Structural prerequisites of speleogenesis in gypsum in the Western Ukraine

Prerrequisitos estructurales en la espeleogénesis de los yesos de Ucrania del Oeste

Klimchouk A.B.; Andrejchouk V.N.; Turchinov I.I.

Ukrainian Speleological Association

Traducción de figuras por J.M. Calaforra (con permiso de los autores)

Resumen

En este artículo se caracterizan las condiciones geológicas, en especial prerrequisitos estructurales, de la espeleogénesis en los yeso miocenos del Oeste de Ucrania. Se presta especial atención a las irregularidades estructurales y texturales del estrato de yeso y su papel en la configuración de la fracturación. Se caracteriza en detalle la fracturación en el yeso, la estructura de los sistemas laberínticos de las cavidades y la morfología de las galerías. Se demuestra que las fracturas del estrato de yeso relacionadas con el inicio de la espeleogénesis son de tipo litogénico y constituyen grandes redes independientes distribuidas en niveles, estando cada nivel confinado en su ubicación a determinadas zonas estructurales/texturales del estrato de yeso. Este hecho determina la estructura en multi-niveles de las cavidades de la región.

Se considera también el problema de la formación de grandes estructuras yesíferas en domo debidas a la recristalización del yeso durante una etapa temprana de la diagénesis, así como el problema de la génesis de la fracturación. La espeleogénesis, dados estos prerrequisitos estructurales, ocurrió en unas condiciones de un sistema acuífero artesiano con distintos niveles, debida a una recarga vertical ascendente a partir del acuífero infrayacente al estrato yesífero.

Palabras clave: karst en yeso, fracturación, control estructural, domos yesíferos; espeleogénesis, acuífero artesiano.

Abstract

In this paper geological conditions are characterized, structural prerequisites in particular, of speleogenesis in the Miocene gypsum in the Western Ukraine. Special attention is paid to consideration of structural and textural irregularities o the gypsum stratum and their role in the formation of jointing. Jointing in the gypsum, structure of unique maza cave systems and morphology of passages are characterized in detail. It is shown that speleo-initiating joints in the gypsum strata fall in lithogenetic type and form largely independent multi-storey networks with each storey being confined within certain vertical structural/textural zones of the stratum. This determines the multi-storey structure of caves in the region.

The problem is considered of the formation of giant dome structures by way of gypsum recrystallization during the early diagenesis stage, as well the problem of jointing genesis is discussed. Speleogenetic realization of existing structural prerequistes occured under conditions of multi-storey artesian aquifer system, due to upward recharge of cave systems from the under-gypsum aquifer.

Key words: gypsum karst, joints, structural control, gypsum domes, speleogenesis, artesian aquifer, Ukraine

INTRODUCTION

The territory of the western districts of Ukraine (Lvovsky, Ternopol'sky, Ivano-Frankovsky, Tchernovitsky) is characterized by extensive development of sulfate karst in the gypsum/angydrite strata of Middle Miocene. Numerous scientific and practical problems of regional geology, hydrogeology, engineering geology, geochemistry and environment protection are related to the sulfate karst of the Western Ukraine. The unique feature of the gypsum karst in the region is an extensive development of maze cave systems. In the region five largest gypsum caves in the World are located (Optimisticheskaya - 189 .000 km, Ozernaya - 111 km, Zolushka - 89 km, Mlynki - 24 km, Kristal'naya - 22 km), with their total length compatible with that of all other known gypsum caves in the World. Being the core of the karst subject as a whole, the problem of cave genesis was controversial one during long period for the Western Ukrainian region and is resolved sufficiently just recently.

Karst development in general, and speleogenesis particularly, is controlled by numerous factors, among which the structural and hydrogeological ones are most important. Structural factors are those determining a structure of initial permeability of karstifiable rocks, jointing first of all. Besides tectonic prerequisites, lithological and textural peculiarities of the Miocene gypsum stratum have played a great role in development of jointing in it. The study of the role of the above factors and prerequisites in speleogenesis is the main subject of the present work. This is considered here using examples of many

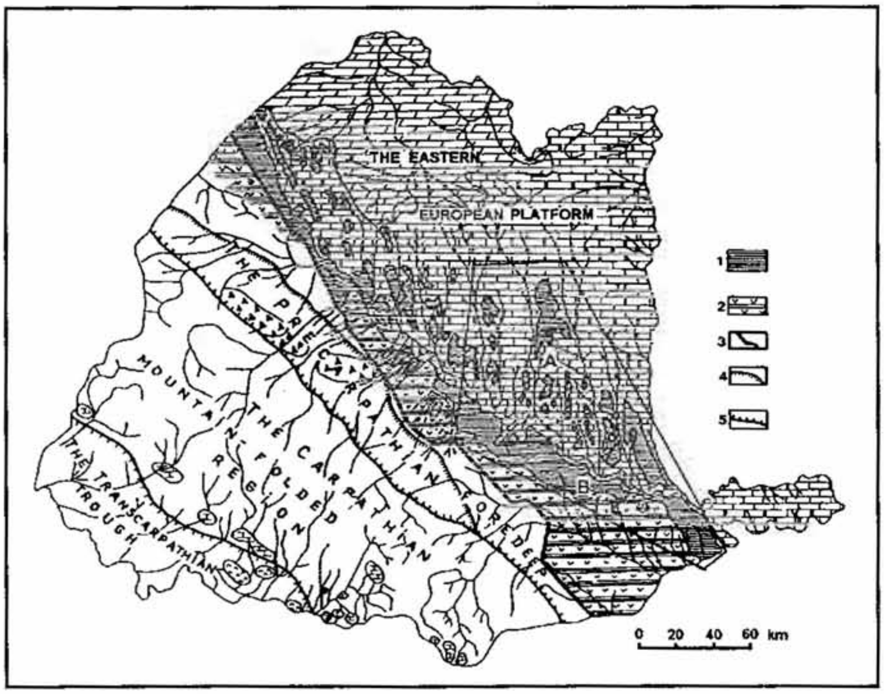


Figure 1. Gypsum karst areas and main tectonic structures in the Western Ukraine: 1- areas with surface karst manifestations; 2- areas without surface karst manifestattions; 3- platform/foredeep boundary; 4- boundary between inner and outer foredeep zones; 5- structural boundaries of the Carpathians. A- Podolia region; B- Bukovinsky region

Figura 1. Areas de karstificación en yesos y principales estructuras tectónicas en el Oeste de Ucrania: 1- áreas con manifestaciones kársticas superficiales; 2- áreas sin manifestaciones kársticas superficiales; 3- límite plataforma/fosa tectónica; 4- límite entre las zonas de fosa interna y externa: 5- límites estructurales de los Cárpatos. A- Región de Podolia; B- Región de Bukovinsky

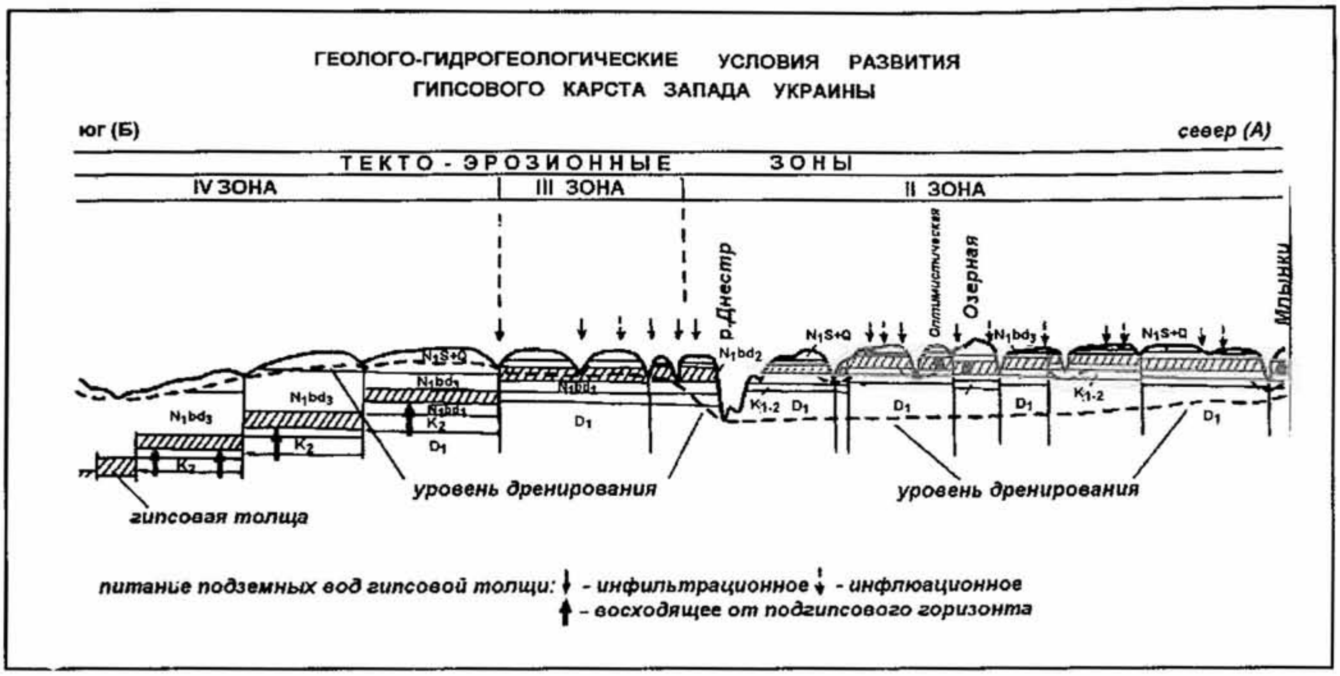


Figure 2. Alteration of geological and hydrogeological conditions of the gypsum karst development in the direcction from the internals of the platform outskirsts towards the pre-Carpatian foredeep (from right to the left)
Figura 2. Alteración de las condiciones geológicas e hidrogeológicas en el desarrollo del karst en yeso desde la plataforma interna hasta la fosa pre-Carpática (de derecha a izquierda)

large caves of the region, but with special reference to the largest gypsum cave in the World - Optimisticheskaya Cave, where the linkage between jointing and morphology, and lithological and textural peculiarities of the gypsum stratum is most prominent.

The authors are grateful to leaders and members of the speleological clubs of Lvov, Ternopol', Chernovtsy and Kiev, especially to M.Savtchin, A.Medvedev, N.Ostyanova, J.Zimel's, S.Epifanov, V.Korzhik, B.Ridush, as well as to former staff members of the Karst and Speleological Department, the Institute of Geological Sciences, National Academy of Sciences, S.D.Aksem, V.Ja.Rogozhnikov and M.L.Tchurubrova for their assistance in collection of data and in pursuance of underground researches. Twenty years of this Department activity were full of many challenging projects and underground adventures, and this period will be forever remembered by the first of present authors as the most instructive and enjoyable one.

GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS OF CAVE DEVELOPMENT

The gypsum strata of Miocene age is widely spread in the southwestern fringes of the Eastern European platform, in the transitional zone between the platform and the pre-Carpathian foredeep, where the strata stretches from southeast to northwest for 300 km by the belt of several to 40-80 km wide. The total area of Miocene sulfate formation within the platform outskirt amounts up to 20 thousands km^2. Two major cave subregions, Podolsky and Bukovinsky, both are situated in the southeastern section of the gypsum/anhydride belt (fig.1).

Precambrian crystalline basement is submerged here to the depth of 1000-1200 m and more. The sedimentary cover is represented with formations of Paleozoic (Hercynian structural stage), Mesozoic and Cenozoic (Alpine structural stage). In the valleys of Dniester and it's left tributaries Lower Devonian, Cretaceous and Miocene sediments are exposed, and only Miocene sediments outcrop in the Bukovinsky subregion.

The Miocene sequence lies on the eroded surface of Cretaceous rocks. The Cretaceous succession is represented here by terrigenous and carbonate sediments, most often by sands, sandstones and detrital limestones belonging to Albian and Senomanian. Thickness of the Cretaceous succession ranges from 5 to 20 m, and it increases towards south and west.

The Miocene succession is composed by Badenian and Sarmatian deposits, and lies on the eroded surface of Cretaceous. Badenian is divided into three units. Lower Badenian (thickness 5-30 m) is represented by quartz sands, sandstones, and bioherm detritic limestones; these sediments replace each other frequently. In the upper part of the unit detritic limestones of 0.3 to 1.0 m in thickness normally occur, which immediately underlie the gypsum strata.

The overlying Tyrassky Formation (Middle Badenian) is represented by the sulfate and carbonate facies. The Gypsum stratum has a thickness of 15 to 25 m in the Podolsky subregion, and up to 40 m in the Bukovinsky one. Toward the foredeep the content of anhydrite increases in the stratum. Horizontal occurrence of the gypsum stratum between the low-karstifiable rocks and almost universal spread of clay coverbeds protecting the strata from vertical percolation of meteoric water are the main factors caused largely lateral development of the cave systems in the gypsum strata, conservation of the stratum and caves within it during prolonged period (Klimchouk, Andrejchouk, 1986, 1988). The detailed consideration of lithological and textural peculiarities of the gypsum stratum is given in the following chapter.

The carbonate facies of the Tyrassky Formation is represented with pelitomorphic chemogeneous limestone, locally named "Ratynsky", 0.2 to 8 m in thickness. Normally it overlies the gypsum stratum; in this case it's thickness does not exceed 1.5 m. In places this limestone replace the gypsum in the cross section attaining it's maximum thickness.

The Upper Badenian unit lies on the Tyrassky Formation, and begins with argillaceous and marly limestones with concretions of lithotamnium (the Ternopol' beds, thickness 1.5 to 3 m). Above, the thickness of clays and marls occurs, the lower part of which is placed to Upper Badenian (Kosovsky Formation), and the upper part belongs to Lower Sarmatian. The total thickness of these sediments attains 40-45 m in the Podolsky subregion, and increases towards the foredeep. On the upland areas pebble-beds of the old Dniester terraces remained from erosion; they are placed to Upper Pliocene.

Quaternary sediments are universally spread over the studied region and are represented by the eluvial cover of watersheds (clay, loams), deluvial sediments of valley slopes (loams with pebbles and debris), and alluvium of terraces (sands, pebble-beds). Their thickness attains 20-25 m.

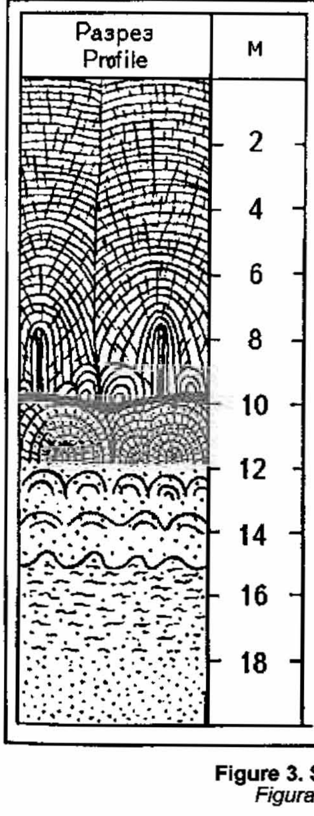
Rocks of Paleozoic and Meso- Cenozoic structural storeys are broken by faults of different ages and orders into numerous tectonic blocks. Predominant orientation of faults in the territory are: 15-30°, 50-70°, 290-300°, and 350-0°; dislocation amplitudes along such faults normally do not exceed 15 m. The block structure is of great significance, as it controls development and appearance of karst processes in the Western Ukraine. In the direction from the platform internals toward the foredeep, the gypsum stratum plunge by steps; such plunging is compensated by increasing thickness of clay coverbeds; the depth of erosional entrenchment concurrently decreases (fig.2). This causes a regular zoned alteration of hydrogeological settings of karst development in the above direction (Klimchouk et al., 1983, 1985; Andrejchouk, 1984, 1988; Klimchouk, Andrejchouk, 1986, 1988).

Of hydrogeological concern the study area corresponds to the south-west part of the Volyno-Podol'sky artesian basin of the platform type, to the Podolsky and Bukovinsky drainage basins of the first order (Shestopalov, 1981; Vodoobmen..., 1989). There are aquifers in Paleozoic, Cretaceous, Miocene, and Quaternary deposits. As a result of intense neotectonic uplifts and deep erosional entrenchment in the Podolsky subregion during Pleistocene, the aquifers in Miocene and Cretaceous deposits had lost their artesian confinement, and became wholly or partially drained. Under the modern conditions, the Miocene aquifer receive localized point recharge from the surface via swallow holes. The aquifer occurs mainly within the under-gypsum unit of Lower Badenian, but toward the internals of intervalley massifs the water table arises into the lower part of the gypsum stratum. The table of the Miocene aquifer is accessible in Ozernaya and Optimisticheskaya caves as cave lakes. Discharge occurs in bottoms and slopes of ravines and river valleys in form of springs with flow rates ranging between 0.5 to 15 l s^{-1} (most frequently 0.8 to 2.0 l s^{-1}). Water is characterized by SO_4-Ca or HCO_3-SO_4-Ca composition, with TDS content of 0.8-2.7 g l^{-1}.

In the Bukovinsky region, as the foredeep is approaching, the thickness of clay coverbeds increases, and the depth of erosional entrenchment decreases, so that the conditions of the fully drained gypsum stratum change to the water table conditions within the gypsum stratum, and then - to the conditions of an artesian aquifer. In the area of Prut river the conditions of an artesian aquifer prevail; only in some most uplifted blocks water table is positioned several meters below the top of the gypsum stratum (the blocks of Zolushka and Bukovinka caves).

