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MORPHOLOGICAL AND HYDROGEOLOGICAL CLASSIFICATION OF SPELEOLOGICAL STRUCTURES (CAVES AND PITS) IN THE CROATIAN KARST AREA

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Key words: speleology, karst hydrogeology, karst morphology, caves, shafts, pits, Croatian karst area.

This paper deals with speleological classification according to the main channel inclination (caves and pits - combined or complex), to morphology (simple, branching, level, knee formed and systems) and according to the hydrogeological function (permanent and periodical springs, permanent and periodical sinkholes, estavelas, vruljas and percolating objects). It is based on the data obtained from some previously investigated speleological objects in the karstic area of Croatia and on the analysis of relevant speleohydrogeological and speleomorphological factors.

Ključne riječi: speleologija, hidrogeologija krša, morfologija krša, spilje, jame, Hrvatski krš.

Na temelju podataka istraženih speleoloških objekata u krškom području Hrvatske, a uzimajući u obzir speleomorfološke i speleohidrogeološke faktore daje se klasifikacija speleoloških objekata prema nagibu glavnog kanala (spilje, jame i kombinirani ili kompleksni), prema morfologiji (jednostavni, razgranati, etažni,koljenčasti i sustavni) i prema hidrogeološkoj funkciji (stalni i povremeni izvori, stalni i povremeni ponori, estavele, vrulje i protočni).

1. INTRODUCTION

Several different classifications of speleological objects have been made up to now. Unfortunately, inconsistencies of some classifications have resulted in the appearance of several criteria within a single division which in turn gave rise to different interpretations and provoked confusion among speleologists and hydrogeologists. For example, the division into caves, pits, "ice holes" and potholes in itself contains classification according to the main channel inclination (caves, pits), according to hydrogeological function (potholes), according to the physical condition of materials in a particular object (ice, snow) and, finally according to local names.

The intention was to create an universal classification of speleological objects using speleomorphologic and speleohydrogeologic criteria. Furthermore, numerous examples of objects investigated in the Croatian karst could not have been avoided. These classifications can be applied in all karst zones of the world (despite different speleogenesis, tectonics, lithostratigraphy etc.). Classifications of speleological objects made in 1976 and 1982 (ČEPELAK & GARAŠIĆ, 1982) served as the starting point for this investigation.

2. SPELEOMORPHOLOGICAL CRITERIA

The shape of a speleological object (cave) depends on lithologic and stratigraphic characteristics of the rocks from which it originates (MOORE & SULLIVAN, 1978), on the intensity and type of tectonic activity, the underground water activity, the karstification rate and, finally on speleogenesis (ALBOY, 1975, GARAŠIĆ, 1989a, 1989b, JASINSKI, 1966).

2.1. TYPES OF SPELEOLOGICAL OBJECTS

While studying the features of caves in the Croatian (Dinaric) karst (GARAŠIĆ, 1986, 1987, GARAŠIĆ & CVIJANOVIĆ, 1985, 1986). It was noticed that their most correct division was based on the main channel inclination (ČEPELAK & GARAŠIĆ, 1982) since, in this way, the speleological objects, i.e. all cavities in the Earth's crust in which a man can be physically present (CURL, 1964, GVOZDECKIJ, 1981), could be divided into caves and pits. It is essential (according to UIS - Union International de Speleologie) that caves must be over 10 meters long, while the depth of pits should exceed 5 meters. Smaller objects are classified only exceptionally if they are characterized by some specific features (e.g., if they are found in rocks where their occurrence is not normally expected or if they are the collapsed parts of some greater objects, etc.).

Other classifications, e.g. into caves, pits, potholes, "ice holes", sinkholes, etc. could not have been regarded as the most appropriate solution since several criteria were adopted in a single division. The same applied for the classification due to local names such as zvekaras, bezdankas, semicaves, potholes, pits,.. etc. as these names are in fact synonyms for the same type of speleo-features.

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Horizontal speleo-features in Croatia are most commonly formed in zones of slightly inclined bedded rocks, along horizontal longitudinal faults or, less frequently, next to nappes.

Vertical speleo-features encountered in Croatia are usually found near deep reverse faults, anticlines and overturned beds and folds.

Over 6000 speleological objects (caves) are registered in Croaitan karst region (Figure 1.) and the data for 5263 of such objects are considered in this paper (i.e. dimensions, strikes, forms, types, geological and hydrogeological characteristics, etc.).

Fig. 1. - Croatian karst area in which speleological objects are located with Inner, Middle and Outer karst zone or region
Slika 1. - Područje hrvatskog krša u kojemu se nalaze speleološki objekti s unutrašnjim, središnjim i vanjskim krškim pojasom

2.1.1. Caves

Caves are one type of such speleo-features (KYRLE, 1923, FORD & CULLINGFORD, 1976) where the main channel is slightly inclined or horizontal. Theoretically, caves include all objects whose main channel is inclined from 0 to 45° (rise or dip) (RENAULT, 1970, MARTINOFF, 1976). About 29% (1526) of all speleo-features encountered in the Croatian karst region are horizontal speleo features. Some examples are: Drljića Cave (Pažarište, Lika), Dančinova Cave (Raduč, Lika), Pčelina Cave (Mogorić, Lika), Veternica (Medvednica, Zagreb), Cave Lipa (Lokve, Gorski Kotar), Kuštrovka (G.Dubrave, Kordun)...total : 1526 caves.

