boundary of the gypsum (see Fig. 5 in Chapter 1.5).

During the final stage of artesian speleogenetic development, when the upper confining bed is breached locally by an incising valley or areas of collapse, groundwater flow through a cave system increases dramatically, due to unconstrained discharge. Accelerated growth of the passages along preferred flow paths results in development of the large trunk passages that are recognized in most of the region's caves. In some cases, passages within a particular part of a maze may be enlarged substantially, relative to average passage sizes in adjacent areas. This is exemplified by the Chamber of Chernovtsy Speleologists in Zolushka Cave, where only small pillars remained within a large space that was formed by the coalescing of enormously enlarged passages. Another mechanism responsible for comparatively rapid passage enlargement, which operates more uniformly within specific areas at a particular level, is horizontal notching in response to dissolution at the water table.

Typical features formed under modern entrenched karst conditions are vertical dissolution pipes, which grow due to a focused descending percolation from overlying formations. They are 1 to 3m wide, extend downwards through the full thickness of the gypsum from its top, and are commonly superimposed upon relict artesian passages. Recent linear through caves carrying active streams are relatively rare in the 1st zone but more common in the 2nd zone. Normally they develop along the base of the gypsum, originating from doline ponors and extending towards the nearest entrenched valley. Some such caves may enter areas of relict mazes, where the active streams dissipate and water filters downwards into the underlying aquifer (as is the case in the entrance passage of Optimisticheskaja Cave). Such areas of the caves are prone to short term flooding after heavy rainfall or active snow melting.

3.5. Cave sediments and formations

By far the predominant clastic sediments in the maze caves of the region are successions of fine clays, with minor beds of silty clays (Klimchouk, 1984). These fill passages to a variable extent and can reach 5 to 7m in thickness. The clay material is derived largely from overlying clayey formations and has been intruded into the caves mainly during the later stages of artesian speleogenesis, when breakdown processes became active and flow velocities increased, allowing some redistribution of clastic material. However, gradient fields within the aquifer remained relatively

uniform, so that the sediments are very fine grained, exceptionally well sorted and maintain a uniform facies over considerable distances. The number of silty beds increases in the upper parts of the clay sediment sequences, reflecting the more variable hydraulic environment of an unconfined aquifer during the subjacent and early entrenched karst stages. Repeated transitional cycles from a reducing to an oxidizing geochemical environment are marked by the presence of Fe/Mn hydroxide layers (Klimchouk & Rogozhnikov, 1982). Massive deposition of Fe/Mn compounds has occurred in Zolushka Cave, where a rapid transition of the type described has been caused by groundwater abstraction during the last 50 years (Volkov, Andrejchuk & Janchuk, 1987). Sandy-gravel sediments occur in the upper parts of the cave fills, but these are limited to areas that surround active ponors. They have been re-worked and redeposited from the old (late Pliocene to early Pleistocene) alluvial sediments that commonly overlie Sarmatian clays.

Breakdown deposits are also quite common in the caves. They include chip, slab and block breakdown material from the gypsum unit, as well as by material from more massive breakdowns which disrupted the overlying formations. Locally the plastic Sarmatian clays can be injected into caves through breakdown zones, due to the pressure of the overburden. Distribution of breakdown deposits is governed by passage sizes, local textural and structural peculiarities within the gypsum of a given area or horizon, and the presence of tectonic faults.

Various chemical deposits, speleothems and formations are quite common in the gypsum caves of the Western Ukraine (Rogozhnikov, 1984; Turchinov, 1993). Calcite speleothems (stalactites, stalagmites, flowstones and helictites) occur locally in zones of vertical water percolation from overlying formations. Among other carbonate minerals, rhodochrosite occurs within a flowstone in Optimisticheskaja Cave (Turchinov, 1993). Gypsum crystals of different habits, sizes and genesis are the most common cave formations. Those covering the walls in many parts of the caves have a largely subaerial origin, being formed by evaporation of saturated solutions moving as thin films on the walls. Also common are gypsum formations deposited by evaporation of interstitial solutions seeping from the host rock (local covers, and "flowers" of fibrous gypsum). Hoar-frost crystals, "gypsum snow" on passage floors, and gypsum rims are assumed to be precipitated from aerosols (Klimchouk, Nasedkin & Cunningham, 1995). Silicates are represented by lutecite, a variety of cristobalite, found in Optimisticheskaja Cave (Turchinov, 1993). Oxides and hydroxides (Fe/Mn compounds) are common within the clay fill of many caves, or can also occur as covers, stalactites and stalagmites (Zolushka Cave). Manganese minerals are also represented by birnessite and asbolan-buserite in Zolushka Cave (Volkov, Andrejchuk & Janchuk, 1987).

4. Gypsum karst and the origin of native sulphur deposits

Large bio-epigenetic deposits of native sulphur in the pre-Carpathian region are genetically associated with the same gypsiferous unit, and are all located within the 3rd zone described above (see Fig. 1). Sulphur is embedded in epigenetic calcite that partially (at the top) or wholly replaces the gypsum. Views on the origin of these sulphur deposits are quite controversial. Recently (Klimchouk, 1997b) a new interpretation, which implies a fundamental role for gypsum karst in sulphur origin, has been suggested. It is evident that, in general, bio-epigenetic sulphur formation

is related to karst, because dissolved sulphates are needed to enable the large-scale sulphate reduction that is a key process within the sulphur cycle. But in the case of the pre-Carpathian sulphur deposits, the role of karst (speleogenesis) as a governor of groundwater circulation in the artesian aquifer system was decisive. The proposed model for the origin of sulphur deposits hinges upon the ascent of groundwater between the sub-gypsum and supra-gypsum aquifers, through karst systems (artesian cave systems) in the gypsum. Such a flow architecture and speleogenetic evolution within the gypsum provided the spatial and temporal framework within which the sulphur cycle processes took place, as well as controlling the geochemical environments, and the migration of reactants and reaction products between them. The model explains the well-accepted relationship of sulphur deposits to buried valleys and karst zones, and resolves many contradictions in earlier interpretation of the geological features of the Tyrassky Formation and the hydrogeological features of sulphur deposits (Klimchouk, 1997b).