LITHOLOGICAL AND TEXTURAL PECULIARITIES OF THE GYPSUM STRATUM

In the Podolsky subregion, the gypsum stratum 10 to 22 m in thickness is characterized by clear vertical structural and textural differentiation. It is expressed most clearly and complete in the southern part of the Seret-Nichlava intervalley massif. This differentiation proved to be the most important prerequisite for the formation of jointing peculiarities, and eventually, for the formation of the cave system structures: their storey occurrence, plan patterns, etc. (Klimchouk, 1986; Klimchouk, Andrejchouk, 1988). This is why the topic is worst of special consideration. The



Зоны и подзоны Zones &subzones		Структура гипсов Gypsum texture	Текстура гипсов Gypsum structure		Примечания Notes
III	III B	Гигантокристаллическая (>10 cm) Giantocrystalline	Куполовидная с диаметром структур: Dome-like, with diameter of structures:	> 3 м	Ядра куполовидных структур вытянуты по вертикали на 1-5 м Core parts of dome-like structures are alongated in the vertical dimention
		Крупнокристаллическая (1-10 cm) Coarse-crystalline			
	III A	Мелкокристаллическая (<0.1 cm) Microcrystalline		< 1 м	Ядра структур изометричны Core parts are isometric
II		Крупно- и мелкокристаллическая Coarse- and microcrystalline	Куполовидная, d < 3 м Dome-like, d < 3 м		Ядра структур изометричны Core parts are isometric
I	I C	Мелкокристаллическая (<0.1 cm) Microrystalline	Волнистая, длина волны > 0.5 m Waved, wave length >0.5m		В массе мелкокристаллического гипса - крупнокристаллические агрегаты In the microcrystalline rock-mass macro-crystalline aggregates occur
	I B	Мелкокристаллическая (<0.1 cm) Microrystalline	Плойчатая, слоистая Plicated, bedded		В массе мелкокристаллического гипса - отдельные крупные кристаллы. In the microcrystalline rock-mass separated large crystalls occur
	I A	Скрытокристаллическая (<0.01 cm) Cryptocristalline	Массивная,полосчатая Massive, eutaxitic		Однородный скрыто- и мелкокристаллический гипс. Homogeneous crypto- and microcrystalline gypsum

Figure 3. Structural and textural differentation of the gypsum strata in the Podolsky region
Figura 3. Diferenciación estructural y textural del estrato yesífero en la región de Podolia

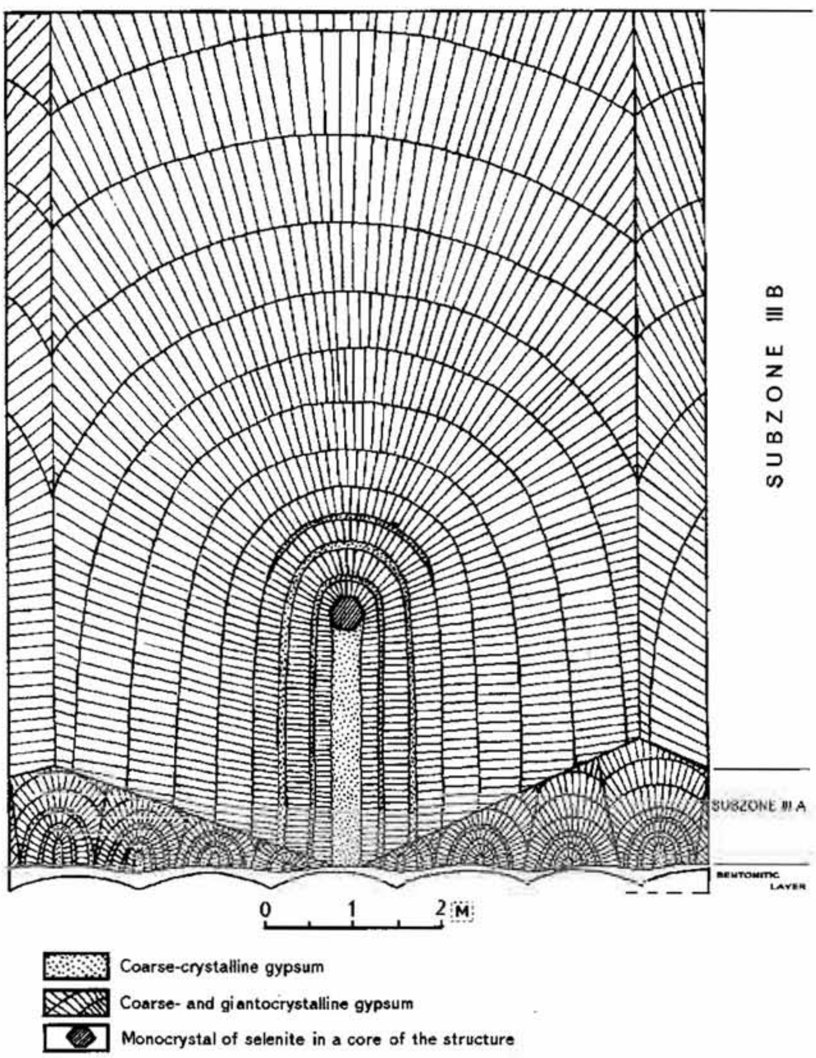


Figure 4. The dome estructure of the upper part of the gypsum strata
Figura 4. Estructura en domo en la parte superior del estrato yesífero

below characteristic of structures and textures of gypsum rocks immediately represents the area of Optimisticheskaya cave, but it can be applied to most of other caves of the Podolsky subregion with minor corrections.

In general, the sizes of gypsum crystals increase from the bottom upward across the stratum. Transitions between structural/textural varieties are rather sharp. This allows to divide the gypsum stratum into three parts (zones): the lower, middle, and upper ones (zones I, II, and III on the fig.3). There is certain differentiation of rock by structure and texture within the zones, which allows to distinguish between sub-zones.

The lower part of the gypsum stratum (the zone I), of 6 to 8 m in thickness, is composed mainly by microcrystalline varieties of gypsum. In the bottom of the stratum rock is represented by homogeneous crypto- and microcrystalline mass of white or light-brown color. It is composed with gypsum grains of 0.1 to 0.4 mm in size, of isometric shape, with irregular or tooth-like contours. The rock texture is equigranular, granoblastic. As impurities, clay particles and grains of carbonates, celestite and barite occur. Frequently, gypsum have the banded structure caused by presence of thin clay films separating thin gypsum layers. Crypto- and microcrystalline gypsum with massive, banded and bedded structures, lying in the bottom of the stratum, have the thickness of 1.5 to 2 m and compose the sub-zone Ia.

Upward in the cross section the subzone Ib is located (2-3 m), which is characterized by an enlargement of gypsum grains up to 0.4-0.8 mm. On the micrograined background, inclusions of larger crystals occur (up to 2.0 mm), so that gypsum attains porphyroid texture. Thin layers of gypsum are deformed by recrystallization processes, and banded structure turns to plicated one.

In the lower part of the gypsum stratum, within the sub-zones Ia and Ib, lenses of argilo-sulfate rythmite occur; the rock is formed by alternating thin (up to 2 mm) beds of gypsum and clay, which had not been encompassed by recrystallization processes.

The top of the zone I, which is distinguished as the sub-zone Ic, has the thickness of 2-3 m and is characterized by presence of light-brown and dark-brown gypsum crystals up to 3-4 cm in size occurring in the white microcrystalline mass. Waved and fan-like structures are distinguished by distribution of these crystals . The length of such "waves" do not exceeds 0.3-0.5 m.

Besides the above varieties of gypsum, macrocrystalline gypsum occurs in the lower part of the gypsum stratum, in zones of old pre-speleogenic jointing. It is represented by tabular and parallel-columnar crystals of brown color, up to 5-10 cm sized, forming veins up to 20 cm in thickness along paleojoints. Their genesis is related to movement of saturated solutions through such joints. In some cases the gypsum is recrystallized to the state of selenite gypsum.

The transition from the lower part of the gypsum stratum (the zone I) to the middle one (the zone II) is rather sharp. It is underlined by the layer of microcrystalline gypsum up to 10 cm in thickness. The contact between the zones is irregular and waved.

The zone II, 2 to 3 m thick, is characterized by concentric occurrence of micro- and macrocrystalline gypsum, forming dome-like structures of 0.5-3 m in diameter (normally - 1 to 1.5 m). These structures are concentric-zoned. Cores are usually isometric in shape and composed with microcrystalline gypsum. They are covered by concentric layers of 1 to 15 cm in thickness, composed by alternating micro- and macrocrystalline gypsum. The thickness of macrocrystalline layers increases from a core toward peripheries. The microcrystalline gypsum varieties are represented by grains of isometric shape, 0.5 to 1.0 mm in size. Macrocrystalline gypsum is composed with crystals of tabular habitus, brown in color, 10 to 15 cm in size.

Dome structures of the zone II are often complicated by deformation and corrugation of concenters. Some largest structures have formed as a results of intergrowth of two or three small

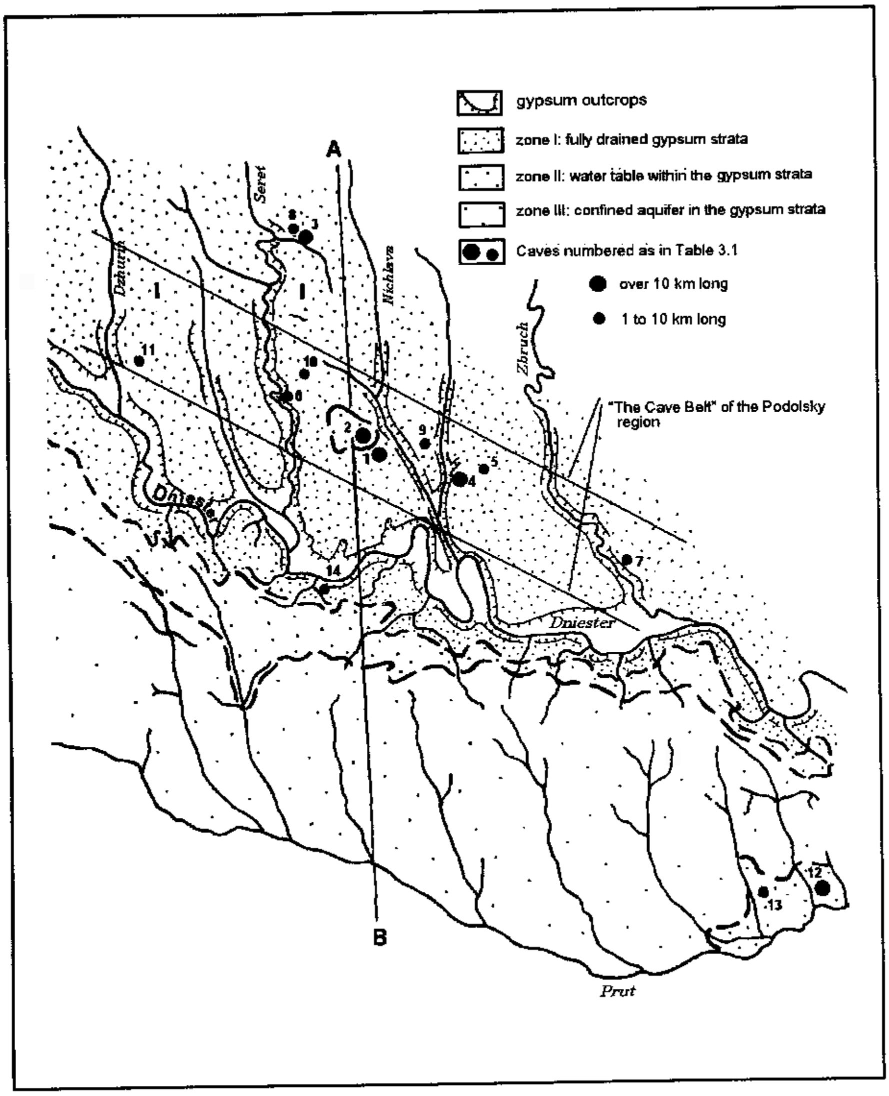


Figure 5. Zonation of development conditions and the location of the main caves of Podolsky and Bukovinsky regions. Numbers of caves correspond to the table 1
Figura 5. Zonación de las condiciones de desarrollo y localización de las principales cavidades de las regiones de Podolia y Bukovina. La numeración corresponde a la reflejada en la tabla 1

structures. Dividing boundaries between structures of the zone II usually are not clearly expressed.

The upper part of the gypsum stratum is separated from the middle part by minor layer of bentonitic clay (1 to 30 cm in thickness, normally 5 to 10 cm). This layer is universally spread through the areas of Optimisticheskaya and Ozernaya caves, and is less expressed and developed in the areas of other caves of Podolsky sub-region. Pinches and swells of the layer are caused by it's deformation in the process of development of underlying dome structures of the zone II.

Bentonitic clays are the result of bentonitization of volcanic ash. This is indicated by frequently occurring relicts of ash in the lower part of swells of the layer. According to thermic analysis bentonitic clays are represented by montmorillonite, with impurities of vermiculite and hydromica.

It is likely that bentonitic layer had played an important role in the process of recrystallization of gypsum and growth of dome structures. It determines, to some extent, the morphology of cave passages in the middle part of the gypsum stratum, developed immediately beneath the layer. Being universally spread within some cave areas (Optimistiches- kaya and Ozernaya caves), and occurring in the areas of some other caves, this layer prove to be the important marking bed, allowing to control an occurrence of the gypsum stratum and it's dislocation in zones of faults, as well as to control and correlate a position of cave passages (networks) in the stratum cross section between distant regions of the mazes. The latter is particularly important if considering difficulties of instrumental control of passages altitudes through long distances.

The most distinctive feature of the upper part of the gypsum stratum (the zone III) is an occurrence of brown-colored macro- and giantocrystalline varieties of gypsum, forming giant dome structures sized up to 8 to 10 m in the transverse dimension. In the average, the transverse dimension of the dome structures (the cross dimension of a polyedral figure formed in the plan view by boundaries dividing structures) is 4-6 m.

The lower part of the zone III (the sub-zone IIIa) is characterized by a presence of rather small dome structures of 0.2 to 2 m in diameter. These structures have a core composed with microcrystalline gypsum. Concenters alter each other from a core toward periphery, having the thickness of 1 to 15 cm and being composed with micro- and macrocrystalline varieties of gypsum.

The sub-zone IIIb is located above, composed with giant dome structures, which growth is determined by the law of geometric selection (Grigorjev, 1961). According to this law, those aggregates grow predominantly which centers are located higher than that of others. Lower aggregates are suppressed in their growth due to the lack of a free space. Growing concurrently, dome structures are getting in touch with each other, forming dividing boundaries, which create a polygonal network in the plan view. Dividing boundaries are normally vertical, if centers of growth of the neighboring structures are located in the same level, or they are inclined if centers of growth are located in different levels.

Dome structures of the zone III (fig.4), in contrast to structures of the zone II, are not regular half- spheres but instead they have the shape elongated in the vertical direction. This is, likely, conditioned by vertical upward movement of saturated solutions in the process of structures growth, which caused recrystallization of gypsum.

Within dome structures of the sub-zone IIIb the core, the near-core and peripheral parts are distinguished. The core part has the shape elongated in the vertical direction. The transverse size is normally of 10-50 cm, and the height is of 2-3 m (in the area of Kristal'naya cave - up to 4-5 m). The core part is composed with microcrystalline gypsum, with grain size of 0.5 to 3 mm. Such gypsum is, perhaps, a relict of primary non-recrystallized or low-recrystallized gypsum. In the very top of the core of the structures a monocrystal of transparent selenite gypsum usually occurs, light-brown in color. Selenite monocrystals in the sub-zone IIIb occur not only in the

№№	Cave name	Parameters of caves					Parameters of cave fields				
		Development, *m*	Amplitude, *m*	Area, *thsnd* m^2	Volume, *thsnd* m^3	Specific volume (midel) $m^3\ m^2$	Area, *thsnd* m^2	Volume of block, *thsnd* m^3	Coefficients of karstification: *Density of passages, km km*^{2}	Of the area	Of the volume
	Podolsky region										
1	Optimisticheskaya	188000	18	240	495	2.6	630	11340	298	0.38	0.04
2	Ozernaya	111000	18	330	665	6	640	11520	173	0.51	0.06
3	Mlynki	24000	12	47	80	3.3	195	2340	123	0.24	0.03
4	Kristalnaya	22000	12	38	110	5	137	1640	161	0.28	0.07
5	Slavka	9100	15	19	34	3.8	77	1155	118	0.24	0.03
6	Verteba	7820	10	23	47	6	38	380	206	0.61	0.12
7	Atlantida	2525	19	4.5	11.4	4.5	15	285	168	0.3	0.04
8	Ugryn	2120	10	4	8	3.8	11	110	193	0.36	0.07
9	Jubilejnaja	1500	20	2	3.5	2.3	5.4	81	277	0.37	0.04
10	Komsomolskaya	1244	10	1.7	2.6	2.1	10	100	124	0.17	0.03
11	Dzhurinskaya	1135	15	1.6	2.7	2.3	9	117	126	0.18	0.02
	Bukovinsky region										
12	Zolushka	89500	30	305	712	8	430	12900	208	0.71	0.06
13	Bukovinka	2408	12	4.3	6	2.5	7.5	135	321	0.57	0.04
14	Gostry Govdy	2000	10	1.3	3.3	1.6	7.4	74	272	0.27	0.04
Totals		464352	-	1021.4	2180.5	-	-	-	-	-	
Avereges		-	-	-	-	3.84	-	-	198	0.37	0.05

Table 1. Parameters of large caves and cave fields
Tabla 1.Parámetros relativos a las grandes cavidades y la superficie y volumen ocupados

cores of the structures, but also along the boundaries which divide structures. In other zones pockets and veins of selenite are usually related to old (pre-speleogenic) fissures or tectonic faults. The near-core part of dome structures has the diameter of 1.5 to 2 m and is represented by alternating concenters of 1 to 15 cm in thickness, composed with micro- and macrocrystalline gypsum. In the parts immediately adjoining the structure core, a corrugation of some thin concenters occurs. In the macrocrystalline concenters uncomplete recrystallization of gypsum is exhibited; large tabular crystals are "cemented" by microcrystalline mass. Towards periphery, the microcrystalline concenters disappear, and in the macrocrystalline concenters a share of microcrystalline mass diminishes.

The peripheral part of a structure is also concentric. Concenters are composed here with giant, often curved, sabre-like and feather-like crystals of brown-colored gypsum, with the length of individual crystals ranging from 0.2 to 1.5 m. There is a tendency of increasing crystals size from the core of the structures toward their periphery.

As primary gypsum containing clay impurities recrystallizes clay is squeezing out into the zones of structures junction, as well as into inter-concenters space and space between tabular and sabre-like crystals. This is expressed most clearly in the east section of Optimisticheskaya cave. As this take place, clear and sharp dividing boundaries form. Argilo-carbonate mass squeezed out into the inter-concenters space, restricts the growth of gypsum crystals, so that their size (and the thickness of concentres) does not exceed 20-30 cm. In case of recrystallization of pure gypsum, dividing boundaries are not clearly expressed, as gypsum crystals of neighboring structures intergrow. In the upper parts of dome structures, where concentres are of greatest diameter and lie almost horizontally, dividing boundaries are not clearly expressed too. In recrystallized pure gypsum crystals are not restricted in their growth, so that the thickness of concentres reaches it's maximum values (up to 1.5 m).

The above lithological and textural differentiation of the gypsum stratum is distinct in most of the territory of the Podolsky sub-region. In some areas differences between the lower and middle parts of the stratum are not so clearly expressed, so that one can speak about two-units construction of the stratum, with crypto- and microcrystalline varieties in the lower part, and macro- and giantocrystalline gypsum in the upper part.

In the eastern part of the Podolsky sub-region, in the area of Atlantida cave, the gypsum stratum has different composition. In it's lower part bedded microcrystalline gypsum prevails, with inclusions of macrocrystalline varieties and argilo-carbonate material. The upper part of the stratum is composed with massive crypto- and microcrystalline rock.

The construction of the gypsum stratum changes also in the south-southwest direction, toward the pre-Carpathian foredeep. In this direction the stratum becomes more and more homogenous, transitions between the zones become more and more gradual. In the area near Prut river the three-units construction of the stratum is not expressed at all; in the areas of Zolushka and Bukovinka caves the whole stratum is composed mainly with crypto- and microcrystalline gypsum. In the middle part of the stratum bedding is characteristic; in the upper part pockets of large selenite monocrystals occur.