The arrangement of caves in relation to hydrogeologic regionalization is different for individual karst regions (HERAK, 1976, 1984, 1986). In other words, most of the caves in Croatia are situated in the Inner Karst region (over 65%), while they are less frequent in the Outer Karst region (about 24%). Caves are distinguished according to the arrangement of the main channel and side channels: simple caves, dendritic caves, level (etage) caves and cave systems.

2.1.2. Pits

Pits are vertical or inclined speleo - features (inclination from 45° to 90°-rise of dip) (BURKE & BIRD, 1966). In the karst region of Croatia the number of registered pits predominates over the number of caves (3631 pits = cca 69%). Some examples are: Golubnjača pit (Podlapac, Lika), pit called "Jama na Kamenitom vršku" (Delnice, Gorski Kotar), Martineza pit (Buje, Istra), Brgud pit (Dragozetići, The Island of Cres), Vilim pit (Lokvice, Mt.Biokovo), Trogrla pit (Mt. Dinara), Duple pits (Zrnići, Mt. Velika Kapela), Đurinka pit (Kosinj, LIka), Jama u gaju (Kozalj vrh, Kordun)... the total of 3631 pits.

Their distribution is unequal in different karst areas of Croatia. Pits account for 76% of all speleo -features in the Outer (Adriatic) Karst belt, and for approx. 30% of such features encountered in the Inner Karst belt. On some localities, pits are almost the only speleo-features, i.e. at Štirovača on Mt. Velebit, Mt. Velika Kapela, on the island of Brač. Pirkovača pit (Lađena, Mt. Biokovo) from the Outer Karst belt is presented in SUPIČIĆ (1981) work. According to the shape and distribution of the main and secondary channels, pits can be: simple, branching, step like pits and pit systems.

2.1.3. Combined or complex speleological objects

It is sometimes very difficult or almost impossible to define the character (type) of a speleo-feature. An object may be a combination of vertical and horizontal speleo-features where no single feature is predominant (FENELON, 1974, BÖGLI, 1980, GEZE, 1965, AUDETAT, 1981). For instance, a speleo-feature with a vertical entrance (pit) may continue as a cave, while a speleo-feature with the horizontal entrance (cave) may continue as a pit (TRIMMEL, 1968, TROMBE, 1973). If vertical and horizontal dimensions are more or less equal, it is impossible to define the type of a speleo-feature. In such cases, we are dealing with complex or combined speleo-features. Such objects account for approx. 2% (106) of all objects found in the Croatian karst and they are linked to the Inner and Middle Karst belt. Some examples are: "Mijatova jama" pit (Mateško selo, Kordun), Kojina cave (Furjan, Kordun), Zakičnica VII pit (Mt. Medvednica, Zagreb), "Vrbanova peć" Cave (Lovinac, Lika)...total: 106 caves.

The complex speleological object of Mijatova pit (Mateško selo, Kordun) from the Inner Karst belt is presented in GARAŠIĆ, 1980).

2.2. MORPHOLOGICAL TYPES OF SPELEOLOGICAL OBJECTS

Types of speleo-features called morphologic types may be differentiated according to the shape and distribution of channels in speleological objects.

After analysing the distribution of different morphologic types of speleological objects in the Croatian

karst, it is possible to conclude that simple pits and caves generally predominate in the Outer Karst belt (Istra, Islands, Mt. Velebit, Mt. Biokovo) and branching speleo-features appear at points where several joint system meet (especially in the Inner and Middle Karst belt - Kordun, partly in Midhighlands of Lika, etc.). Also, the level speleo-features are located in the areas of the neotectonic uplift (Mt. Velebit, Mid-Hightlands of Lika, Mt. Dinara, etc.) in the Inner and Outer Karst belt, and the steplike pits most often appear in areas with alternation of limestones and dolomites, i.e. in areas with lithologically and sometimes even stratigraphically different units (i.e. Pit of Bunovac on Mt. Velebit) in Triassic limestones and dolomites, Šimunova pit on Mt. Mala Kapela-the alternation of the Jurassic limestones with cherts and dolomites etc. Finally, the cave and pit systems are located in the tectonically very active zones where even hydrogeological relations are such that several speleo-features are joined into a single feature (Kordun, Lika, Gorski Kotar).

2.2.1. Simple speleological objects

Simple speleological objects have only one channel (horizontal or vertical) without secondary ones. Although one might think that simple speleological objects are usually of smaller dimensions, it is not always the case: some caves are more than 200 metres deep (Mamet pit, Mt. South Velebit) and might be over 400 m long (Kuruzovićeva cave, Vaganac, Lika) and are still considered to be simple speleo-features.

It can generally be stated that such objects originate in compact rocks, and that their sepeleogenesis started from one source.

About 20% (1115) of total number of speleo-features in the karst of Croatia are simple pits and caves (including abries - that are formed almost exclusively by the sea or lake wave action). Some examples are: Mamet pit (Štikada, Mt. Velebit), Kuruzovićeva cave, (Vaganac, Lika). Podgračišće II pit (Pražnice, Brač Island), Semič pit (Semič, Istra), Vrtlina cave (Visočica cave, Velebit), Kovačićeva cave (Pražnice, Brač Island), Pećina kod Plasa (Brinje, Lika), Ponor Sušik sinkhole (Drežnica, Gorski Kotar), Pražić ponor sinkhole (Zrnići, Mt. Velika Kapela), Mamulna cave (Bunić, Lika), Zelena cave (Bunić, Lika), Karinčica (Karin, Ravni kotari),... total: 1115 caves.