References

ANDREJCHUK, V.N. 1988. The tectonic factor and peculiarities of the sulphate karst of Bukovina: geology, geomorphology and hydrogeology of karst. Sverdlovsk. 66 pp. (in Russian).

DUBLJANSKY, V.N. & IVANOV, B.N. 1970. Karst of the Podol'sko-Bukovinsky karst region. In: Fisicheskaja geografija I geomorfologija, 4. Kiev: Kiev University. (in Ukrainian).

DUBLJANSKY, V.N. & SMOL'NIKOV, B.N. 1969. Karstological and geophysical investigations of karst cavities of the Pridnestrovskaja Podolija I Pokutje. Kiev: Naukova dumka. 151 pp. (in Russian).

IVANOV, B.N. 1956. On typology of karst landscapes of planes, on the example of Podol'sko-Bulovinsky karst region. In: Voprosy izuchenija karsta na juge Evropejskoj chasti SSSR. Yalta. 131-156. (in Russian).

IVANOV, B.N. & DUBLJANSKY, V.N. 1966. Superficial and underground karst of the south-west flank of the Russian Platform. In: Voprosy izuchenija karsta Russlkoj ravniny. Moscow. (in Russian).

KLIMCHOUK, A.B. 1984. The experience of the detailed study of water-mechanical sediments of a large cave system. In: Peshchery (Caves). Perm: Perm University Publ. 70-88. (in Russian).

KLIMCHOUK, A.B. 1990. Artesian genesis of the large maze caves in the Miocene gypsum of the Western Ukraine. Doklady Akademii Nauk Ukrainskoj SSR ser.B, 7. 28-32. (in Russian).

KLIMCHOUK, A.B. 1992. Large gypsum caves in the Western Ukraine and their genesis. Cave Science 19 (1). 3-11.

KLIMCHOUK, A.B. 1994. Speleogenesis under confined conditions, with recharge from adjacent formations. Publ. Serv. Geol. Luxembourg v.XXVII. Comptes Rendus du Coll. Int. de Karstol. a Luxembourg. 85-95.

KLIMCHOUK, A.B. 1997a. The role of speleogenesis in the Miocene gypsum in the Western Ukraine in groundwater circulation in the multi-storey artesian system. In: (G.GUNAY & I.JOHNSON, eds.): Karst Waters & Environmental Impacts. Rotterdam: A.A.Balkema Publ. 281-292.

KLIMCHOUK, A.B. 1997b. The role of karst in the genesis of sulfur deposits, pre-Carpathian

region, Ukraine. Environmental Geology. (In press).

KLIMCHOUK, A. 1997c. Speleogenetic effects of water density differences. 12th Internat. Congress of Speleology, La Chaux-de-Fonds, Switzerland.

KLIMCHOUK, A.B. & ANDREJCHUK, V.N. 1988. Geological and hydrogeological conditions of development of large gypsum caves in the Western Ukraine and their genesis. In: Peshchery (Caves). Gypsum and Anhydrite Caves. Perm: Perm University Publ. 12-25. (in Russian).

KLIMCHOUK, A.B., ANDREJCHOUK, V.N. & TURCHINOV, I.I. 1995. Structural pre-requisites of speleogenesis in gypsum in the Western Ukraine. Kiev: Ukrainian Speleol. Assoc. 104 p.

KLIMCHOUK, A.B. et al. 1985. Geological and hydrogeological conditions of karst development of the Pridnestrovsky Podolia. In: I.L.SOKOLOVSKIJ & A.B.KLIMCHOUK, eds.: Fizycheskaja Geographija i Geomorphologija, vol.32. Karst of the Ukraine. Kiev: Vyshcha shkola. 47-54. (in Russian).

KLIMCHOUK, A.B., NASEDKIN, V.M. & CUNNINGHAM, K.I. 1995. Speleothems of aerosol origin. NSS Bulletin 57. 31-42.

KLIMCHOUK, A.B. & ROGOZHNIKOV, V.Ja. 1982. Conjugate analysis of the development history of a large cave system (on example of the Atlantida cave). Kiev: Inst. Geol. Nauk. 58 p. (in Russian).

POLKUNOV, V.F. 1990. Mineral concentrations of native sulfur. In: Geotektonika Volyno-Podolii. Kiev: Naukova Dumka. 229-232.

ROGOZHNIKOV, V.Ja. 1984. Water-chemical deposits in karst labyrinthic caves of the Podol'sky Pridnestrovje. In: Peshchery (Caves), Perm: Perm Univ. 46-55. (in Russian).

TURCHINOV, I.I. 1993. Secondary mineral formations of gypsum caves of the Western Ukraine. Svet (Light) 3 (9), Kiev. 29-37. (in Russian, English summary).

SHESTOPALOV, V.M. (Ed.). 1989. Water exchange in hydrogeological structures of the Ukraine. Water exchange under natural conditions: Kiev, Naukova Dumka. 288 pp. (in Russian).

VOLKOV, S.N., ANDREJCHUK, V.N. & JANCHUK, E.A. 1987. Modern iron-manganese formations of the Zolushka Cave. In: Mineralogicheskij Sbornik 4 (1). Lvov: Lvov University. 79-83. (in Russian).