GENERAL CHARACTERISTIC OF THE LARGE GYPSUM CAVES OF THE WESTERN UKRAINE

Of 14 known large caves of the region (those caves having development exceeding 1 km), 11 are located north of the Dniester valley, within the Podol-

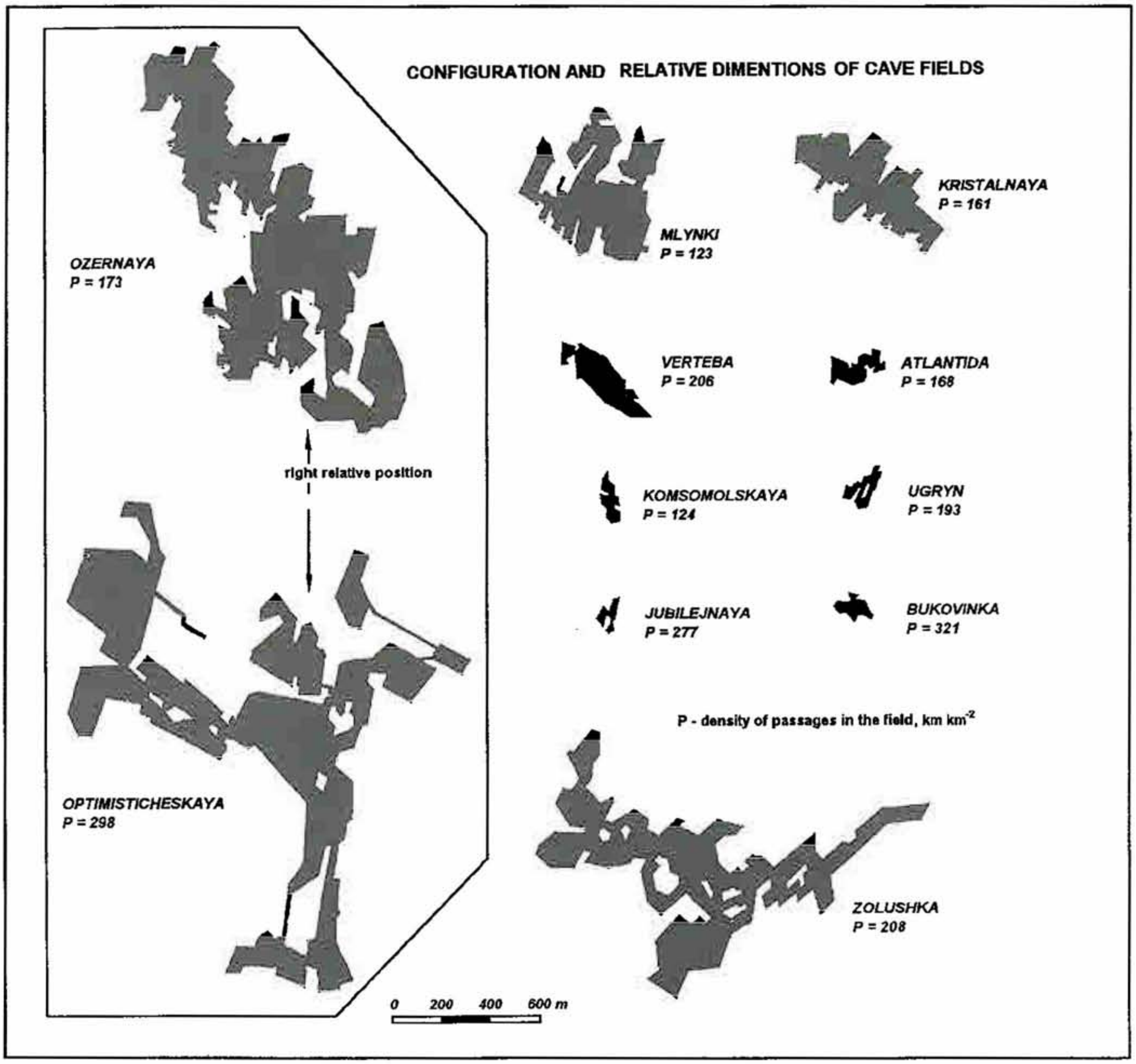


Figure 6. Configurations and relative dimentions of some cave fields. All contours are pictured in the same scale. The right relative position of Optimisticheskaya and Ozernaya caves is saved

Figura 6. Configuración y dimensiones relativas de algunos sectores de cavidades. Todos los contornos se han dibujado a la misma escala. La posición realativa de las cavidades Optimisticheskaya y Ozernaya se ha conservado

sky sub-region. Of them 9 caves are located within the narrow belt stretching sub-parallel to the Dniester valley (fig.5). Two caves (Mlynki and Ugryn') drop out of this belt, and are located some 15-20 km to the north. All these caves are situated now under conditions of the fully drained gypsum stratum, as well as one more cave, Gostry Govdy, recently discovered on the right bank of Dniester. Two other large caves, Zolushka and Bukovinka, are situated in the Bukovinsky subregion, near Prut river, in the area of artesian flow in the Miocene aquifer, but within the azonal area of the most uplifted blocks, where the upper part of the gypsum stratum is entrenched and drained by the valley (see the block 47 on the fig.7). Because of this, the water table conditions in the gypsum stratum occur in this area.

All the large gypsum caves in the region are mazes developed along networks of vertical and steeply inclined joints. Aggregating passages form lateral two to four storey systems which occupy areas of up to 0.7 km^2.

From data of cave surveys various morphometric parameters are derived, giving quantitative characteristic of a whole cave, or it's certain regions. The main morphometric parameters for the large gypsum caves of the region are given in the table 1. This table also contains some parameters of the cave fields and of their karstification.

The area of a cave field is the area of a polygon which includes contours of mapped passages networks, with the exception of integral internal non-karstified areas, if present. The volume of a cave block is determined by the area of a cave field multiplied to an average thickness of the gypsum stratum, because of cave systems develop through whole vertical dimension of the stratum.

The absolute parameters of cave systems and their fields are subjects of change, depending on exploration efforts; they constantly grow in the course of speleological explorations. The length of the aggregated systems of passages in the study region amounts tens and first hundreds of km, and the area of the cave fields reaches tens and hundreds (up to 640) of thousands of m^2.

Specific parameters are more informative. Specific volume (midel) of a cave characterizes "largeness" 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 per linear meter; in the average for the region specific volume is of 3.84 m^3/m. No regularities in variations of this parameter through the region are found; it is controlled by local conditions of speleogenesis.

It is convenient to characterize the density of passages networks by the ratio of a cave length to an area unit 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 density of passages networks does not display regional trends too. It is shown in the chapter 4 that the density of passages networks is determined by the density of speleo-initiating jointing.

The coefficient of area karstification of the gypsum stratum vary from 17% (Komso- mol'skaya cave) to 7496 (Zolushka cave). High values are inherent in the fields of Verteba cave (6196), Bukovinka cave (5796), Ozernaya cave (5196). The average value is of 37%. The coefficient of volume karstification vary from 3% (caves Mlynki, Slavka, Komsomol'skaya cave) to 12% (Verteba cave) whilst the average value is of 5%.

Figure 6 shows relative sizes and configuration of the cave fields. It is evident that cave networks often form elongated figures. Elongated elements correspond rather clearly to directions inherent in the regional tectonic: northwest, northeast, and meridional.

STRUCTURAL PREREQUISITES OF SPELEOGENESIS AND THEIR REALIZATION

Tectonic faults, block and microblock structures

The Neogene succession within the platform outskirt is broken into blocks by numerous faults of different orders. In the interiors of the platform outskirts (the Podolsky sub-region) faults of northwest, northeast and meridional orientation separate numerous blocks of various shapes, with cross-dimensions of 2 to 6 km, and with displacements between adjoining blocks varying from 5 to 15 m (Klimchouk et al., 1983, 1985). Towards the foredeep, the block mosaic construction alters to the block-step plunging of the gypsum stratum; as this takes place, amplitude of displacements and thickness of clay cover increases (Andrejchouk, Kunitsa, 1985; Andrejchouk, 1984, 1988; see also fig. 7).

Within cave fields the gypsum stratum is divided by lesser tectonic faults into some microblocks, usually without displacement, or with displacements within first meters. Such faults can be mapped and are indicated in caves by zones of destruction, brecciation or recrystallization, linear zones of breakdowns and injections of overlying rocks, or by large joints dissecting the whole gypsum stratum. Slickensides are observed sometimes. Carbonate flowstones and chalcedoni mineralization often occurs in the zones of faults.

Hydro-levelling of the marking bentonitic layer through the field of Optimisticheskaya cave in different directions has allowed to reveal the structure of the gypsum stratum within the tectonic block, amplitude of the stratum dis-

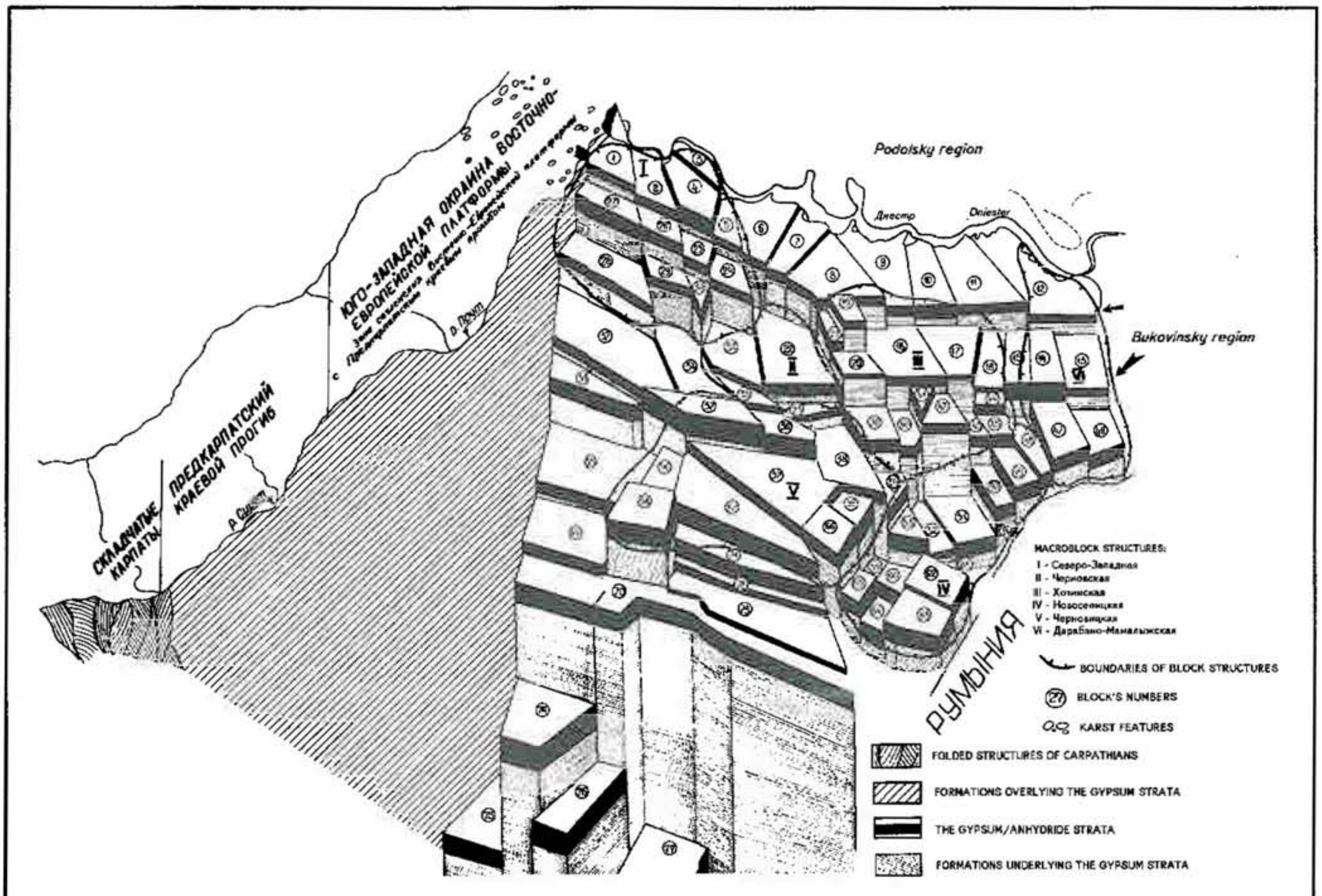


Figure 7. Block structures in the Bukovinsky region (Andrejchouk, 1988)

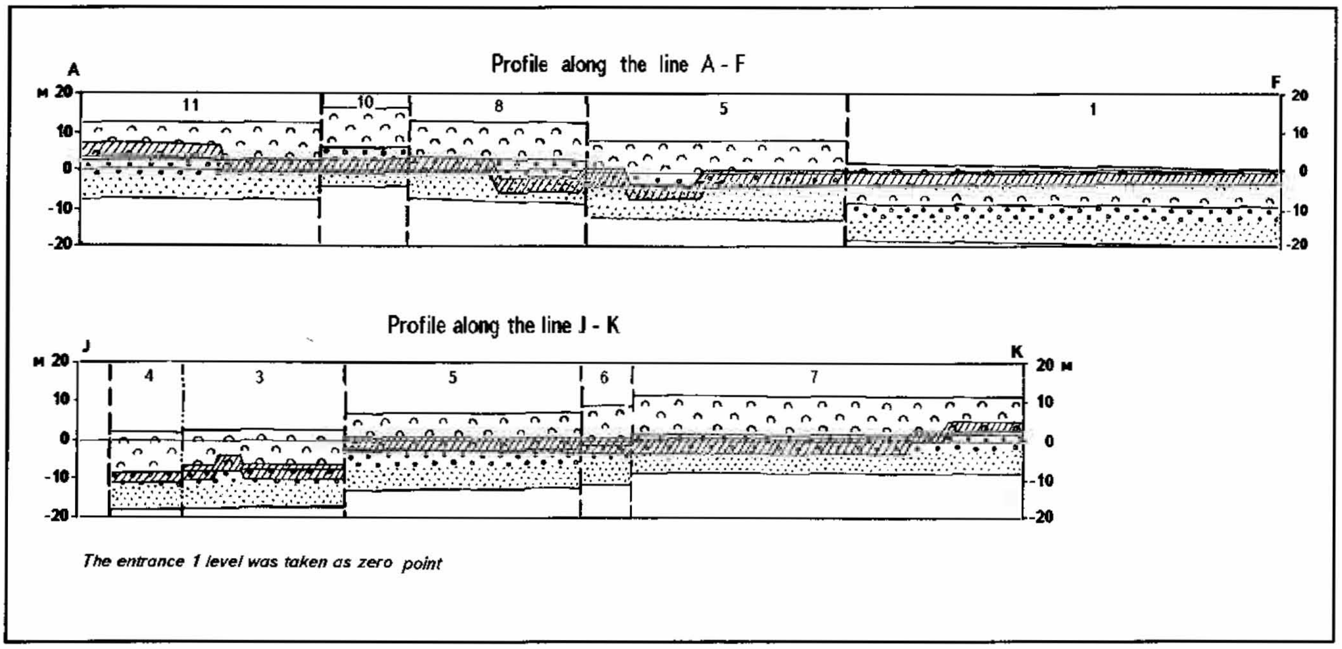


Figure 8. The profile of the gypsum stratum across the field of Optimisticheskaya. For key and psoition lines see fig. 14

Figura 8. Perfil del estrato yesífero a lo largo del área de la cavidad Optimisticheskaya. Para la leyenda y posición de los perfiles véase la figura 14

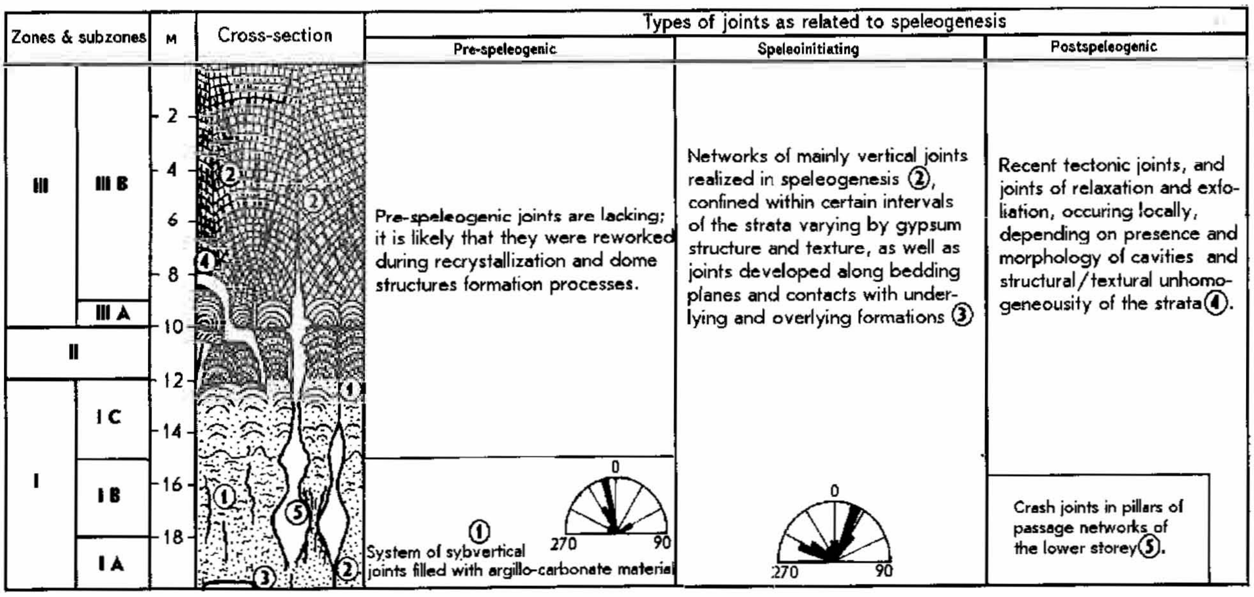


Figure 9. Types of joints as related to speleogenesis (on the example of Optimisticheskaya cave)

Figura 9. Tipos de fracturas y su relación con la espeleogénesis de la cavidad Optimisticheskaya

placement in the zones of faults (fig.8). The largest displacement is found between microblocks Ozerny and Zaozerny, Tsentral'ny and Svezhaya Voda (4-6 m). Displacements along other faults do not exceed of 1-2 m. Generally, there is a tendency to submerging of the gypsum stratum from the south to the north, and from the west to the east.

Tectonic faults are of different ages. In the Optimisticheskaya cave the oldest fault is, likely, the one bordering the Svezhaya Voda region to the southwest. It is represented by the zone of destruction composed with boulder breccia, cemented with argilo-carbonate material. Boulders are sized up to 1 m and represented by macrocrystalline gypsum. This fault had formed prior to the formation of speleo-initiating jointing, which is indicated by passages crossing this fault zone. Besides the above paleo-fault of 50° orientation, in some places of the cave the zones of minor old faults are found, expressed by veins of recrystallized gypsum. Their orientation is 70°, 315°, 350°. Other microblock faults had been forming during the period of active formation of speleo-initiating jointing. They are oriented 20-30° and 120-130°, less frequently 90°-100°.

Microblocks are usually of quadrangular shape, with length of sides of 300 to 500 m. Each of them contains the region of the cave with peculiar orientation and morphology of speleoforms developed on each of storeys present (if the above characteristics are compared between cavities of the corresponding storey that are developed in different regions; distinctions between cavities of different storeys are always essential, even within the same region). Within a cave region the distribu-

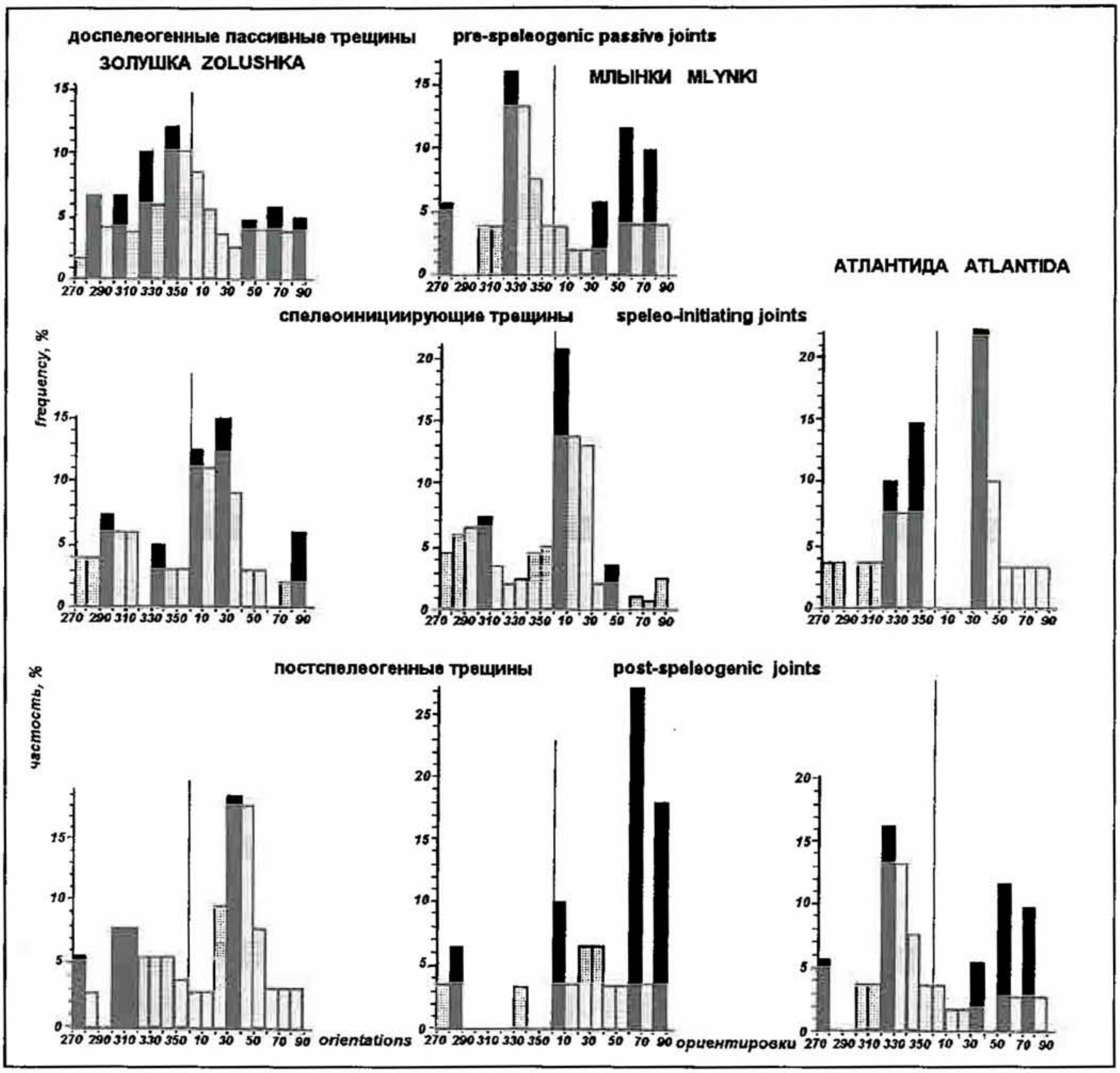


Figure 10. Orientations diagrams of joints of different generations in some cave blocks
Figura 10. Diagramas de orientación de fracturas de distintas generaciones en algunas cavidades

tion of passages (joints) is rather homogenous, and parameters of networks of each storey are quite stable in the lateral direction.