Simple caves and pits are not equally distibuted within karst belts: they are most often found in the Outer Karst belt. The simple cave of Vrtlina on Mt. Velebit is presented in PAVLIČEVIĆ(1966), whereas the simple pit Podgračišće II near Pražnice on the island of Brač is shown in Figure 2.

2.2.2. Branching speleological objects

Speleo-features with at least one secondary channel of the horizontal or vertical type are considered a branching type. The size of branching speleo-features

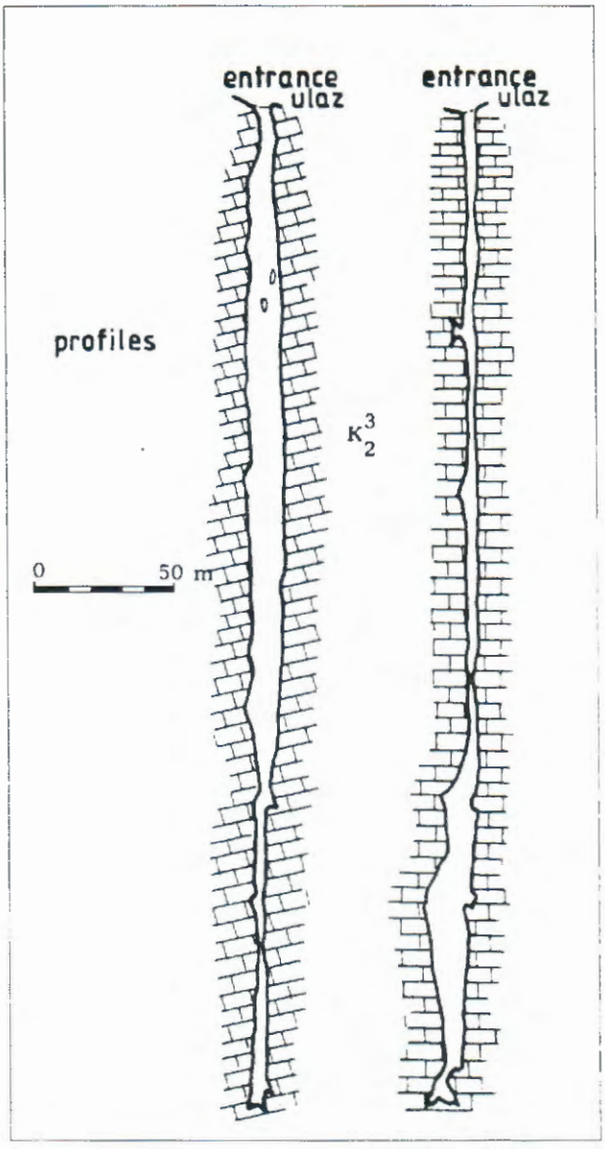

Fig. 2.- Simple pit - Podgračišće II (Pražnice, Island Brač) after GARAŠIĆ (1974)
Slika 2. - Jednostavna jama - Podgračišće II (Pražnica, otok Brač) prema GARAŠIĆ (1974)

is variable (i.e. from several tens of meters to several kilometers). Within the total number of speleo-fetures found in the karst of Croatia, the branching type is represented by cca. 30% (1526). Some examples are: Cerovačka Lower cave (Cerovac, Lika), Gospodska cave (Cetina river spring, Dalmatia), Rudelića cave (Civljanje, Dalmatia), Cave on Gromački vlak (Dubrovnik, Dalmatia), Zala cave (Gornje Dubrave, Kordun), Cave near Veliki Kozarac (Vrbovsko, Gorski Kotar), Hajdova hiža cave (Kuželj, Gorski Kotar), Bezdan pit in Sadilovac (Mt. South Velebit), Đukić caves (Tušice, Lika), Mačje pits in Medačka staza (Mt. South Velebit), Golubnjača pit (Veliko Rujno, Mt. Velebit), Gajića cave (Gračac, Lika), Bijela voda cave (Karin, Ravni kotari),...total : 1526 caves.

Most caves are characterized by maximum of 3 different joint systems parallel to the cave (pit) chan-

nels. Branching speleo-features are most often encountered in the Inner Karst belt, but they are also frequent in the Middle Karst belt. In the Outer Karst belt branching speleo-features are less represented. This is understandable if one takes into account the fact that this type develops mostly in the horizontal speleo-features that are less common in the Outer Karst belt. The branching speleo-feature Barićeva cave (Ličko Petrovo selo, Lika) located in the Inner Karst belt is presented in ČEPELAK (1965).

2.2.3. Level speleological objects

Level speleological objects are the objects where cave channels are developed in several different levels or floors. Horizontal speleological objects are by far more numerous than vertical ones. In the Karst of Croatia, they account for approx. 9% (474) of the total number of the registered speleo-features. Some examples are: Veternica (Mt. Medvednica, Zagreb), Cave near Luka (Sića, Kordun), Ostojića cave (Štikada, Lika), Pivnica cave (Mt. of Žumberak), Babina cave (Lovinac, Lika), Lokvarka cave (Lokve, Gorski kotar), Bibička cave (Trošt Marija, Gorski kotar), ...total : 474 objects.