Diversity of age of joints in the gypsum stratum

Jointing within microblocks is one of the main factor controlling speleogenesis. It is important to underline that networks of joints in the gypsum are composed with elements of diverse ages. For the purposes of speleogenetic analysis, three main generations can be distinguished among joints occurring in the gypsum (Klimchouk, Rogozhnikov, 1982a; 1982b):

1) Pre-speleogenic passive joints: those formed prior to the period of speleogenesis, and by that time yet filled with lithified argilo-carbonate material. Such joints did not show hydrogeological activity later on; they are indicated by "ribs" and partitions projecting from the walls of passages.

2) Speleo-initiating joints: those hydrogeologically active during the main phase of speleogenesis, and reworked into passages due to dissolution action of moving waters. Markings of such joints are always can be seen along the axis of speleoforms, and in blind ends of passages. The networks of speleo-initiating joints are "displayed" by the maps of the maze caves of the region.

3) Post-speleogenic joints: those formed after the end of the main phase of speleogenesis; they are indicated by sharp "recent" edges at the points of their intersections with dissolution surfaces. Such joints are usually gaping, with openings up to 10-15 cm. Post-speleogenic joints are often novels, but it is not rare that they inherit speleo-initiating joints, which become gaping at this.

The mapping of jointing in the gypsum stratum using this classification, performed in some caves of the region (Atlantida, Dzhurinskaya, Zolushka, Mlynki, Ozernaya, Optimisticheskaya), as well as analysis of the structure of cave systems in the plan and vertical views, allows to consider in details features of joints of different generations, and to reveal their role in speleogenesis (fig.9). Below, pre-speleogenic and

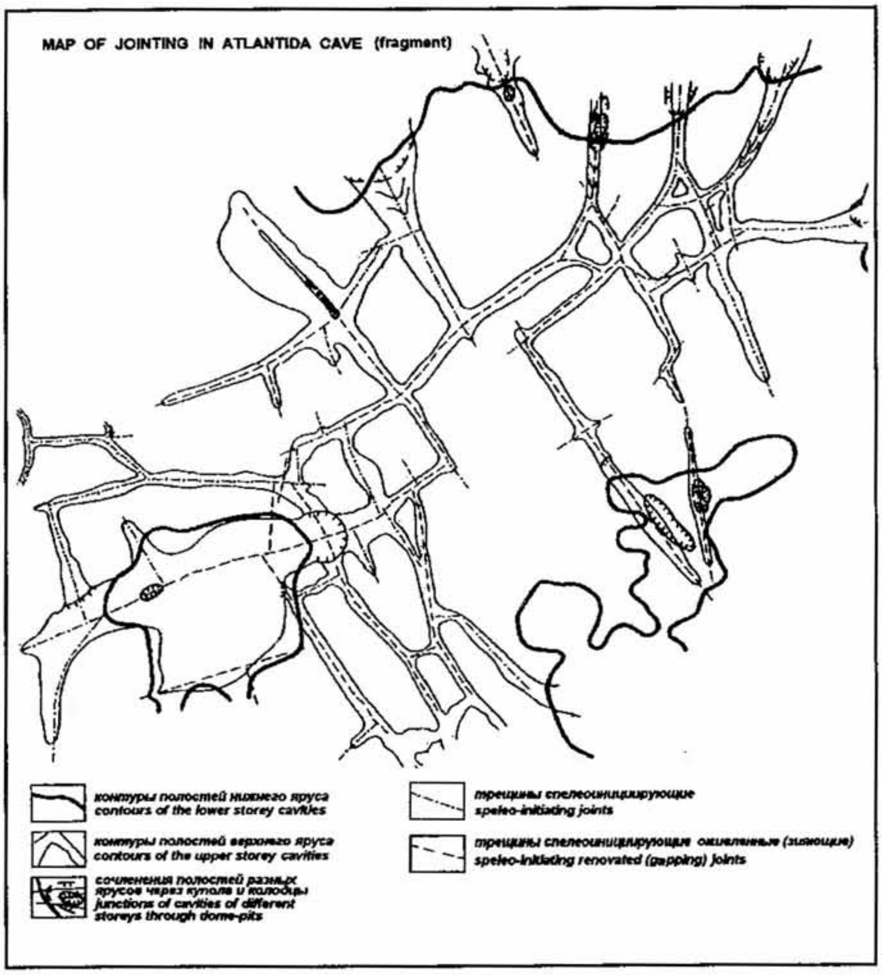


Figure 11. Jointing control upon occurence of passages of the upper storey in Atlantida Cave

Figura 11. Control de la fracturación sobre la localización de galerías en el nivel superior de la cueva Atlantida

post-speleogenic jointing is characterized briefly; a consideration of speleo-initiating jointing, immediately controlling the structure of cave systems, is given in the next section.

Pre-speleogenic passive joints are found in many caves of the Podolsky sub-region (Atlantida, Mlynki, Ozernaya, Optimisticheskaya, Slavka, and others) where they form "ribs" of lithified filling, projected from the walls of passages into cavities. They are most clearly expressed in the Bukovinsky sub-region (Zolushka cave), where such "ribs" are abundant and large, often completely partitioning off passages (so called "wings").

Pre-speleogenic jointing in the caves of Podolia occurs predominantly in the lower part of the stratum (the sub-zones Ia and Ib). The surface of the walls of joints is irregular. The openings are normally 0,5 to 5 cm wide, but swells are frequent. This is interpreted either as a result of dissolution action during hypothetical old phase of karstification, or as a result of deformations due to recrystallization of gypsum.

Orientations distribution of the of pre-speleogenic joints networks has been studied in Atlantida, Mlynki and Zolushka caves. The diagrams show polymodal distribution (fig.10), which differs considerably from that of joints of later generations. Similar peaks of orientations of pre-speleogenic joints (340-350° and 70-80°) are inherent in for Optimisticheskaya cave as well.

Pre-speleogenic joints constitute the earliest generation of jointing in the gypsum stratum, which had been formed, likely, during Late Badenian. During Kosovsky and Early Sarmatian time these joints were filled with argilo-carbonaceous material, and were not hydrogeologically active later on. However, it is likely that pre-speleogenic joints have played an important role controlling the processes of recrystallization of gypsum, being preferential paths for migration of interstitial water, pressed out from the rock.

The predominance of joints of NW and NNW orientation among pre-speleogenic joints is in agreement with their old age and indicates an activity of faults of northwest orientation during Late Badenian - Early Sarmatian. This is also supported by the fact that quantity and width of pre-speleogenic joints increases considerably from the caves of Podolsky sub-region to the caves of Bukovina, so - from the platform internals toward the foredeep.

Post-speleogenic ("recent") joints are spread in all the caves of the region. They practically have not been touched by dissolution processes. The study of their relations with dissolution surfaces and secondary deposits in the caves has allowed to state that post-speleogenic joints have diverse age, yet within post-speleogenic period (Klimchouk, Rogozhnikov, 1982a, 1982b). These joints differ also by their genesis: they can be resulted by the late neotectonic activity, or be of gravitational genesis (joints of relaxation, crush joints, etc.). Neotectonic joints, formed due to tectonic stresses after Middle Pleistocene (after the ending of the period of active speleogenesis), are common in Mlynki and Atlantida caves, but they are rare in Optimisticheskaya cave. Orientations diagrams of such joints show polymodal distribution. Some peaks are inherited from the earlier generations, but the novels peaks appear at the directions poorly represented, or absent at all, on the diagrams of joints of older generations . It is characteristic, that in the caves of the Podolsky sub-region the orientations diagrams of post-speleogenic joints show rather clearly the sub-latitudinal and sub-meridional directions, while these directions are poorly represented in the earlier generations.

Gravitational joints are present in all caves, but they tend to focus on certain areas. In the Optimistic cave, for instance, relaxation joints are developed predominantly in the lower part of the stratum. In the upper part they form mainly along the inter-concenters surfaces of dome structures. Crush joints are characteristic in the pillars between passages of the lower storey. Pressure of above-situated rock cause deformation of the thin pillars, their crashing and destruction. The phenomena of the pillars crashing is observed in the lower part of the stratum only (in the zone of homogenous microcrystalline gypsum).

Speleo-initiating jointing and the structure of cave systems

Speleo-initiating jointing is of particular interest, as it determines development of cave systems and their patterns. In the region, the spatial structure of cave systems is fully controlled with the structure of speleo-initiating jointing of the gypsum stratum. As it

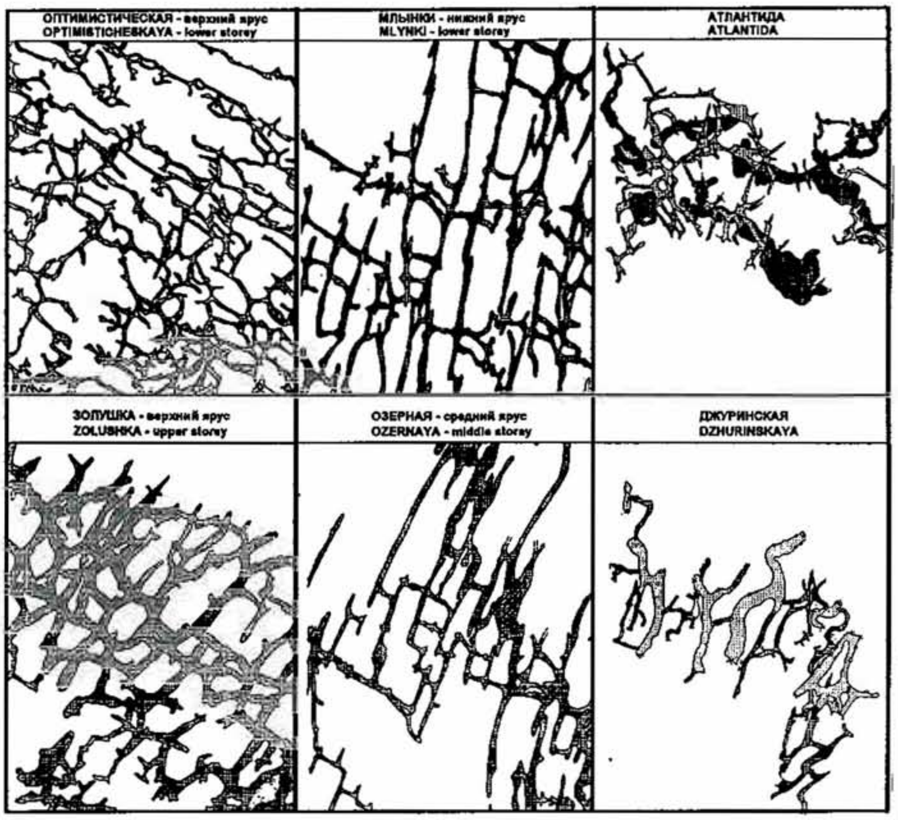


Figure 12. Different patterns of passage networks in caves of the Western Ukraine. All maps are pictures in the same scale
Figura 12.Diferentes modelos de redes de galerías en las cavidades de Ucrania del Oeste. Todos los mapas se han dibujado a la misma escala

was noted above, the joints networks are "displayed" by the cave maps, so that it is proper using the cave maps for studying speleo-initiating jointing. In order to assess a correctness of such a substitution of the objects, the jointing survey has been performed on the large-scale (1:100 - 1:200) maps of the certain caves. Analysis of the maps (fig.11) has shown, that parameters of passages and passage networks obtained from cave maps, such as passages lengths, distances between passages in the set (or, the frequency of passages of the same orientation), orientation, the shape of between-joints polygons, the type of networks, the network connectivity, the number of beams in the joints intersection, in general characterize adequately the corresponding properties of speleo-initiating joints and their networks. However, a consistency between speleoforms and joints is complicated in large rooms and galleries with considerable gravitational reworking of the morphology: such speleoforms are usually a combination of several passages. When using cave maps to obtain jointing parameters, such areas are to be excluded from the analysis. Some other uncertainties and inconsistencies resulting from the above substitution of the objects will be noticed below. To avoid repeating, in further consideration we will mean speleo-initiating joints when using the term "joints", unless otherwise specified.

Even the brief consideration of the maps of the caves of the region demonstrates the diversity of types of passage (joint) networks and their characteristics (fig.12). In the works by V.N. Dubljansky et al. (1969, 1980) and I.D. Gofshtain (1979) the distinctions in the characteristics of passage networks between certain large caves were interpreted as the sign of their occurrence in different tectonic blocks. Later on, further exploration has considerably enlarged the areas of the cave fields, and it became evident that significant diversity exist of characteristics of passage networks between regions (areas) of a single large cave systems which occur within a single block.

It has proved to be the most important point for understanding of distinctions in the networks characteristics the recognition of the fact that the joint networks and the cave storeys are confined to the certain constant intervals within the gypsum stratum, corresponding to the different lithological/textural horizons (Klimchouk, Rogozhnikov, 1982; Klimchouk, 1986; Klimchouk, Andrejchouk, 1988). At this, joints (passages) of the certain storeys form largely independent networks with quite distinct parameters. The storey differentiation of the passages (joints) networks of different types, and that of corresponding areas of the large cave systems, is expressed more or less in all the caves of the region; this is considered in details in the next section.

Vertical (storey) differentiation of joint and passage networks

Multy-storey structure of cave systems

It is found that in the most cases joints in the gypsum do not dissect the whole vertical thickness of the stratum, but are confined within certain intervals corresponding to certain lithological/textural horizons (zones). This is the main cause of the storey structure of the cave systems (Klimchouk, 1986, 1992; Klimchouk & Andrejchouk, 1988).

One of the authors has conducted special inspection of jointing on the areas of the cave fields where passages of different storeys are superimposed, and where a survey is available precise enough to enable identification of the points of passages superposition. At the places of passages superposition no trace can be normally found of speleo-initiating joint which control an occurrence of the contiguous storey. Only in rare cases passages of contiguous storeys are controlled by the same single joint propagating though several lithological/textural zones. The exceptions are also the cases where speleo-initiating joints experienced a post-speleogenic revival, or novel post-speleogenic joints were formed.

The recognition of storey differentiation of cave regions and areas in the most of the large caves has allowed to interpret obvious differences in morphology and characteristics of passages (joints) networks as the result of their development in the different lithological/textural horizons of the gypsum stratum.

In the comparatively small caves, for which the high-grade surveys and altitudes of passages floor and ceiling are available, the storey structure can be easily revealed from the cave maps (Atlantida, Dzhurinskaya). In the large cave systems with extensive lateral development, usual cave maps do not allow identifying storeys of passages in different parts of a system. Obvious morphological differences between passages developed on different storeys were previously interpreted as between-regions differences (Dubljansky, Lomaev, 1980; Savchin, Gunjovsky,

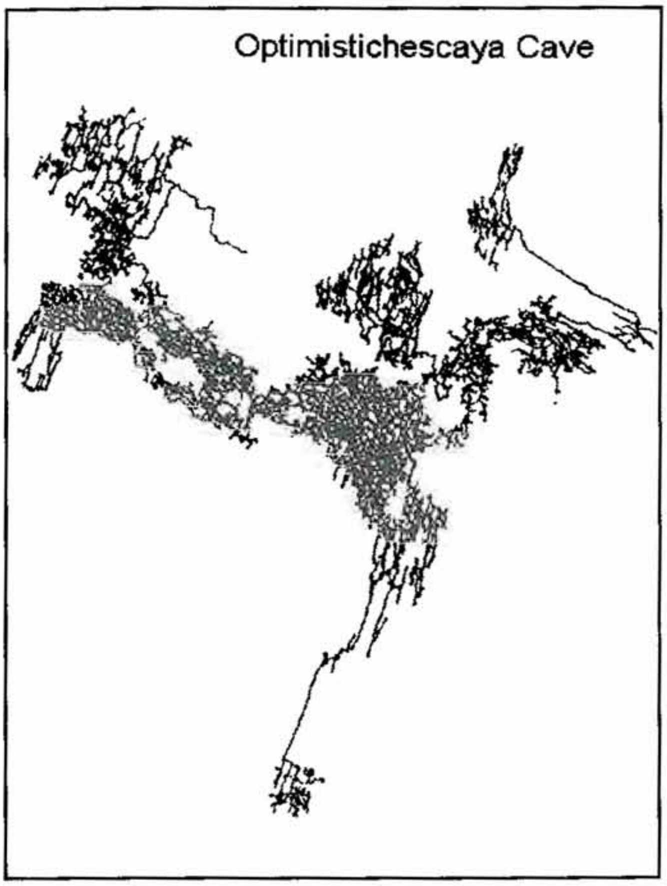


Figure 13. Optimisticheskaya cave. Survey was provided in 1966-1990 by the Lvov Speleo-Club. Some regions explored in 1990-1994 are lacking in the plane
Figura 13. Cavidad Optimisticheskaya. La exploración se realizó entre 1966 y 1990 por el Espeleo-Club de Lvov. Algunas zonas exploradas durante 1990-1994 no aparecen en el mapa

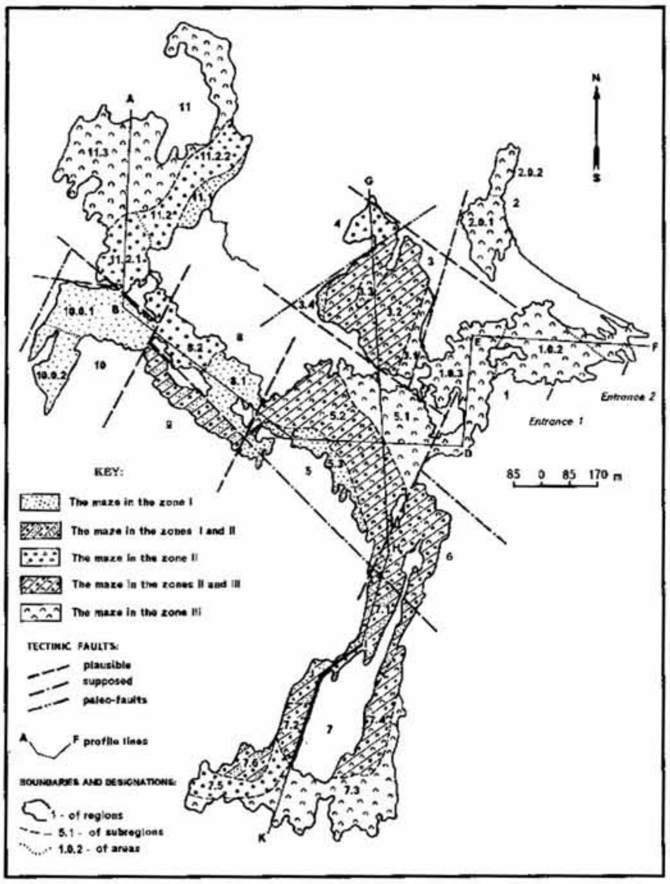


Figure 14. Scheme of microblock/storey differentation and morphological regionalization of Optimisticheskaya cave
Figura 14.Esquema de diferenciación en microbloques/niveles y regionalización morfológica de la cavidad Optimisticheskaya

1970; Savchin, Kachkovsky, 1971, and others).