Such speleo-features are the most numerous in the Inner and Middle Karst belt, particularly in the well bedded limestones. The level speleo-features usually exceed 100 meters in length, while some branching level caves ar more than several kilometers long. The level cave called Mala Hajdova hiža (Kuželj, Gorski Kotar), located in the Middle Karst belt is presented in Fig.3.

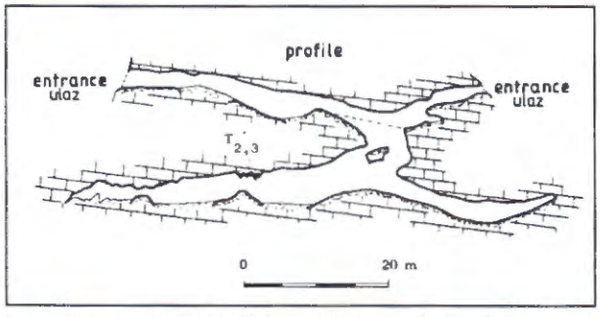

Fig.3. - Level cave - Little Hajdova hiža cave (Kuželj, Gorski kotar)
Slika 3. - Etažna spilja - Mala Hajdova hiža (Kuželj, Gorski kotar)

2.2.4. Knee formed speleological objects

Knee formed speleological objects are those that have two or more vertical steps. This morphologic type accounts for approx. 40% (2095) of total number of speleo-features in the Croatian karst and is therefore the most frequent morphologic type. This is due to the fact that they are developed exclusively in the vertical speleofeatures (pits) that are more frequent that are more frequent than caves. Some examples are: Pepelarica sink hole (Jadovno, Mt. Velebit), Vilimova pit (Lokvice, Mt. Biokovo), Jama pit near Rašpor (Rašpor, Istra), Sink hole near Klana (Klana, Rijeka), Jama kod Matešić stana (Gornji Humac, Brač Island), Sink hole Ponikva II (Skrad, Gorski kotar), Batluška pit (Batlug, Istra), Balinka pit (Plaški, Lika), Gligina jama (Studenci, Lika), Jama na Vršćiću (Kuselj, Lika), Ćampari pit (Beli, the Island of Cres),..the total of 2095 objects.

Cave scallops in the step like (knee formed) speleological object Jama pod Debelom glavom (Veljun, Kordun) (GARAŠIĆ 1990) are presented in photo 1. Knee formed speleological objects are most frequently found in the Outer and Middle Karst belt, especially in the areas with the horizontal or slightly inclined bedding, and with distinct lithologic and stratigraphic changes (i.e. changes in Triassic limestones and dolomites on Mt. Velebit, or the alternation of Jurassic limestones, dolomitic limestones and dolomites on Mt. Biokovo). Their size can vary from a few tens of meters to several hundred meters. The knee formed pit located on the Grgin brijeg (Mt. Velebit) is presented in GARAŠIĆ (1982).

2.2.5. Cave or pit system

This is the most complex morphologic type of speleo-feature of the Croatian karst. This type can briefly be defined as two or more speleological objects joined into a single unit. The system must have at least two entrances. Only several tens of cave systems approx. 1% (53) are registered in the karst of Croatia and only some of them are a few kilometers long. Smaller speleo systems are found in the Outer Karst belt, while the greatest and most complicated systems are located in the Inner Karst belt - more than 15 kilometers long. Some examples are: Đulin ponor - Medvjedica cave (Ogulin, Gorski kotar), Muškinja cave - Panjkova cave (Kršlja, Kordun), Jopičeva cave - Spring Bent (Brebornica, Kordun), Kiceljeve pits (Little and Big) (Ravna Gora, Gorski kotar), Matešića peć cave system (Lađevac, Kordun),...total : 53 objects.

All cave and pit systems found in the karst of Croatia have strong active water streams which leads us to the conslusion that they are still in the second phase of the speleogenesis. These systems are formed in the Cretaceous and Jurassic limestones, partly in the dolomitic limestones. The number of very complicated systems found so far does not correspond to the actual distribution - I believe that these sustems are more numerous.

Cave systems are located in the tectonically very fractured rocks with prominent bedding, and powerful active underground water streams. Cave system Mukškinja cave - Panjkova cave (Kršlja, Kordun) located in the Inner Karst belt is presented in GARAŠIĆ (1984b).

3. SPELEOHYDROGEOLOGICAL CRITERIA

3.1. SPELEOLOGICAL OBJECTS AND KARST HYDROGELOLOGY

The dependence between the good understanding of karst hydrogeology and the speleological objects has been known for a long time (CASTANY, 1982). Speleological features with a hydrogeological function, i.e. sink holes, ponors, springs or percolating objects be-

long to the circulation chain of the karst water. Some authors (JENNINGS, 1971, 1985, GAMS, 1974, JAKUCS, L. 1977, COLLIGNON, 1989) even explain the Paleo-conditions in various types of karst hy establishing a direct relation with speleological features.