In order to reveal vertical differentiation of passages networks in the large and complicated cave system, the high-grade hydro-levelling have been performed in Optimisticheskaya cave, during which the altitudes of passages and contacts between different lithological/textural horizons of the gypsum stratum were carefully controlled. Particular attention have been paid to the bentonitic layer of 1 to 10 cm in thickness, which divides the middle and upper parts of the gypsum stratum. This layer is universally spread within the cave field and can be identified as the marking layer (see chapter 2). The profiles have been made through the whole cave field, from the east to the west, and from the north to the south.

It was found that the marking layer and boundaries between the lithological/textural horizons of the gypsum stratum are quite steady within tectonic microblocks; vertical range within 1 m is related to post-sedimentation deformations during recrystallization of the gypsum stratum. The passages storeys are steady as well, and strictly confined within certain lithological/textural horizons of the stratum. Thus, it has proved to be appropriate using the lithological/textural criterion and the marking layer for the storey identification during morphogenetic survey, even without continuous levelling of passages. Such an opportunity is especially valuable in case of extensive cave systems.

The morphogenetic survey, performed in some caves continuously (Atlantida, Dzhurinskaya, Optimisticheskaya) or in parts (Ozernaya, Mlynki, Zolushka) has clearly demonstrated the storey differentiation of the passages networks.

Cavities occurring on a certain storey, can form networks well connected laterally on their own storey through a considerable area, but can remain isolated having no lateral connection with each other. In some cases two or even three storeys of cavities are developed through the same area, resulting a superposition of networks, but more frequently they are developed on the adjoining areas, being laterally connected along the common contour. This is inherent in the large cave systems of the Podolsky region (Optimisticheskaya, Ozernaya, Mlynki).

Let us consider in details variants of relationship of passages of different storeys.

Optimisticheskaya cave (fig.13). In this largest and most complicated cave system three main storeys of passages are distinguished, each confined to different lithological/textural horizon, or zone, of the gypsum stratum. Figure 14 demonstrates the scheme of the storey differentiation of passages networks for the whole cave field. Most frequently passages of only one storey are developed within the certain area, and at this, networks of the adjacent storeys (so, of the adjacent areas) are connected along the common contour in a plan view. However, there are areas where networks of two adjacent storeys are developed together, being superimposed. Networks of the each storey are largely independent, being connected with each other in some, but far from every points of superposition of linear speleoforms in a plan view. There are considerable distinctions in the structures of passages networks developed on different storeys, as well as distinctions in morphology of cavities.

Ozernaya cave (fig.15). The gypsum stratum here is also consist of three units, that is most typical for the Podol-

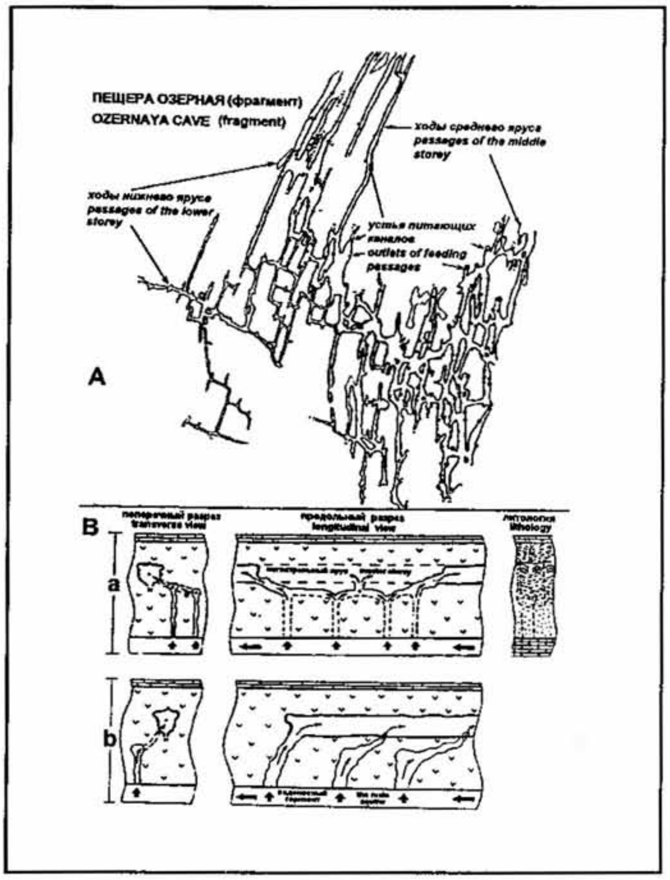


Figure 15. Ozernaya cave. Survey was provided in 1968-1988 by the Ternopol'Speleo-Club

Figura 15.Cueva Ozernaya. La exploración se realizó entre 1968 y 1988 por el Espeleo-Club de Ternopol

Figure 16. A- The part of morphogenetic map of Ozaernaya cave; B- the model of formation of the cave; a) the case of interconnected local network of the lower storey, feeding master network; b) the case of separate feeding cavitiesof the lower storey. (Klimchouk, 1992)

Figura 16. A- Mapa morfogenético parcial de la cavidad Ozernaya; B- modelo de formación de la cavidad; a) en el caso de redes locales interconectadas del nivel inferior, alimentando la red principal; b) en el caso de alimentación de cavidades separadas del nivel inferior

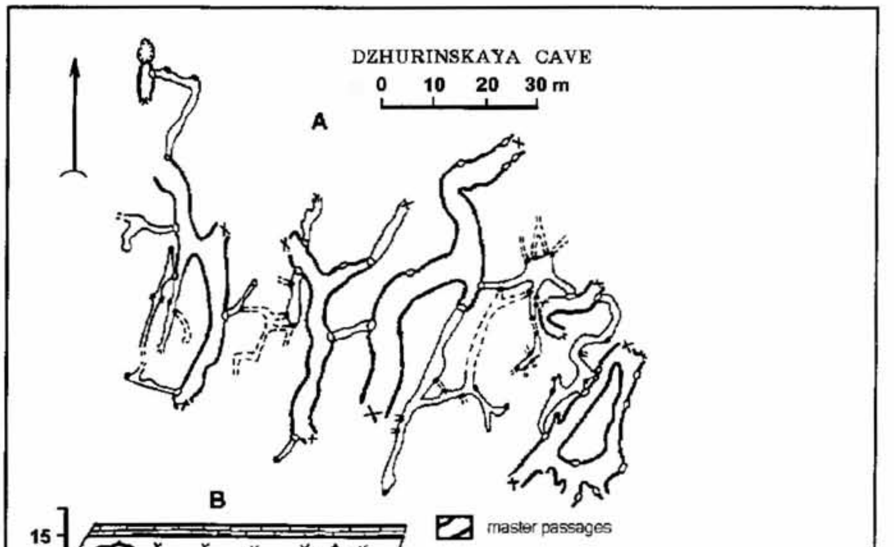


Figure 17. Dzhurinskaya cave. A- plan; B- shematic profile showing the relationship between cavities of the different storeys

Figura 17. Cueva Dzhurinskaya. A- planta, B- perfil esquemático mostrando las relaciones entre cavidades de disitintos niveles

sky region. The overhelming majority of passages in the cave is developed in the middle part of the gypsum stratum, immediately beneath the marking clay layer, forming extensive regions of the maze. Such regions are separated whether by tectonic faults, being connected by single passages on the same level, or by local passages networks of the lower storey.

Cavities of the lower storey are represented whether by separated conduits of an "ascending" morphology, or by local networks of narrow passages. In the first case, separated conduits may be inclined or pit-shaped forms, ascending from the bottom of the stratum and attached to the side or to the end of an above situated master passage (fig.16-B-b). Such conduits are often filled with clay sediments, same as those filling the lower section of master passages, but they can be easily recognized by presence of characteristic outlets in form of a shell or mini-crater, at the points of conduits connections with master passages. Morphogenetic mapping has shown that there are thousands of such outlets distributed

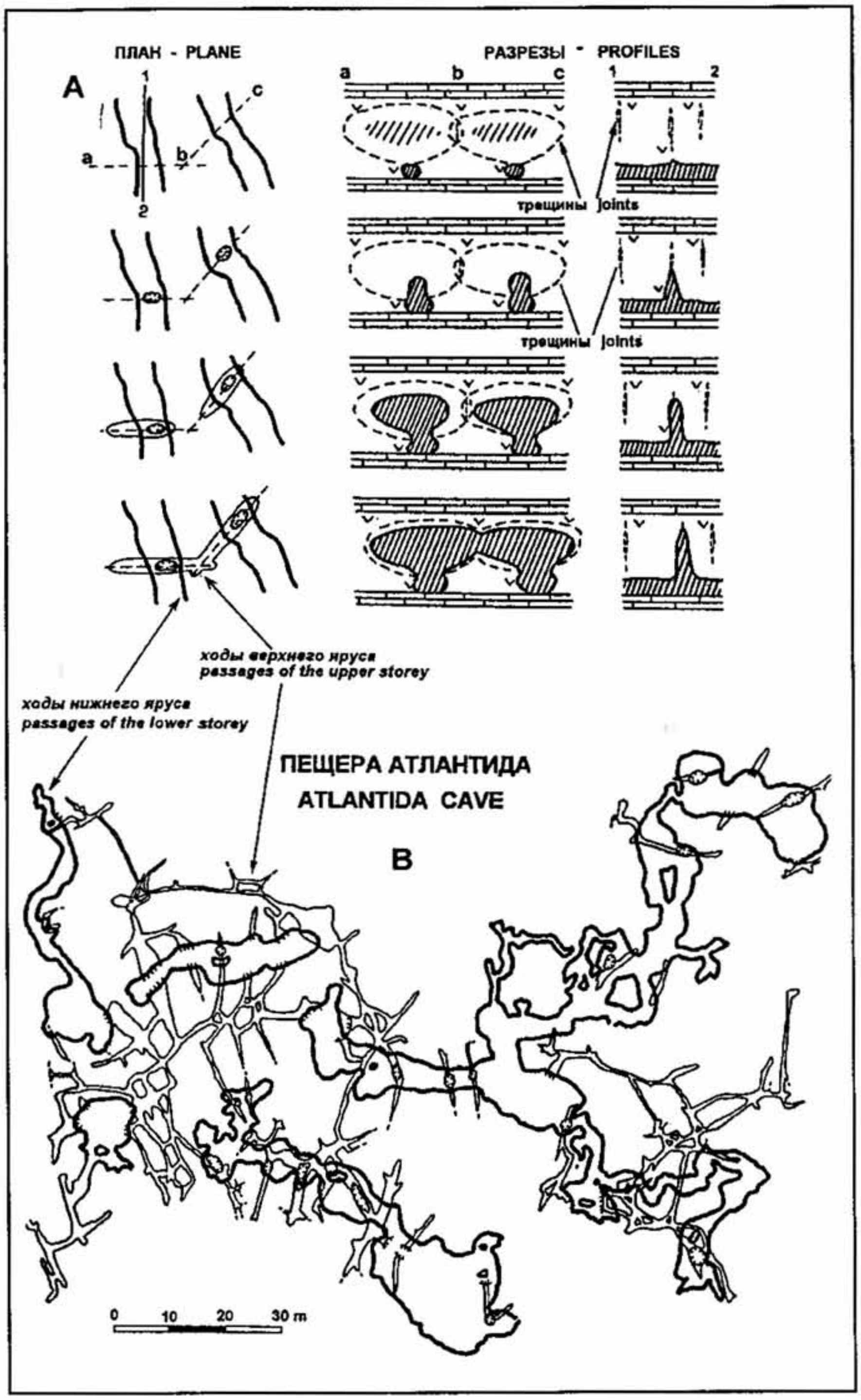


Figure 18. Atlantida cave and the model of development of the upper storey networks (after Klimchouk and Rogozhnikov, 1982)

Figura 18. La cueva de la Atlantida y el modelo de desarrollo de la red del nivel superior. (Klimchouk and Rogozhnikov, 1982)

rather uniformly along the master passages network (fig.16-A).

In the second case, passages of the lower storey form local networks connecting different regions of master passages developed in the middle storey: the "Transitional" region is good example, the part of which can be seen in the southwest corner of the map in figure 16-A.

Passages in the upper storey are poorly developed in the cave, rarely forming small networks. Their morphology indicates confined flow (domes, blind ends, etc.), and some passages reach the bottom of the overlying formation.

Dzhurinskaya cave (fig.17). The gypsum stratum of 12-15 m in thickness has the two-units composition in this area, with crypto- and microcrystalline gypsum in the lower part, and macro- and giantocrystalline gypsum in the upper part. The explored section of the cave represents the part of a large cave system, limited by breakdowns (fig.17). In the upper storey large sub-parallel master passages are developed. Conduits of two subordinated lower storeys are situated between master passages and connect them. Outlets of lower conduits have the characteristic view of a shell at points of their connection with master passages. Subordination of conduits of different storeys is clearly expressed (see profile on the fig.17B).

Atlantida cave. In the area of Atlantida cave the gypsum stratum also has the two-units composition. In it's lower part bedded microcrystalline gypsum prevail, but with frequent inclusions of macrocrystalline gypsum and argilo-carbonate material. Unlike the most of the Podolian territory, the upper part of the stratum is composed here with homogenous crypto- and microcrystalline rock. Transitions between the lower and upper parts of the stratum are gradual.

In the structure of the cave system two storeys are clearly expressed (fig.18). The lower storey is represented by large master passages developed along the lower contact of the stratum, as well as by small systems of low winding passages with complex shapes adjoining to master passages. Conduits of the lower storey were developed as a system of local lateral flow in which larger master passages stand out as result of hydraulic competition (Klimchouk, Rogozhnikov, 1982). Caves of the upper ("transitional") storey have fissure-like of rounded cross sections and clear smooth morphology. They have no continuous connectivity on their own level, and are often represented with isolated conduits, developed laterally in both sides from domepit in the ceiling of master passages , being blind ended. In the areas where master passages lie close to each other, passages of the upper storey form small networks between them providing for passing from one master passage to another.

The morphogenetic analysis provided for Atlantida cave, has allowed, for the first time for the region, to reject the conventional theory of the evolutionary "descending" storey formation, and to suggest the model of the "ascending" formation of the upper storey passages from master galleries (Klimchouk, Rogozhnikov, 1982; fig.18, A). At the points where growing master passages intersected the joints of the next higher level, blind cupolas begun to develop upward along these joints (the case 1 on the fig.19). Within the interval of maximum opening of the upper level joints speleoforms received lateral development in both sides from a dome-

stratum. Uncertainty is due to universally spread clay filling which hide the lower part of the cross section. In some regions, where clay filling is washed out, the middle canjon-like part of the cross section is exposed, with corrugated walls.

It is inherent in Zolushka cave the presence of vertical pits of 3 to 8 m in diameter, and 10 to 23 m in depth, connecting local networks of the lower storey with the maze of the upper storey. If the bottom of such pits is not filled with clay, then windows of the water table is accessible. Above such pits smooth cupolas are usually present, indicating an upward flow from pits. There are about 38 pits within the explored part of the maze.

Cavities of the lower storey are indicated by drilling data, observations in the quarry, by a presence of subsidences in clay filling in the floor of the upper storey passages, and from direct observations. Diving in the pit in the north east section of the cave has revealed a presence of the small network of passages in the lower storey extending for 50-60 m from the base of the pit. It is likely that networks of the lower storey have no continuous development and lateral connectivity on the own level, but they developed isolated, being connected with master passages of the upper storey via pits.

Distinctions in structure of networks of joints and passages developed on different storeys

In the comparatively small caves (Atlantida, Dzhurinskaya) differences in the plan structures of cavities occurring in different storeys are obvious (see fig.17 and 18-B). In the large cave system, where extensive networks are developed in different storeys, distinctions in the networks structure are evidenced in such networks parameters as distribution of orientations, passages length, distances between passages in a set, etc. Apparently, such distinctions are conditioned by peculiarities of the structure of speleo-initiating jointing developed in corresponding intervals of the gypsum stratum. These peculiarities, in turn, are pre-determined by the lithological/textural differentiation of gypsum within the stratum cross section (see chapter 2). Most clearly, the relation between jointing and lithological/textural peculiarities of the stratum are expressed in Optimisticheskaya cave (fig.21). The diagrams on the figure 22 demonstrate distinctions in parameters of passages networks developed in different storeys in Optimisticheskaya cave.

The Vkhodnoy region is developed at the upper storey (zone III), the Svezhaya Voda region consists of two storeys developed in the upper and middle parts of the stratum (zones III and II), the Poltora Saraya region represents the networks of the middle storey (zone II), and the Averbakha and Aljonushka regions represent the networks of the lower storey (zone I). The diagrams demonstrate clear distinctions in the azimuths structure of the networks: in amount of the modal orientations (sets), in orientation of prevailing sets, in distribution of passages by length and orientations. Generally for the whole cave, passages of 2 to 4 m long prevail, but in the lower storey networks their maximum corresponds to the direction of 290-300°, but in the upper storey networks - to the direction of 0-10°.

Within the lower part of the stratum (zone I) the joint network is characterized by rather distinct anisotropy of orientations (with 2 main and 1-2 minor peaks on the diagram), a predominance of 4-beams intersections of passages, quadrangular shape of polygons. Joints are rectilinear, their walls is even (fig. 21).

Within the zone II a character of speleo-initiating jointing is quite different. Under influence of both internal (lithogenetic) and external (tectonic) stresses a rock to splits along the planes, which divide small dome structures occurring here, so that joints formed attain zigzag-like configuration. In fact, such joints consist of several single joints sequentially connected to each other, but 2-beams connections are topologically indistinguishable from joints turns. When taking parameters from cave maps, an orientation of such joints is approximated by a straight line corresponding to the axis of a passage. In this case 4-beams connections of a map usually corresponds to two 3-beams connections of joints. In networks of the middle storey orientations anisotropy is also evident, but yet in lesser extent than that in the zone I.

In the upper part of the gypsum stratum (zone III) composed with giant dome structures, joints form predominantly along the planes that divide structures. The formation of joints is eased by a presence of argilo-carbonate material, pressed out in the process of gypsum recrystallization. In case of firm intergrowth of dome structures, rock can split not necessarily along the dividing planes, but often across the structure. Sometimes, the structures are split from the center to periphery.

When joints develops along the plains dividing dome structures, a joints network forms for which following features are characteristic: 5-6-angular shape of polygons, predominance of 3-beams connections, an absence of clearly expressed main orientations (prominent peaks on diagrams, - fig.21). Such features are inherent in networks of lithogenetic joints.

Type of a joints (passages) network is the most general characteristic (Rats, Tchernyshev, 1970; Tchernyshev, 1983). Analysis of cave maps and the description of networks given above shows that studied networks fall into the intervening type between two classes: of systematic and polygonal networks. In Optimisticheskaya cave prominent sets are most clearly expressed in networks of the lower storey, in lesser extent but still rather clear - in networks of the middle storey. Expressed systematic networks (those with few prominent sets of orientations) are characteristic of neighboring Ozernaya cave, where they are developed in the middle storey (zone II). Two sets are sharply predominant here. Verteba cave and those regions of Optimisticheskaya cave that are developed in the upper storey (in the zone III), are examples of polygonal networks. In many other cases networks have an intervening character well corresponding to the special type of "systematic polygonal networks" distinguished by M.V.Ratz and S.N.Tchernyshev (1970).

Morphology of cavities of different storeys

Jointing of the gypsum, spatial distribution of joints, and lithological/textural peculiarities of the rock pre-determine not only the structure of cave systems, but features of meso-morphology of cavities as well (Demedjuk, 1982; Klimchouk, Rogozhnikov, 1982; Klimchouk, 1986; Demedjuk et al., 1988; Klimchouk, Andrejchouk, 1988). Peculiarities of occurrence of cavities and of their morphology are characterized below with the example of Optimisticheskaya cave, where influence of lithological/textural factor is most prominent (fig.23).