The first scientific theories on karst and levels of subsurface waters are based on data derived from the knowledge about speleological features - (GRUND, 1903, KATZER, 1909, CVIJIĆ, 1925). Recent investigations, (BAHUN, 1968, 1969, BAHUN & FRITZ, 1971, BOJANIĆ & FRITZ, 1970, HERAK & STRINGFIELD, 1972, MAGDALENIĆ, 1971, 1984A, MILANOVIĆ ,1979), using the modern scientific hydrogeological approach, stress the importance of "Subsurface geology" - speleogeology results, that contribute to better understanding of the Croatian karst (JURAK, 1984).

In some karst areas of Croatia, especially near the dividing line of Adriatic and Euxinic drainage areas, speleological features can be significant indicators for defining the dividing line (i.e. Kamenak cave near Vodotеč in Lika - MAGDALENIĆ (1984b), or Rokina bezdana near Jezerane in Lika . HERAK &STRINGFIELD (1972), MILANOVIĆ, (1979) and BAUĆIĆ (1965) analyze some caves located in the Croatian karst area, where the subsufrace connections between sink holes and springs had been established by dyeing. These connections were later confirmed by speleological methods - general strike of cave channels in that area with respect to the direction of underground flows (i.e. Imotsko polje, Sinjsko polje). ZÖTL (1974) also describes the importance of understanding the karst hydrogeology during the tunnel construction in karst. During the excavation of practically all longer traffic or hydrotechnical tunnels in Croatia, caverns, i.e. speleological features without the natural surface exit - were found (BOŽIČEVIĆ, 1983, MALEZ, 1956, GARAŠIĆ, 1988) in Učka tunnel (over 1350 meters long) Vrbovsko - Stubica (17 caverns up to 50 meters long), tunnel for "Obrovac" reversible power plant (caverns longer than 1,5 kilometres and chambers bigger than 100 metres) and during the construction of some other structures. The necessity of hydrogeological and speleological explorations during the construction of such structures is obvious. In the karst of Croatia in urban areas (i.e. Rijeka, Split, Dubrovnik) of away from them (i.e. HPP Sklope in Lika), speleological features that might endanger the stability of constructions at those sites were found during the construction works. Speleological explorations helped to gain more knowledge about the hydrogeology of those areas (BONACCI, 1987), indirectly about engineering geolgical characteristics of rocks on particular sites, and about the possiblities for the safe and correct execution of works. It is nowadays widely accepted that the full knowledge about the karst hydrogeology is not possible without the proper knowledge about morphology and hydrogeology of speleological features. That is the reason why the spelological features have been treated as an important part of hydrogeological cadastres (ŠARIN & URUMOVIĆ, 1980)

3.2.HYDROGEOLOGICAL FUNCTION OF SPELEOLOGICAL OBJECTS

The inseparable relationship between the karst hydrogeology and speleological features that is derived from the verycomes just from the hydrogeological function (rule) of speleo-features is well known, no matter if it relates to the past or present function (KEMPE, 1972, BRETZ, 1942).

If we sort speleo-features with permanent or periodical ground water occurrence that can be found in the karst of Croatia, we may differentiate the following types:

a. Periodical Springs (caves or pits)
b. Permanent Springs (caves or pits)
c. Periodical Sink holes (caves and pits)
d. Permanent Sink holes (caves and pits)
e. Estavelas
f. Vruljas (submarine springs)
g. Percolating speleological objects.

3.2.1. Periodical springs

Periodical spirings are such speleo-features from which water springs during the rain season. There are 3,5% (193) such springs registered in the Croatian karst. Periodical springs are more often caves than pits, but more than hundred meters deep pits, taken as periodical springs have also been registered (i.e.near Vrgorac, Župa, Pavlinovići in Biokovo hinterlands and in Imotska krajina). The spring cave Vrelo (Jasenak, Gorski kotar) that periodically springs water is presented in GARAŠIĆ (1986) work. Some of periodical springs (caves and pits) are: Špilj (Polojska kosa, Kordun), Šutina jama (Potok, Kordun), Zagorska cave (Josipdol, Lika), Mračna pećina cave (Perušić, Lika), Borina pećina cave (Vrbovsko, Gorski kotar), Duća jama (Katići, Kordun), Pits of Betine (Kokorići, Vrgorac), Gospodska cave (Cetina river spring, Dalmatia), Čavle cave (Muškovci, Zrmanja, Dalmatia). Periodical springs caves are most often located along the rims of karst poljes (Ličko, Gacko, Krbavsko, Sinjsko, Ogulinska zavala etc,) in Middle Karst area. Their function (springing) directly defines the underground water level in the defined period. The springing duration is different (from a few hours to a few months in a year), and depends on numerous factors (the drainage area, the underfound water links, the width and the size of cave galleries , the altitude, lithostratigraphic properties of rocks, hydrometeorological conditions etc.). "Potajica" (intermittent spring), that yields water periodically within strict time intervals also belongs to this group of speleofeatures (Rikavica, Jablanac, Croatian littoral).

3.2.2.Permanent springs

Permanent springs of cave or pit shapes are such speleo-features from which water springs throughout

the year. The quantity outflow may vary even few hundred times, and it depends on the rain and dry seasons of the year. In the karst of Croatia 0,7% (37) such speleo-features are registered. Some examples of permanent springs (caves and pits) are : the Bistrac (Gornje Dubrave, Kordun), Crno vrelo (Kordunski Ljeskovac, Kordun), the Kupa river spring (Gorski kotar), the Rječina river spring (Rijeka), Bent (Brebornica, Kordun), Jastrebinja (Frketić selo, Kordun), Cave near Čankovići (Gračac, Lika),...the total of 37 objects.

Until present time, more spring caves than spring pits have been registered, but that does not need to be the final conclusion about their distribution. Namely, spring pits can be explored exclusively by diving (i.e. the Kupa river spring, the Slušnica river spring, Sinjac spring), but that is still an insufficiently used speleological technique (BURGES, 1976, EXLEY, 1973, 1980). At the same time, exploration of spring caves is possible by means of very simple methods (i.e. walking in rubber boots, by caving boats etc.). Permanent springs appear more often in the Inner Karst belt, but they are also found in the Middle Karst belt. Sources of almost all karst rivers are located in speleological features, but many of them have not as yet been explored. (i.e.the rivers Zrmanja, Una, Mrežnica, Krupa, Krnjeza, etc.). The spring pit Sinjac (Plavča Draga, Lika) is presented in GARAŠIĆ (1986).

3.2.3.Periodical sink holes

Periodical sink holes are such speleological objects that funnel water from surface to underground, so they (caves and pits) act as sink holes during the rain period of the year. All together 5% (258) periodical sink holes are registered in the karst of Croatia. Examples: Ponor on Grgin brijeg (Jadrnovo, Mt. Velebit), Panjkova cave (Kršlja, Kordun), Ponor Jovac (Bročanac, Kordun), Ponor Vratimnice (Ječmište, Mt. Žumberak), Ponor near Ramna Kala (Čimuš, Mt. Žumberak) Jelar ponor (Gračac Lika),...the total of 258 objects. These are relatively frequent speleological features and their relation with periodical springs is variable, but periodical sink holes are more numerous. The cause should be in the quantity of precipitations that reach the karst surface and immediately sink underground by means of periodical sink - caves and sink - holes. The periodical sink cave Tumarna cave (Perjasica, Kordun) is shown in GARAŠIĆ (1981a), while the periodical sink hole Jama u Zelinu (Crni Lug, Gorski kotar) is presented in GARAŠIĆ (1986).

3.2.4. Permanent sink holes

Permanent sink holes are speleo-features into which water sinks all the year round. The water quantity oscillates a few hundred, and even a few thousand times (i.e. Novokračina cave near Rupa in Istra swallows permanently at least 1 to 2 l/sec, but during rain periods even more than 10 m^3 /sec, Pepelarica ponor sinkhole that swallows from 1 l/sec to few m^3/sec etc.). In Croatian karst 1% (55) such speleological features, that act as permanent sink holes, have been registered. Examples are: Perinka pit (Švica, Lika), Sinkhole Ponor on Bunovac (Mt. South Velebit), Tumarna (Perjasica, Kordun), Đulin ponor (Ogulin, Gorski kotor) premanently in past, and now periodically, Ponor Gusci (Točak, Kordun), Ponor Bele vode (Crni lug, Gorski kotar), Ponorac (Rakovica, Kordun), Pit in Pazin (Pazin, Istra) ...the total of 55 objects. They are located near superficial water streams, i.e. by the river banks (the Korana , Krka, Zrmanja, Krnjeza, Krupa etc.) and lakes (the Peruča lake, the Plitvice lakes), or along the rims of karst poljes when they act as main sink holes (ponors) of sinking rivers (the Lika, Gacka, Ričica, Obsenica, Lička Jasenica etc.). The sinkhole Ponor on Bunovac (Mt. South Velebit) that acts as permanent sink hole is presented in GARAŠIĆ (1978).

3.2.5. Estavelas

Estavelas are morphologically complex speleo-features (FORTI & CIGNA, 1978), that are hydrogeologically acting as periodical springs and periodical sinks. The water springs from estavelas during the high level of the underground waters (rain seasons), but with the falling water level, estavelas became sink holes. In the karst of Croatia 7,5% (387) estavelas are registered. They are situated exclusively in the Middle Karst belt. Examples are: Velika pećina (Blata, Lika), Markarova pećina (Stajnica, Lika), Dabar pećina (Dabar, Lika), Pećina kod Tisovca (Lika), Budilovica pećina (Lička Jasenica, Lika), Pećina pod Sitnikom (Dabar, Lika), Crnačka pećina (Jezerane, Lika), Crna pećina (Pazarište, Lika),...the total of 387 objects. GARAŠIĆ (1986) shows the estavela Markarova pećina (Stajnica, Lika) located in the Middle Karst belt. Photo 2. shows phreatic channels in the estavela Velika pećina (Blata, Lika) after GARAŠIĆ & KOVAČEVIĆ, (1990).

3.2.6. Vruljas

Vruljas are speleo-features situated under the sea level (EXLEY & YOUNG, 1982) that act as fresh water springs. They may be permanent or periodical depending on the fresh water supply. They are characteristic exclusively for the Outer Karst belt (ALFIREVIĆ, 1969). In the karst of Croatia, such 0,3% (9) speleo-features have to this date been explored. Examples are: vruljas near Ika, Volovsko, Novi Vinodolski, Senj, Jablanac, Makarska,...the total of 9 objects. Their length varies from 8 to 23 meters, and the depth from 10 do 30 meters, and pits are predominant. Presently available data are insufficient for generalization. Fig. 4. shows Vrulja in the "Podvelebitski kanal", near Senj in the Adriatic sea.