In the upper part of the gypsum stratum (sub-zone IIIb), which is composed with giant dome structures, cavities most commonly occur along joints following the planes dividing the structures. Such passages usually have fissure-like and triangular (7, 15)2 section, less

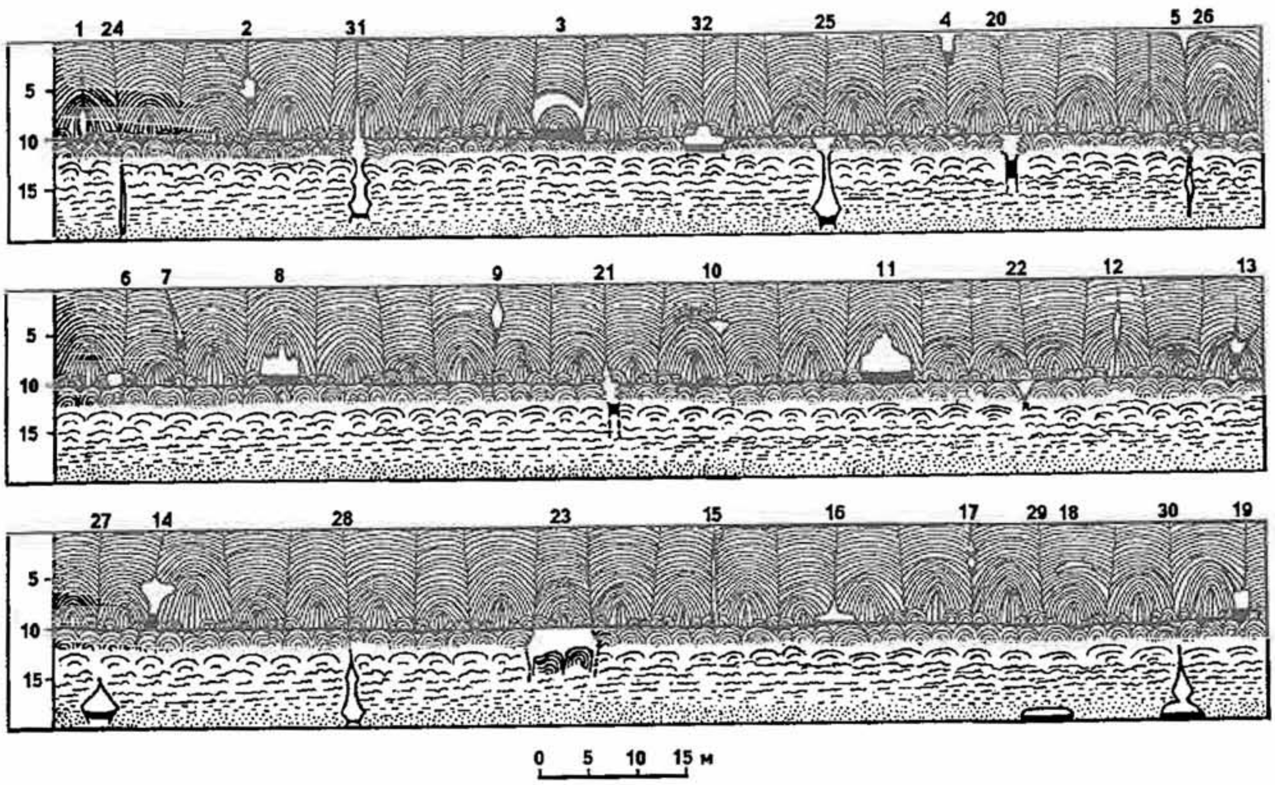


Figure 23. Occurence in the gypsum stratum and morphology of passages of different storeys in Optimisticheskaya cave. Numbers are referred to in the text.
Figura 23. Posición en el estrato de yeso y morfología de las galerías de los distintos niveles en la cavidad Optimisticheskaya. Véase el texto para el significado de la numeración

frequently - rhomb-like (9) or rectangular (19) sections. In some places pinches occur in the central part of a cross section (17), sometimes dividing a passage into two sub-storeys. Passages occurring near the bottom of the overlying limestones, have a plan ceiling (4, 5) composed with the above rocks. Morphology of cavities in the sub-zone IIIb is often complicated by small niches, shelves and ridges (2). The axis of passages here are normally vertical, less frequently - inclined (7).

Sometimes cavities occur along joints radially splitting dome structures (1, 12, 13). There are also cavities developed along surfaces dividing concenters of the structures (18) or, less frequently - along intersections between vertical joints and inter-concenters surfaces (10).

In the upper part of the gypsum stratum some large galleries and chambers occur, which formation is controlled by tectonic, hydraulic and lithological/textural factors. Simple cases are represented by Tsyclop, Jubilejnaya, Vechno Junykh galleries (14) which have rounded and oval sections complicated by fissure-like extension on the bottom. More complex cases are characteristic of the Zaozerny and Anakonda regions (8, 11). The presence of cupolas in the ceiling is common, formed by dissolution of the core and near-core parts of dome structures. Cupolas are of 5 to 6 m in diameter. In the top of cupolas selenite monocrystals often occur, exposed in the process of dissolution of surrounding rocks. In the Anakonda region cupolas are complicated with vertical tooth and ridges (8) formed as a result of selective dissolution of concenters, composed by microcrystalline gypsum, or by dissolution along inter-concenters surfaces. This phenomena is common for Kristal'naya cave as well.

A peculiar kind of cavities forms when blocks of gypsum detach along the surfaces between concenters in dome structures (3). At this, large spheroid boulders form ("stone balls", or "globes'). The ceiling shape follows contours of such boulders.

Within the sub-zone IIIa low (up to 1-1.5 m) passages of rounded shapes are developed (6), often complicated with speleoforms of lower order. Along the contact between the zones II and III wide (5-6 m and wider) and low (1-1.5 m) cavities are developed.

Cavities of quadrangular shape are common for the zone II; a ceiling is controlled by the bottom of the zone III (20). Such cavities form along joints occurring within the zone II and ending in the bentonitic layer. Some of such passages have narrow and deep fissures in the bottom. Passages crossing the central parts of dome structures of the zone II have a peculiar section. Their ceiling is in 15 to 30 cm below the bentonitic layer. Sometimes cavities occur with a section in form of triangular taken upside down (22).

Walls of cavities of the zone II are characterized by complex micro-relief, with numerous ridges and cornices. They are formed due to selective dissolution of microcrystalline concenters of dome structures. Prominent forms are composed with less soluble macrocrystalline gypsum.

Cavities in the lower part of the gypsum stratum (zone I) normally have rhomb-like cross sections (27). Combinations of two rhombus occur frequently (28). Such sections form due to episodes of prolonged stay of a water

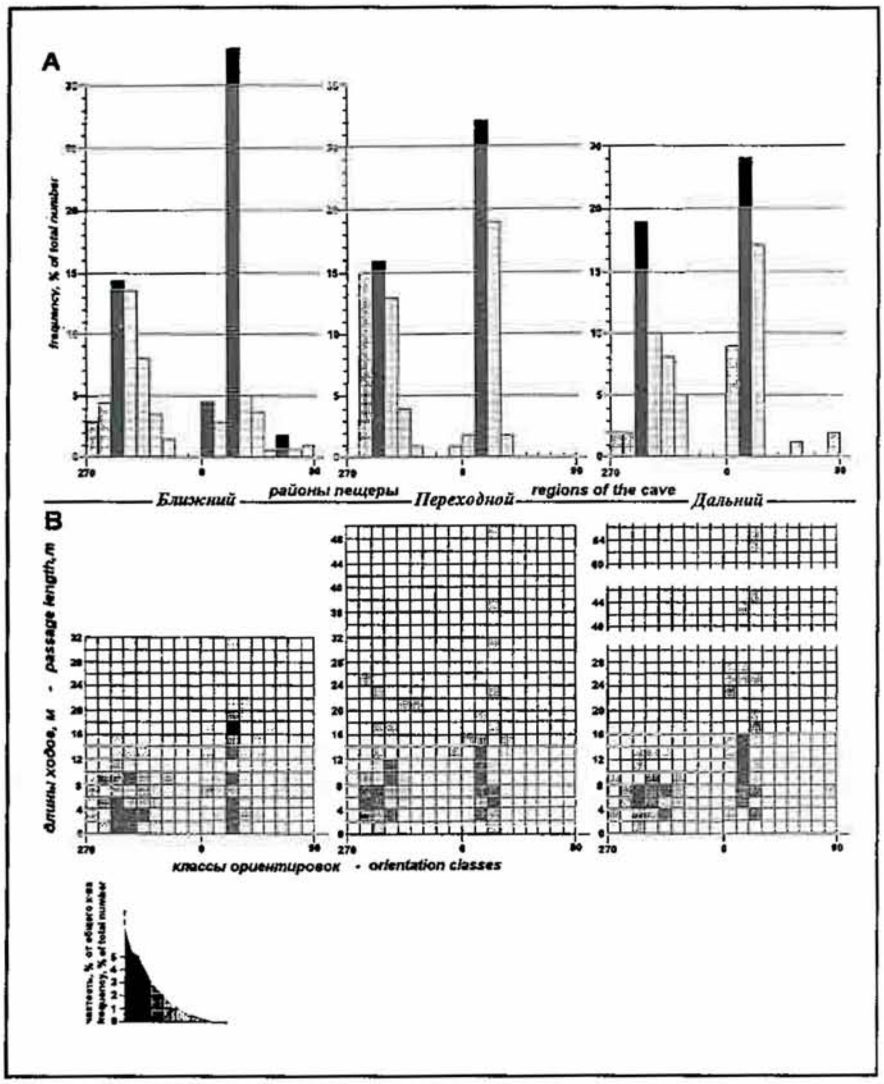


Figure 24. Distribution of orientations (A) and distances between passages (B) in networks developed in the same storey but in different microblocks (regions) of Ozernaya cave.
Figura 24. Distribución de las orientaciones (A) y distancias entre galerías (B) desarrolldas en el mismo nivel pero en diferentes microbloques (regiones) en la cavidad Ozernaya

table at certain position, within the stage of dewatering of the gypsum stratum. Fissure-like passages (24, 26) are less frequent here. Wide and low passages with plane ceiling occur along the contact of the gypsum stratum with the underlying formation (29). Internal surfaces of cavities in the zone I are smooth, moderately complicated by microforms: "ribs" of pre-speleogenic joints and isolated large gypsum crystals. Within maze networks developed in the lower part of the stratum (Averbakha. Aljonushka, Ozerny regions, etc.) vertical conduits are widely spread, ascending from the bottom of the stratum and having outlets that widens upwards. Such conduits are interpreted as points of upward recharge of the maze from the under-gypsum aquifer (Klimchouk, 1990; 1992; Klimchouk, Shestopalov, 1990; Klimchouk, 1992;).

Cavities which occur along joints dissecting the whole gypsum stratum, or most of it's thickness, have most complicated morphology. Such passages (21, 25, 30, 31) represent combination of several speleoforms described above, characteristic of a certain part of the gypsum stratum.

Lateral variability of the cave systems structure and passage morphology

General regularities

As it was shown above, the differences in the structure of networks and morphology of passages between different areas of the cave system are caused chiefly by their occurrence in the different vertical intervals (lithological/textural zones) of the stratum that have their inherent characteristics of speleo-initiating jointing.

Networks occurring in the same interval but through different areas of a cave system show a similarity in the most essential features of the structure and morphology of passages (network type, distribution of orientations, cross sections shape) but may have some distinctions. The structural distinctions are expressed, chiefly, in networks density, distance between sub-parallel passages in systematic networks, distribution of passages by length and orientation (fig.24). Such aerial distinctions between networks of the same storey are determined by their occurrence in different microblocks, which tectonic identity is not essential however. The structural distinctions may be enhanced if networks are compared developed in different tectonic blocks; for instance, the same storey networks of Optimisticheskaya and Ozernaya caves. Between-area distinctions in morphology of passages of the same storey can be also induced by hydraulic factors, such as a degree of flow focusing, or flow rate that depends from initial opening of joints, position of a network in a hydrologic system and a degree of network's connectivity with zones of recharge and discharge; the two latter factors determine a local hydraulic gradient.

It is important question how uniform is jointing and distribution of passages in the lateral direction. Analysis of cave maps allows to bring some light to this question but one must have in mind that contours of fields of mapped passages and networks of passages within are not exhaustive complete. However, consideration of cave maps clearly shows that jointing is quite uniformly distributed in lateral direction, with some characteristic density, within a certain cave area. Such areas, defined above as microblocks, are normally restricted (separated) by large joints or faults that stretch for rather long distances, dissect the whole gypsum stratum and are of obvious tectonic origin. A jointing network within an area (within a microblock) is characterized by quite steady density that do not vary from periphery toward the center.

Differences in the jointing structure between microblocks are expressed also by the fact that a network of a certain storey can be not expanding into the adjacent microblock at the same storey; in this another microblock a network of joints (passages) at another storey can be developed and laterally connected through the area. Some cave maps also demonstrate a presence of not karstified ("blank") areas surrounded by passage networks, or se-

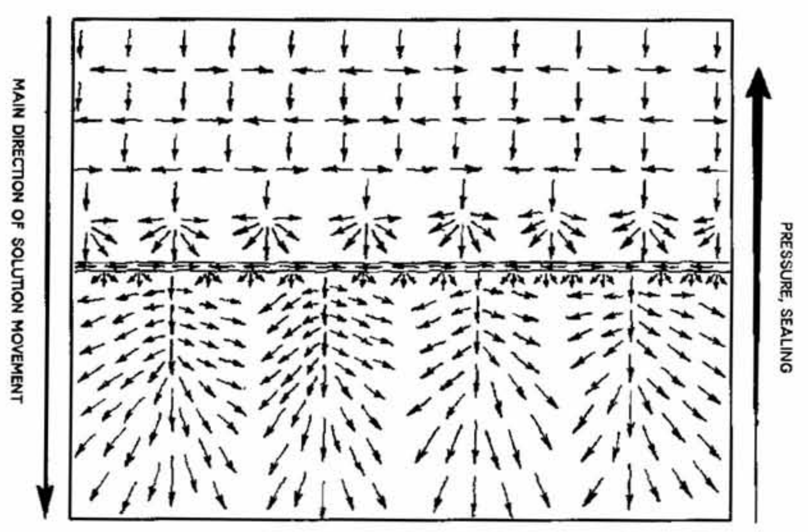


Figure 25. Scheme of interstitial waters movement in the course of early diagenitic transformations of gysum stratum.
Figura 25. Esquema del moviento del agua intersticial en la etapa diagenética temprana de transformación del estrato de yeso

parating adjacent cave areas. In the scale of the order of hundreds meters or first kilometers (the most important scale in a practice of hydrogeology and engineering geology) the distribution of jointing at a certain storey can not be treated as homogenous: karstified areas (microblocks) alternate with those that are not karstified at all. However, strictly speaking, area irregularity of karstification does not immediately indicates that jointing is not homogeneously distributed; it may just indicate that speleogenic realization of jointing networks is not uniform that can be conditioned by hydraulic factors .

Regionalization of large cave systems

Continuous mapping of area and storey differentiation of passage morphology and networks performed in Optimisticheskaya cave, has allowed to provide for morphological regionalization of this largest cave system. Morphological region of the cave is defined as a part of the cave that occurred within a certain tectonic microblock, with peculiar orientation and morphology of speleoforms developed on each of storeys present. Boundaries between regions follow tectonic joints or faults. Within a region sub-regions and areas can be distinguished; the former are defined as parts of regions with the same set of storeys, and the latter are consolidated parts of regions or subregions with passages developed in one of storeys, with steady passage morphology characteristics.

Totally, 11 regions, 18 subregions and 9 areas are distinguished in Optimisticheskaya cave (see fig.14). Peculiarities of structure and morphology of networks and passages are described in details in Russian text.

SOME CONTROVERSIAL TOPICS

Among problems, related to the above considered structural prerequisites of speleogenesis, following ones are most interesting: 1) causes and mechanisms of vertical structural/textural differentiation of the gypsum stratum and of formation of unique giant dome structures; 2) genesis of jointing in the gypsum stratum; and 3) hydrogeological conditions of realization of the structural prerequisites of speleogenesis.

Diagenesis of sulfate sediment and genesis of the dome structures

Lithological and structural peculiarities of the gypsum of the Western Ukraine attracted attention of various investigators. Some of them (Gofshtain, 1979; Dubljansky & Lomaev, 1980; Dubljansky & Smolnikov, 1969) treated the dome structures as hydration folds, the result of rock deformation during transformation of anhydrite to gypsum. Other workers (Korzhenevsky & Rogozhnikov, 1978) considered these structures as the result of diagenesis of mud with colloid structure.

The dome structures are know also in the middle part of the Miocene gypsum in the Southern Poland, where the sulfate belt of the Western Ukraine stretches to. Views of Polish investigators on the genesis of the structures are contradictory (Babel, 1986). A.Malicki (1947) thought that the formation of the dome structures is the result of deformations induced by hydration of anhydrite. J.Flish (1954) treated them as pingo forms, frost hummocks with an ice core. K.Witrwalski (1976) considers the dome structures as primary phenomena formed in result of parallel crystallization of successive layers on bulges of the lagoon bottom. The view about the primary nature of the discussed structures is shared by M.Babel (1986) who noted that macrocrystalline and giantocrystalline (sabre-like) crystals grow outside from the chaotically arranged core reaching radial orientation, that is exceptional feature of the sabre-like gypsum and regarded by Babel as an evidence of the primary nature of the structures. However, Babel admits that the primary nature of the dome structures was not proved.

The discussed dome structures can not be formed as a result of hydration of anhydride. It is proven (Koltun et. al, 1972; Kropacheva, 1981; Kudrin, 1966; Petrichenko et.al, 1988) that in the studied region gypsum was primary deposited mineral but not anhydrite. Thickness and pressure of the overburden in the platform outskirts never was high enough to allow further dehydration of primary gypsum. This is also evidenced by the presence of gypsum with remaining primary structures (bedded gypsum, argilo-sulfate rythmits, etc.) that would be inevitably destroyed during the dehydration/hydration cycle.

The hypothesis about formation of the dome structures in the result of diagenesis of mud with colloidal structure. It is known that newly deposited evaporate minerals do not form colloidal mixture, and that primary gypsum sediment form friable mass of 10 to 50% porosity impregnated with water (Sonnenfeld, 1988; Strakhov, 1962), rather than many meters thick mud suspension of colloidal structure. Besides that, crystallization of colloid would be complete and homogenous, and dividing surfaces between adjacent domes would be even, without intergrowth of

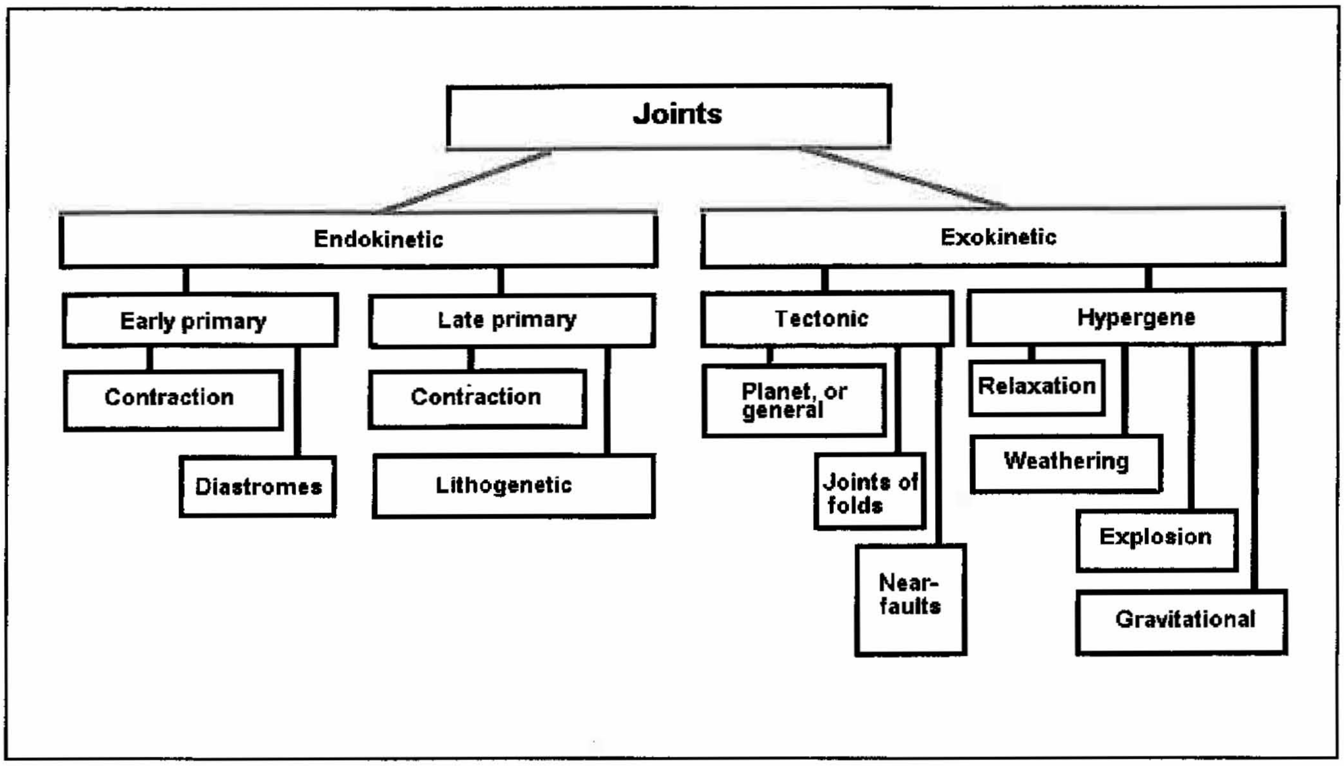


Figure 26. Genetic classification of joints (after Tchernyshev, 1983)
Figura 26. Clasificación genética de fracturas (Tchernyshev, 1983)

crystals of the adjacent structures (Lebedev, 1965). In our case crystallization of gypsum within the structures is unhomogenous and intergrowth of crystals between the structures is common; this supports that grows of the dome structures did not occur in the colloidal media.