3.2.7. Percolating speleological objects

Percolating speleo-features are those where the active water stream percolates through, but neither comes from the surface (sinkholes), nor springs at the entrance (spring cave). Such speleological features are the most numerous in the Croatian karst and 17% (903) such

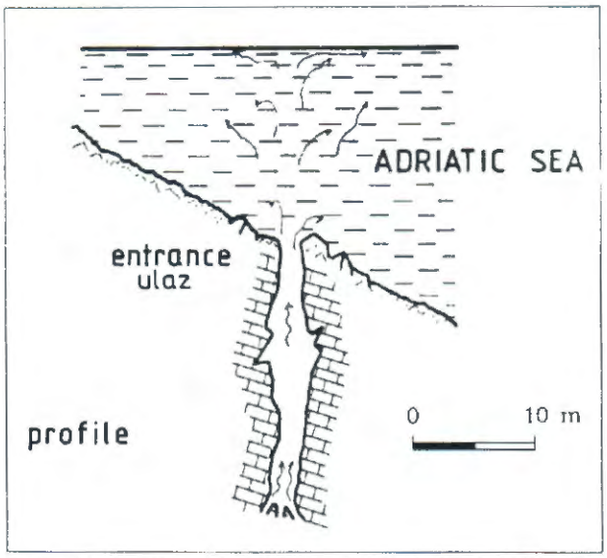

Fig.4. - Vrulja - Unnamed vrulja near Senj in the Adriatic Sea, after GARAŠIĆ (1986)
Slika 4. - Vrulja - Neimenovana vrulja kraj Senja (Jadransko more) prema GARAŠIĆ (1986)

features have been registered. They represent the real treasure of hydrogeological data because the presence of underground water in the particualr karst areas can only be determined by their direct explorations. Percolating speleological objects are the most ususal in the Inner and Middle karst belts. GARAŠIĆ (1986) shows the percolating cave Tamnica (Potok, Kordun). The examples for percolating speleo-features are: Veternica (Mt. Medvednica, Zagreb), Jopičeva cave (Brebornica, Kordun), Tamnica cave (Potok, Kordun), Mijatova jama (Mateško selo, Kordun), Mandelaja (Oštarije, Kordun), Babina cave (Raduč, Lika), Cave Jama pod Debelom Glavom (Blagaj, Kordun), Rokina bezdana (Jezerane, Lika), Javornica cave (Mt. Medvednica, Zagreb).

3.3. WATER IN THE SPELEOLOGICAL OBJECTS

The analysis of the hydrogeological function of the speleological objects in Croatian karst shows that 35 % (1842) of the total number of speleo-features have the hydrogeological function (have the active water), and about 65% (3421) speleo-features are dry. However, even among the "dry" speleological objects there are some with dribbling water of moisture, but in negligible quantities. It should be noted that many speleo-features are not speleologically explored so that it is not possible to exactly define the number of permanent spring caves and pits in Croatian karst. After statistical analysis of 35 % (1842) of all speleological objects with water, the following results were obtained : 10,5% (193) periodical springs, 2% (37) permanent springs, 14% (258) periodical sink holes, 3% (55) permanent sink holes, 21% (387) estavelas, 0,5% (9) vruljas and 49% (903) are percolating objects.

The analysis shows that hydrogleologically percolating speleological objects and estavelas are the most frequent in Croatian karst. Most estavelas are located along the rims of poljes (Ličko, Stajničko, Crnačko, Drežničko, Krakarsko, Ogulinsko, Blata, Gračačko, etc.) in the Middle Karst belt. Estavelas are related to the contacts of permeable and impermeable strata (most often Jurassic and Cretaceous limestones and dolomites with Quaternary clays).

If we consider the water present in speleo-features, we might say that it is the most abundant in Mt. Mala and Velika Kapela (estavelas and sink holes), i.e. Jasenak, Drežnica, Crnac,Krakar, Stajnica, Glibodol, Dabar, Jezerane, Lička Jasenica, Blata, Plaški, Latin, Josipdol, Musulinski potok etc., and in Lika region - Mid-highlands of Lika, Vrebac, Mogorić, Ploča, Lovinac, Sv. Rok, Raduč, Štikada, Gračac, Bunić, etc. Percolating speleological objects are also most often found in Lika (Švica, Komplje, Raduč, Perušić, Pazarište, Korenica, etc.) and in Kordun (Perjasica, Primišlje, Donje and Gornje Dubrave, Potok, Tounj, Kukača, Slunj, Rakovica, Skradska gora, Polojska kosa, Tržačka kosa etc.). Speleological objects with permanent water are rare in Istria (ie. Pincinova pit near Poreč or in the cavern in tunnel "Učka") and on the islands. But, on the islands of Kornati there are 47 registered pits with brackish water (so called bunar pits). In the Bukovica, North Dalmatia and Ravni kotari some speleological objects with water are located near the canyons of the rivers Zrmanja, Krka and Karišnica (Muškovci, Karin, Islam Latinski, Žegar etc), periodical spring caves Bijela voda cave (Karin), Čude cave (Obrovac), Čavle cave (Muškovci). The Krnjeza river spring is significant (the flow estimated in July 1977 was $2m^3/sec$). The speleological objects with water in South Dalmatia are rare - Cave Močiljska, Cave near Gromački vlak near Dubrovnik and cave Šipun in Cavtat (brackish water). The Inner region of Biokovo hinterland has plenty of water in speleological objects, predominantly in pits (i.e. Gvozdenica cave near Zagvozd, Pit in Pavlinovići, Rebići, Župa, Orah, Kokorići, Vrgorac etc.). In the Northern Gorski kotar there are speleological objects with permanent function as springs. (i.e. Trbuhovica cave near Prezid, Tejina pit near Čabar, Zeleni vir spring near Skrad, Pit on the Prezidanski Berinšćek, Cave in Tršće etc.), but the largest number of speleological features in that area have the sinking function. Almost as a rule, the sink holes in Gorski kotar are located at the contact between Triassic or Jurassic limestones or dolomites and older Paleozoic clastites (sandstones, micaceous schist and shales etc.)