We believe that structural/textural differentiation of the gypsum strata in the Western Ukraine is the result of recrystallization of primary cryptocrystalline gypsum sediment on the stage of late diagenesis. This is supported by the following facts: a presence of cryptocrystalline gypsum in the core parts of the dome structures, a presence of concenters composed with cryptocrystalline gypsum, uncomplete recrystallization of gypsum in the near-core parts of the structures, etc. Mechanism of recrystallization of primary gypsum is not well understood, as well as factors that caused recrystallization. It is clear only that recrystallization of gypsum occurred under conditions of ascending movement of saturated interstitial waters.

The mechanism of late diagenetic transformation of the gypsum stratum can be assumed as follows. Gravitational sealing of gypsum rock led to squeezing out of interstitial waters into the upper, less closely packed, beds of the stratum (fig.25). In the lower, more closely packed part of the stratum interstitial waters moved in both vertical and lateral (along bedding planes) directions. At this growth of macrocrystals of gypsum occurred along bedding planes, that was accompanied by formation of porphyraceous, plicated and undulatory structures. In the middle part of the gypsum stratum, near the contact with the bentonitic layer, interstitial waters moved upward. At this, the dome structures of the zone II were forming.

When interstitial waters were penetrating through the bentonitic layer, their local redistribution occurred, with further upward movement into the upper part of the gypsum stratum. Vertically oriented channels at the intersections of primary joints could serve as preferential paths for this upward movement. This can explain anomalous vertical elongation of the dome structures of the zone III. Such primary jointing was destroyed later on during recrystallization.

Upward movement of interstitial waters along vertical channels was rather fast, so that gypsum in this sub-zone was poorly recrystallized. Above, where the rock was lithified at lesser extent and joints were poorly expressed in it, water movement was retarded. Here an intense recrystallization occurred, up to the stage of selenite gypsum. From this area interstitial waters moved in different directions from the center to periphery, under conditions of homogenous media and low gradient pressure, so that concenric-zoned and radiated-fibrous texture was formed in the periphery parts of the dome structures. At the outer parts of the dome structures the water movement was most slow, recrystallization of the rock was also slow and prolonged, so that forming crystals attained a considerable size.

Slow movement of waters in lateral and vertical directions could occur under conditions of growing pressure resulted from deposition of overlying clay thickness (the formation of an artesian basin). Sonnenfeld (1988) has pointed out a possibility of diagenetic transformation of evaporate rocks under the conditions of artesian uplift of brines.

Diagenetic transformations of the gypsum stratum began immediately after precipitation of sulfate sediment, and continued after the overlying formations had been deposited. This is evidenced by the presence of veinlets of fibrous gypsum developed along joints and bedding planes in the Upper Badenian clays. Such veinlets were formed in resulted of penetration of saturated waters from the gypsum stratum into the overlying formations.

The problem of the late diagenesis and recrystallization of gypsum has many poorly understood aspects. It can not be ruled out that recrystallization processes continue also on the katagenesis stage. For instance, in the Lower Permian gypsum and anhydrides in the Gor'kovsko-Alatyrsky uplift area the upper 30 m thick part of the stratum is recrystallized with recrystallization pro-

Characteristic of intersections of joints of different genesis, and cave passage intersections

Types of joints	Number of beams at an intersection						4-beam/3-beam intersections ratio
	3	4	5	6	7	8	
Primary joints *(Tchernyshev,1983)*:							
Glaze	78	21.6	0.4	0	0	0	0.28
Lava sheet	73.4	24.3	2.2	0	0	0	0.33
Desiccation cracks in mud:							
1	84.4	15	0	0.6	0	0	0.17
2	91.5	8.5	0	0	0	0	0.09
3	90	8.8	1.2	0	0	0	0.1
4	80.9	10.1	0	0	0	0	0.12
Speleo-initiating joints in the gypsum in the Western Ukraine:							
Atlantida Cave, the upper storey	83	16	1	0	0	0	0.19
Dzurinskaya Cave	92.4	7.6	0	0	0	0	0.08
Mlynki Cave, the Western Series	82.3	16.6	1.1	0	0	0	0.2
Optimisticheskaya Cave, Entr.Sr.	79	20.7	0.3	0	0	0	0.26
Zolushka Cave	71.6	28.4	0	0	0	0	0.4
Tektonic joints (near Nurek, C.Asia)	20	80	0	0	0	0	4

Note: For Atlantida and Dzhurinskaya caves the maps of joints have been used in analysis, for other caves - maps of cave passages.

Table 2. Characteristics of intersections of joints of different genesis, and cave passage intersections.
Tabla 2. Características de las intersecciones de fracturas de distintas génesis e intersecciones de galerías en cavidades

cesses have occurred in post-Paleogene time (Parfenov, 1966). It is not yet clear the cause of alteration of crypto- and macrocrystalline concenters in the dome structures. Perhaps, it is caused by progressive recrystallization that accompany the interstitial waters movement. It is poorly understood the genesis of giant sabre-like and feather-like gypsum crystals. M.Babel (1986) considers these as a primary formations, but this view is not proven. Lastly, it is not well studied the regularities of regional distribution of the gypsum with the dome structures and with other types of structures. To resolve the above mentioned and other relevant problems further study of paleogeographic conditions of the gypsum deposition and transformations in the region is needed. It is obvious that speleological methods offer unique opportunities for paleogeographic and lithological/petrographical investigations.

Genesis of joints in the gypsum strata

The problem of genesis of joints in the gypsum is crucial for an adequate understanding of regularities of secondary porosity of the strata. The vast majority of researchers treated speleo-initiating jointing as of tectonic origin, referring to the prevalence of two or three sets in orientation diagrams. It has been demonstrated above that anisotropy of orientations is expressed in different extent and not in all cases in the caves of the region. It was the work by A.B.Korzhenevsky & V.Ya.Rogozhikov (1978) where the possibility of another interpretation of the genesis of jointing in the gypsum was mentioned for the first time. Further studies resulted in much data that allowed the more detailed consideration of this topic.

From materials presented in the chapter 4 the following summary can be given of speleo-initiating jointing in the gypsum strata in the region:

1) All joints in the gypsum are tension joints. The vast majority of them are vertical. They do not dissect the whole stratum in vertical direction but are restricted within certain intervals (storeys) that correspond to specific structural/textural horizons (zones).

2) Parameters of joint networks demonstrate the storey and area differentiation, but are quite steady within a single geological position (within a certain storey and area).

3) Distribution of joints within microblocks is quazi-uniform and does not display any trends in direction from tectonic faults (boundaries of microblocks) toward internals of microblocks.

4) By the general structure joint networks most frequently fall into the intervening category between systematic and polygonal networks. In the extre-

me cases networks can be with well expressed two or three prevailing sets of joints (anisotropic networks) or be purely polygonal without prominent sets at all.

First of all, it should be noted that in general the problem of jointing genesis is very complicated and far from sufficient resolution. There is no well accepted genetic classification of jointing in rocks, but there are some rather established concepts about joints genesis (Tchernyshev, 1979, 1983). One of the complicating factor is inherited development of joints in different stages of geologic history of a rock (stages of lithogenesis, tectonic deformations, hypergenesis). Therefore, considering conventional genetic classifications of joints one must take into account that they refer only to novice joints formed during corresponding stages. Having in mind the existence of some steady geometric types (patterns) of natural joints networks one can also consider the genesis of networks. In the context of the present work we are interested, first of all, in the genesis of networks of speleoinitiating joints in the gypsum stratum.

We regard as the most representative the general scheme of genetic classification of joints published by S.Tchernyshev in 1983 (fig.26). At the first level joints are classified according to genesis and source of energy that form joints. Two main classes are distinguished: 1) endokinetic joints, formed in the coarse of petrogenesis processes at the expense of energy stored by a rock; and 2) exokinetic joints, formed at the expense of external energy impact on a rock. At the next level further division is made on the basis of stages which generation of joints is confined to. In the earlier version of this classification (Tchernyshev, 1979) the sub-types of "purely lithogenetic joints" and of "lithogenetic joints formed with influence of the outer field of stresses" had been distinguished within the type of primary joints.

The above given characteristic of joints networks in the gypsum of the Western Ukraine obviously corresponds to properties of lithogenetic jointing. One more typical sign of lithogenetic jointing can be revealed when examining topologic peculiarities of networks - the ways how joints are conjugated in nodes). It was shown in the above works of Tchernyshev that nodes to which three joints converge are predominant in networks of lithogenetic joints. Amounts of nodes with larger numbers of joints diminishes drastically. In a contrast, it is typical for networks of tectonic joints that 4-beam junctions sharply predominate in which one joint crosses another. This feature indicates that joints are formed under main influence of outer field of stresses which is homogenous in all blocks of a given massif.

The results of this kind of examination of topology of cave passages networks are given in the table 2 where the data of M.V.Ratz & S.M.Tchernyshev (1970) are also included characterizing joints networks of knowingly lithogenetic and tectonic genesis. At this, the ends of joints (one beam) were excluded from the analysis because the "blind" appearance of element in our cave maps does not necessarily means that there is no junction in reality, and 2-beam nodes were excluded as well because they topologically can not be separated from a turn.

The analysis of the table demonstrates that amount of 3-beem junctions in networks of speleo-initiating joints sharply predominate (vary from 71.6 to 92.4%; the average value 81.7%) and closely corresponds to the amount of such nodes in networks of knowingly lithogenetic joints (vary from 73.4 to 91.5%; the average 83.0%). The ratio between amounts of 3-beam and 4-beam junctions vary from 0.09 to 0.33 for lithogenetic joints networks and from 0.08 to 0.39 for speleo-initiating joints networks in the gypsum. These features differ sharply from that of tectonic jointing (see the table).

Empirically revealed peculiarities of lithogenetic joints networks, such as their polygonal pattern, restriction to a lithologically homogenous horizons and other properties, have a theoretic explanation derived from energy and geomechanics consideration (Ratz & Tchernyshev, 1970; Tchernyshev, 1983). The prevalence of 3-beem junctions is interpreted within the concept of the autonomic development of each area of the network: if the main source of stresses is confined within the polygon then the induced joint does not extend beyond the earlier formed joint - the boundary of the polygon. The development of joints proceeds in the other way if the outer source of stresses is present. The outer force creates rather homogenous field of stresses in each block of a massif so that joints extend from one block to another, that is resulted in the formation of 4-beam junctions in networks. One should note that superposition of outer fields of stresses onto the field of contraction stresses lead to the same results, therefore forming networks can attain well expressed anisotropy.

The above consideration strongly supports the lithogenetic nature of the studied joints networks in the gypsum stratum of the region. However, when distinguishing the type of lithogenetic jointing one usually imply it's primary origin and formation during the period of lithification of sediment. In our case the age of jointing is knowingly more recent than the early diagenesis period. As it has been shown, speleo-initiating jointing present at least the second, after the pre-speleogenic jointing, generation of joints that had been formed yet in the lithified sediment. Thus, one can place studied networks into the lithogenetic category only if the extended interpretation of a formation time and a nature of the lithogenetic jointing is implied, namely: that it can be formed also on the stage of the late diagenesis (katagenesis), in relation with the continuing into a solid rock processes of squeezing out and redistribution of interstitial waters and of recrystallization.

The fact that anisotropy is more or less expressed in network patterns does not contradict to the placing the studied jointing into the lithogenetic category, but it just indicates an influence of the field of outer, tectonic stresses. It was shown in the above cited works of Ratz & Tchernyshev that the character of the primary jointing can be influenced by the stress state and dynamic conditions in adjoining formations (the effect of a "mobile frame"). Lithogenetic tension joints in a consolidated rock, experiencing vertical compression due to it's occurrence at a certain considerable depth, can not be formed without influence of the "frame", stresses transmitted to the gypsum stratum from the adjoining formations. Thus, in the polygonal joints network those directions may become more expressed that corresponds to the distribution of the main normal stresses in the massif, so that anisotropy of the network forms. This situation corresponds well to the intervening type of systematic polygonal networks distinguished by Tchernyshev in his geometric classification, and to the sub-type of "lithogenetic joints formed with influence of the outer field of stresses" in the genetic classification.

It is shown in the that differentiation of the networks parameters by areas (microblocks) is inherited in speleo-initiating jointing, while these parameters remain steady within an area. Regions boundaries are outlined by large extended joints or mall faults of the clear tectonic nature, that divide the gypsum stratum into microblocks. The microblock structure of a cave field has been demonstrated by V.N.Andrejchouk (1988) for Zolushka cave, and can be

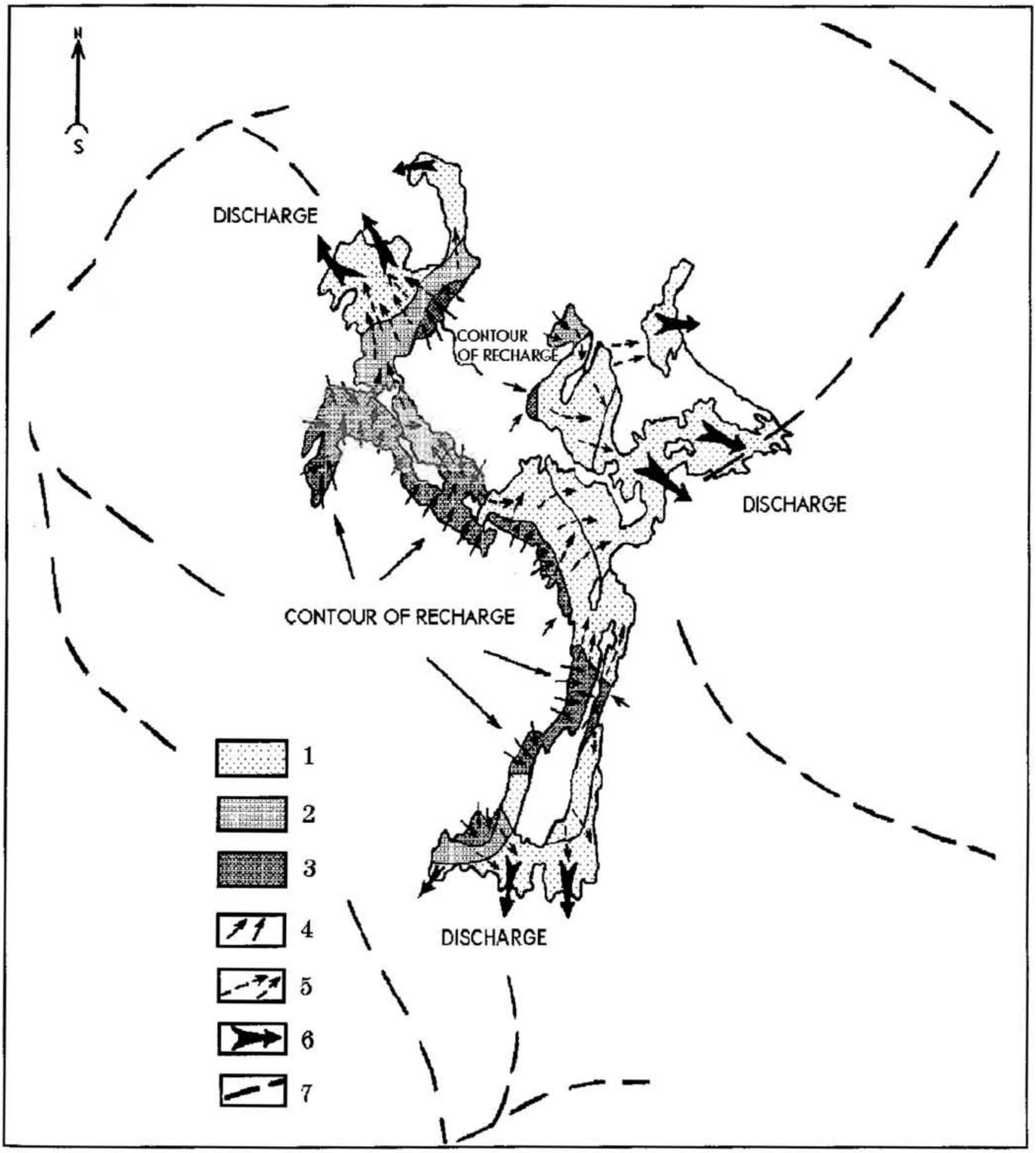


Figure 27. Areas of recharge, transit and discharge of underground waters of the gypsum at the period of the formation of Optimisticheskaya cave. Areas of passage development in different storeys: 1- upper, 2- middle, 3- lower. Movement of underground water: 4- upward recharge from the under-gypsum aquifer, 5- transit between and within storeys, 6- discharge into the overlying aquifer and to valley bottoms. See profile on figure 28.

Figura 27. Áreas de recarga, circulación y descarga de las aguas subterráneas relacionadas con el acuífero yesífero durante el periodo de formación de la cavidad Optimisticheskaya. Áreas de desarrollo de galerías en diferentes niveles: 1- superior, 2- intermedio, 3- inferior. Movimiento del agua subterránea: 4- recarga hacia arriba desde el acuífero yesífero inferior, 5- circulación entre los distintos niveles, 6- descarga al acuífero suprayacente y al fondo de los valles. Véase perfil en la figura 28

easily recognized in all of the large caves of the region. In the light of the above discussed it becomes quite clear the cause of the microblock differentiation of parameters of the joints networks: the resulting effect of the "frame" stresses and the field of the internal stresses can be individualized to a certain extent in the elementary tectonic units - microblocks, whereas within the block a quazi-uniform network forms with steady parameters. However, this resulting effect is differentiated even more by vertical structural/textural zones of the gypsum stratum (storeys) that evidences that the internal fields of stresses, which have a different configuration in the each of the structural/textural horizons, do play the leading role in a network formation.

It is interesting to note that the given above characteristics of joints networks in the gypsum are very close to those of jointing distinguished as the

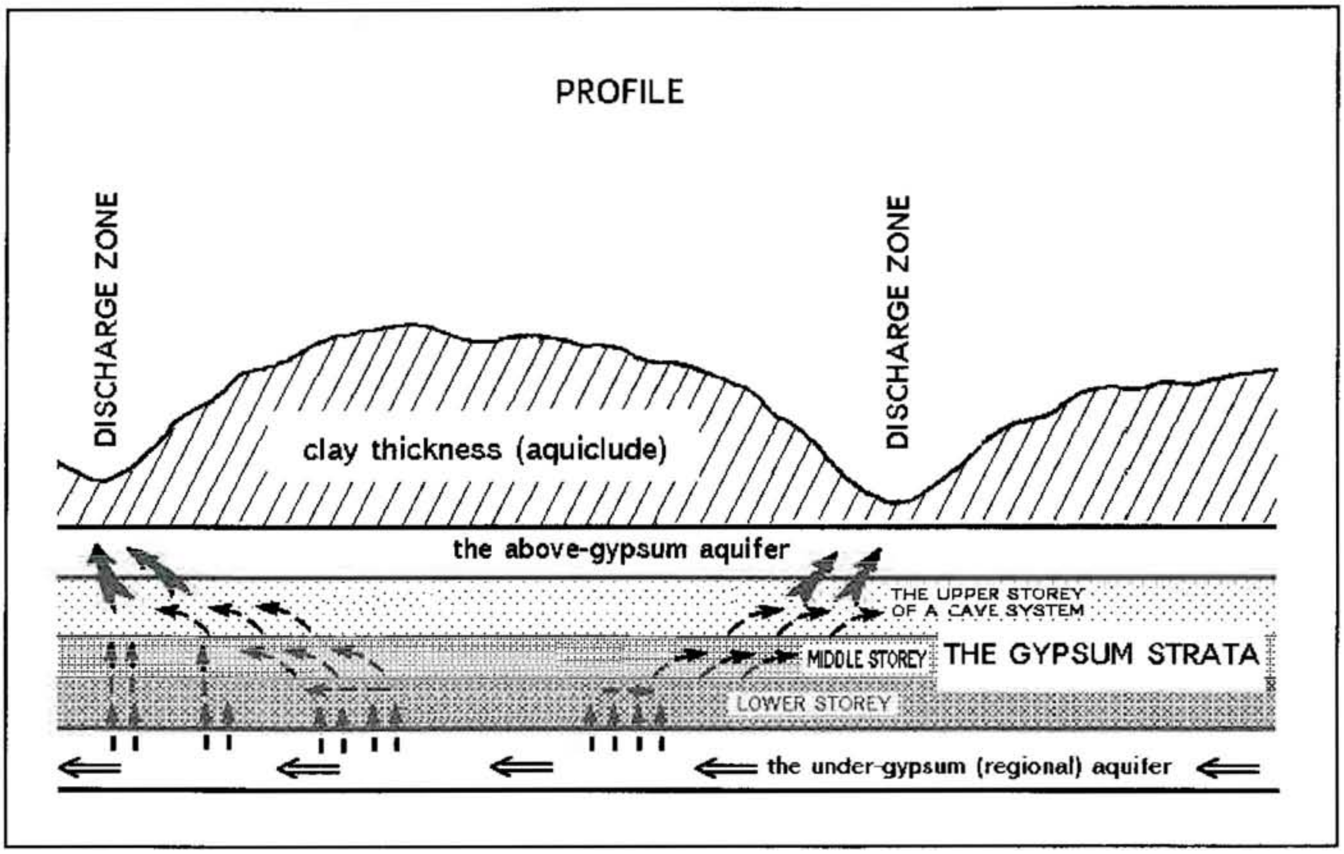


Figure 28. Scheme of recharge, transit and discharge in a storey artesian karst system (the case of Optimisticheskaya cave)
Figura 28. Esquema de recarga, circulación y descarga en un sistema kárstico artesiano con distintos niveles (en el caso de la cavidad Optimisticheskaya)

genetic type of the "general" (systematic) jointing. Jointing of this type form, along with the primary one, a background of jointing in platforms. The "general" jointing is usually placed to the category of the tectonic jointing (Belousov, 1962; Ratz & Tchernyshev, 1970; Tchernyshev, 1983), although a mystery of it's genesis is underlined. Joints of this type are extremely widely spread through platforms, group into two sets, usually of NE and NW orientations, are perpendicular to the bedding and, as a rule, do not extend beyond the limits of a single bed. It is though that the general joints differ from lithogenetic ones by expressed anisotropy and larger length. In the light of the above consideration it seems proper the opinion expressed by V.A.Velikanov & V.S.Zaika-Novatsky (1971) on the basis of study of jointing of Upper Proterozoic formations in the Eastern Podolsky region, that the "general" jointing is not related to tectonics but is formed due to processes of the late diagenesis, so that it can be placed into the category of lithogenetic jointing.

Thus, the problem of the nature of speleo-initiating jointing in the gypsum of the Western Ukraine still can not be resolved in a single way, at least within the present day genetic classifications and concepts. Perhaps, it would be correct to talk about the complicated process of the formation of jointing in the course of lithogenesis (katagenesis) of the gypsum stratum, under simultaneous impact of lithogenetic and tectonic stresses and strong control of structural/textural irregularity of the rock on joints occurrence (Klimchouk, 1986; Klimchouk & Andrejchouk, 1988).

And, lastly, it is worst to touch the topic about retention of joints in the gypsum stratum. The materials presented above support the view about the prolonged process of formation of present jointing in the gypsum and their different ages. The prolonged retention of joints contradicts to the widely accepted opinion about the self-healing of jointing in gypsum due to gypsum plasticity and flowage. Because of this, gypsum massifs are often regarded as monolithic and of low permeability for fluids. This view is true in part in case of thick massifs or sequences of sulfate rocks that are not clamped rigidly between adjoining formations. One of the authors was able to see this situation in the gypsum areas of Northern Italy, Sicily, Southern Spain and New Mexico. However, the peculiarity of tectonic position of the Western Ukrainian gypsum is that the stratum is spread through considerable area in the form of the rather thin bed clamped between adjoining rigid formations. Perhaps, this is the main cause of prolonged retention of quazi-uniform jointing in the gypsum, that prove to be the most important structural prerequisite of the formation of the immense maze cave systems. This feature determines a uniqueness of the gypsum karst of the region in comparison with other gypsum karsts in the world.

5.3. Hydrogeological conditions of realization of the structural prerequisites of speleogenesis

Although the main objectives of the present work are restricted to the consideration of the structural prerequisites of speleogenesis, it is reasonable to go briefly through the problem of hydrogeological conditions of their realization. The resolution of the issue implies revealing of the time of the cave formation, the type of the aquifer (aquifers system) on the main stage of speleogenesis, recharge/discharge conditions in this stage, the nature of dissolving capability of underground waters. The comprehensive consideration of these issues is supposed to be done in the separate work; below only some main aspects are touched, discussion of which is stimulated by the above presented materials.

Not going deeply into consideration of the development of ideas regarding speleogenesis in the gypsum in the Western Ukraine, we should only mention the recent radical change of an approach to the problem. During long time the genesis of the caves in the region had been interpreted within the "point recharge - through flow" theory suggested by V.N.Dubljansky (Dubljansky & Smolnikov, 1969; Dubljansky & Lomaev, 1980). According to this theory, caves were formed during Early and Middle Pleistocene due to sinking of perennial and intermittent surface streams into the gypsum stratum. Development of caves occurred under shallow phreatic and water table conditions. Underground lateral flow between sub-parallel river valleys was assumed to occur through the gypsum stratum. A multi-storey structure of cave patterns was assumed to result from cycles of uplift and stability, river valley entrenchment, and corresponding lowering of the karst water table (Dubljansky & Smolnikov, 1969; Dubljansky & Lomaev, 1980).

In the last decade one of the present authors has suggested and developed the new artesian theory of speleogenesis in the gypsum of the region (Klimchouk, 1986, 1992; Klimchouk, 1990, 1992; Klimchouk, Shestopalov, 1990). The formation of caves occurred in the confined conditions of the multi-storey shallow artesian system due to vertical water exchange between aquifers through the gypsum. Maze caves were formed due to dispersed upward recharge from the under-gypsum aquifer, that enabled uniform solution widening of all available speleo-initiating joints. Cave systems were developed in zones of piezometric lows, where the cupping aquitard became thin due to an entrenchment of erosional valleys and (or) tectonically weakened. In such zones conditions for upward discharge of the Miocene aquifer system established; this was accompanied by intense upward flow through the gypsum strata. Because of further uplifts of the territory and entrenchment of erosional valleys the aquifers system became unconfined, and the gypsum strata became drained, with inversion of the recharge/discharge scheme and further transformation of cave systems to the relict state.

The peculiarities of the structure of the cave systems considered above, strongly support the artesian theory of speleogenesis.

The multi-storey structure of the caves in the region is preconditioned by the storey occurrence of speleo-initiating joints, that in turn is determined by the structural/textural differentiation of the stratum and by lithogenetic nature of jointing. On the general background of an upward water flow in the system in zones of piezometric lows, the flow received a considerable lateral component within those intervals of the gypsum strata where network had well developed lateral connectivity. In general, the multi-storey structure of cave systems and considerable lateral development of speleoforms in certain horizons is conditioned by incompatibility between the structures of primary permeability of the different structural/textural horizons of the gypsum stratum.

All the caves have some structural elements in the lower part of the gypsum stratum, that provided for upward recharge of cave systems from the bottom of the strata (from the under-gypsum aquifer). In most of cases joints near the bottom of the stratum do not form extensive connected networks, so that recharge of continuous networks at the next upper storey occur through single joints or local networks (caves Ozernaya, Slavka, Dzhurinskaya, Zolushka, some areas of Optimisticheskaya cave). Such feeding cavities are uniformly distributed through areas of the master storey; this provides for dispersed inflow of aggressive water into cavities of the master storey and for possibility of relatively uniform solutional widening of all available joints in a network. In some other cases (Atlantida cave) lateral flow occurred chiefly along the bottom of the gypsum, but cavities of the upper storey developed locally providing just for water exchange between adjoining master passages.

Optimisticheskaya cave have the most complicated storey structure. There are areas of continuous spread of passage networks in the lower storey adjoining along the common contour with areas where the middle storey networks are developed . These later areas, in turn, border with areas where networks of the upper storey are developed (fig.27). At this, areas of the lower storey tend to surround non-karstified areas forming "contours of recharge". Such regular transition of the labyrinth from lower storeys to upper ones in certain directions become understandable when one superimpose the contour of the cave system and it's regions on the scheme of the surface erosional valleys which served as focuses of an upward discharge from the system. Upward flow occurred through the gypsum stratum from recharge areas to discharge areas step by step, attaining considerable lateral component on the each step, according to the structure of networks of speleo-initiating joints at the each horizon and peculiarities of connectivity between networks of different storeys (fig.28).

Distribution of karstified areas in the plan view, contours of cave fields, particularly contours of the lower storey passages areas are determined not only by distribution of jointing in the gypsum strata and relative position of recharge and discharge areas but also by the plan configuration of zones of enhanced permeability in the under-gypsum aquifer. One can assume that characteristic elongated contours of the cave fields indicate in general a position of zones of enhanced permeability in the Lower Badenian aquifer. This issue is of a great significance for prediction of karstification in the gypsum and needs in further studies.

Thus, the field data about structure of the large cave systems in the region fit well to the artesian model of speleogenesis. It is easy to show that within other conventional models, for instance - within the criticized model of "point recharge - through flow" in the gypsum, the speleogenetic realization of the present structural prerequisites would be completely different.

Conclusions

1. The gypsum stratum of the Tyrassky formation of Middle Badenian, that normally have the thickness of 15-30 m, is characterized by clear vertical structural/textural irregularity. Size of gypsum crystals usually increase from the bottom toward the top of the stratum. For the most of the Podolsky region the three-unit construction of the gypsum strata is inherited in. The uppermost part is characterized by development of giant (up to 8-10 m in diameter) concentric/zoned and radiated/fibrous dome structures of macro- and giantocrystalline gypsum.

2. The structural/textural differentiation of the gypsum stratum was formed, likely, at the stage of late diagenesis, as a result of recrystallization of primary cryptocrystalline gypsum sediment. Recrystallization occurred under conditions of upward movement of saturated interstitial waters.

3. Vertical structural/textural differentiation of the gypsum strata have preconditioned spatial position of networks of speleo-initiating jointing. Most of joints do not dissect the stratum for the whole thickness but occur by storeys within certain intervals (structural/textural horizons), forming largely independent networks with rather different parameters. Speleo-initiating

joints in the gypsum stratum and their networks display properties characteristic for the genetic types of lithogenetic and "general" jointing.

4. The structure of the cave systems in the region is determined by the structure of speleo-initiating jointing. All the large caves demonstrate two or three storey structure. Network parameters and morphology of passages considerably differs from storey to storey and, to the lesser extent, from area to area between microblocks, but these parameters are quite steady within a single geological position (within a certain storey and microblock).

5. The field data about structure of the large cave systems in the region fit well to the artesian model of speleogenesis. Cave systems were formed due to upward water exchange through the gypsum between aquifers of the multi-storey artesian system in the areas of upward discharge through the capping aquitard (in zones of piezometric lows). The multi-storey structure of cave systems and their considerable lateral development is determined by incompatibility between structures of primary permeability of the different structural/ textural horizons of the gypsum stratum.

References

Andrejchouk V.N., (1984). *The regularities of karst development in the southeast of the zone of junction between the Russian platform and pre-Carpathian foredeep.* Thesis of cand.of sci.dissertation. Perm

Andrejchouk V.N. (1988). *Tectonic factor in the karst development of Bukovina.* Sverdlovsk: preprint of the URO AN SSSR. 68

Andrejchouk V.N. & Kunitza M.N., (1985). *The role of tectonic factor in the karst development in the Mamalyzhsky karst area.* Physical geography and geomorphology, vol.32: 50-57

Andrejchouk V.N. & Turchinov I.I., (1992). *Deformation of gypsum pillars in Optimisticheskaya cave, Western Ukraine.* Study of Ural caves: Abstracts of papers, Perm: 130-132

Belousov V.V., (1962). *The principal topics of geotectonics.* Moscow: Gosgeoltechizdat: 607

Velikanov V.A. & Zaika-Novatsky V.S., (1971). *Genetic types of jointing of Upper Proterozoic rocks of the Pridnestrovjel.* Collectoin of scient.papers, Kiev University, 7: 14-18

Gorbunova K.A. & Andrejchouk V.N., (1985). *Hypergene structures of gypsum and gypsum hummocks.* Modern problems of geography. Abstracts of papers, Perm.: 101 *(russ)*

Gofshtain I.D. (1979). *Neotectonics of the Western Volyno-Podolia.* Kiev: Naukova dumka.: 156

Grigorjev D.P., (1961). *Ontogeny of minerals.* Lvov: Izd. Lvovskogo universiteta: 284

Demedjuk Yu.N., (1982). *Relationship between morphology of passages of Optimisticheskaya cave with lithology of karstified rocks.* Physical geography and geomorphology, vol.32: 130-135

Demedjuk Yu.N., (1988). *Genesis and stages of development of Optimisticheskaya cave.* Peschery (Caves), Perm: 31-36

Dubljansky V.N. & Lomaev A.A. (1980). *Karst caves of the Ukraine.* Kiev: Naukova dumka: 180

Dubljansky V.N. & Smol'nikov B.M. (1969). *Karstological and geophysical prospectings of karst cavities of Pridnestrovsky Podolia and Pokut'e.* Kiev: Naukova dumka: 151

Ivanov B.N., (1961). *Karst phenomena in the territory of Ukraine and their economic significance.* Trudy 1-go gidrogeol.sovesch., Kiev: 53-62

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

Klimchouk A.B. (1992). *Speleogenesis under artesian conditions.* Svet (The Light, the Newsletter of the Kiev Karst and Speleological Center), 3(5): 7-13

Klimchouk A.B., Aksem S.D., Shestopalov V.M. & Lisichenko G.V. (1985). *Geological and hydrogeological conditions of karst development of Pridnestrovsky Podolia.* Fizycheskaja Geographija i Geomorphologija. Vol. 32. Kiev. Vyshcha Shkhola: 47-54

Klimchouk A.B. & Andrejchouk V.N. (1988). *Geological and hydrogeological conditions of the development of large gypsum caves in the Western Ukraine and their genesis. Peshchery (Caves).* Perm. Perm University: 12-25ç

Klimchouk et.al, (1983). *The study of recharge, flow and discharge of underground waters of the karstified block in the intervalley massif of Seret-Nichlava intended for setting up of a karst stationary lab.* Scientific report. Kiev. Institute of Geol.Sciences, vol.1 & 2: 114-161.

Klimchouk A.B. & Rogozhnikov V.Ya. (1982). *Diversity of age of joints in the gypsum of Podolia and speleogenesis.* Sostojanie i zadachi izuchenija glubinnogo karsta SSSR. Abstracts of papers. Moscow.

Klimchouk A.B. & Rogozhnikov V.Ya. (1982). *Conjugate analysis of a development history of large cave system (on example of Atlantida Cave).* Kiev: Inst.of Geol Sci., 58

Klimchouk A.B. & Shestopalov V.M., (1990). *The large caves in the gypsum of the Western Ukraine: speleogenesis in artesian conditions.* Geol.Jurn., 5: 93-104

Korzhenevsky B.N. & Rogozhnikov V.Ya., (1978). *About significance of contraction jointing in the formation of karst maze caves in the gypsum of Podolia.* Voprosy genezisa, dinamiki, formirovania podzemnykh. Kiev: Naukova dumka: 147-152

Kropacheva S.K., (1981). *A comparative analysis of structure of sulfur-bearing galogenous formations.* Moscow. Nedra, 120

Kudrin L.N., (1966). *Stratigraphy, facies and ecological analysis of fauna of Paleogene and Neogene sediments of the Pre-Carpathian region.* Lvov. Izd. Lvovsk. univers. 126

Lebedev L.M., (1965). *Metacolloids in endogenous deposits.* Moscow: Nauka. 119

Petrichenko O.I. et.al., (1988). *Genetic peculiarities of sulfur-bearing sulfate-carbonate sediments of evaporate formations.* Lvov. preprint IGGI AN Uk.SSR. 45

Ratz M.V. & Tchernyshev S.N. (1970). *Fissuring and properties of fissured rocks.* Moscow. Nedra. 160

Savtchin M.P. & Gunjobsky I.M. (1970). *Optimisticheskaya cave in Podolia. Physical geography and geomorphology.* Kiev University, vol. 4: 60-64

Savtchin M.P. & Kachkovsky I.V. (1971). *Optimisticheskaya cave.* Peschery (Caves), Perm: 84-89

Savtchin M.P. & Ostyanova N.M. (1972). *Optimisticheskaya cave - one of the longest cave in the world.* Peschery (Caves), vol.12-13: 197

Sonnenfeld P. (1988). *Brines and evaporates.* Moscow: Mir: 478

Strakhov N.M. (1962). *Basics of the theory of lithogenesis.* Vol.3. Moscow: izdatelstvo AN SSSR: 549

Srebrodolsky B.I. (1987). *Mysteries of mineralogy.* 160p

Tchernyshev S.N. (1979). *Water movement in joint networks.* Moscow. Nedra: 141

Tchernyshev S.N., (1983). *Joints of rocks.* Moscow. Nauka: 240

Shestopalov V.M. (1981). *Natural resources of underground water of platform artesian basins of the Ukraine.* Kiev. Naukova Dumka:195

Babel M. (1986). *Growth of crystals and sedimentary structures in the sabre-like gypsum (Miocene, Southern Poland)* . Pregled Geologicny, Warshaw, 34(4): 204-208.

Flis J. (1954). *Kras gipsowy Niecki Nidzianskiej* . Pr.Geogr. nr.1.

Klimchouk A.B. (1986). *Genesis and development hystory of the large gypsum caves in the Western Ukraine* . La Grotte d'Italia, (4), XIII, Bologna: 51-71.

Klimchouk A.B. (1992). *Large Gypsum Caves in the Western Ukraine and their Genesis* . Cave Science, vol.19, No.1: 3-11.

Malicki A. (1947). *Zabytki przyrody nieozywionej na obszarach gipsowych dorzecza Nidy* . Chronmy Przyrode Ojezysta, nr.7/9.

Wytrwalski K. (1976). *Przebieg i prognozowanie procesow egzogenicznych na obszarze plateau gipsowego Busko-Wislica w aspekcie ochrony srodowiska geologicznego.* Praca magist. Archiwum IGP UW.