The quantity of water in speleological objects may in a certain way show even the reserves of underground water in some areas of Croatian karst. For instance, the quantities of water in Rokina bezdana pit near Jezerane (Mt. Mala Kapela) were estimated. On average flow in the dry season was between 0,5 and 2 m^3/sec (from 1971 do 1988, it was measured eleven times in October and November). The flow rises a few dozen times during the rain seasons (estimated by the erosion marks on rocks in the cave and detritus deposited on the higher terraces inside the cave). In Velika pećina near Blata (Lika), there is 10000 to 20000 m^3 of water that does

not flow out of the cave during the dry season. In the cave under Sitnik (Dabar, Lika), the steady inflow during July and August (5 measurements in 1976, 1981, 1983, 1987 and 1990) is between 300 and 500 l/sec. In Babina cave, that is located near Opsenica sink hole (Lika), during the summer months the flow ranges from 0,9 to 1,5 m^3/sec, in spite of the smaller volume of water in Opsenica sinking hole during the superficial flow (it even dries out completely). Furthermore, lakes 250 to 650 metres long with some 25000 m^3 of water were found in Panjkova and Muškinja cave. A steady flow in dry months (measured in 1983 and 1987) varies from 100 to 200 l/sec. Even during the big drought in the autumn of 1983, this cave system had plenty of water. Such examples are numerous in the Croatian karst, i.e. Krčić, Crno vrelo, river Radašica spring, river Lička Jasenica spring, river Slušnica spring etc.

On several occasions, I witnessed, the rapid rise of water in the sink holes of Croatia and I estimated the quantity, i.e. in Novokračina cave (Rupa, Istra) on November 17, 1967. The amplitude of the wave was 1 meter, and the length 10 metres, the speed was 3m/sec, and the flow was approx. 30m^3/sec. In the Ponor pit on Bunovac (Mt. South Velebit), the flow registered on July 13 ,1977 was 2 m^3/sec at the depth of 65 metres, and in Panjkova cave, the flow registered on November 25, 1985 at the cave entrance was 2 - 3 m^3/sec. GARAŠIĆ, M. (1981c, 1986, 1990) quotes the data about some speleological objects with water in Croatian karst and specifies the water quantity (flows) for some of them.

4. CONCLUSION

Based on the data of large number (5263) of researched speleological objects (features) in Croatian Karst, morphological and hydrogeological classification was made. It is a matter of large number of objects, the largest accumulated at one place in Croatia up to now. Situation, morphology, hydrogeological function, as well as the genesis type of speleological object show particular regularity in appearances of these phenomena in Croatian karst. Since the Croatian karst, due to hydrogeological districts (areas) and according to hydrogeological function, is divided in Inner, Middle and Outer karst region (zone), the incline and form classification of the cave channels (morphologicaly), excatly add and build an additional part to the mentioned hydrogeological districts (areas). For example, in the Outer karst region vertical speleological object (shafts and pits) predominate (simple or knee type), whereas in the Middle karst region branching or level speleological features with estavela function predominate.

Speleogenesis, not especially prominent in this work, but serving as a classification base, by all means caused the appearance of type of every speleological object (feature) in tectonic function (especially neotectonic), in lithostratigraphic and hydrogeological functions and geological processes of erosion, corrosion, abrasion etc.

The orientation of the main channels of speleological objects is closely connected with the appearance of faults, folds, anticline crests in certain areas of the Croatian karst. About 66% (3474) of speleological objects are oriented in the direction NW - SE, the so called "Dinaric direction", while 16% (842) of the objects are almost vertical on that direction, and 18% (947) of the objects are oriented in different directions.

In the Croatian karst, 29% (1526) of the caves (horizontal objects) were registered, mostly in the Inner and Middle karst region. Also were found 69% (3631) of the pits and shafts (vertical objects), and they were mostly in the Outer and Middle karst region. In the Inner karst region there were 2% (106) of speleological objects that were combined or complex.It was the difficult to determine wheather they were pits of caves.

According to the form and distribution of the channels in the objects, Croatian speleological features are divided in simple caves and pits 20% (1115), branching objects 30% (1526), level objects 9% (474), knee formed objects 40% (2095) and cave systems 1% (53).

From the hydrogeological standpoint, speleological objects are divided according to the hydrogeological function - dry objects 65% (3421) and objects with water 35% (1842). Water is continually present in about 19% (1000) of the objects, and in 16% (842) of the objects it depends on the season . In the Croatian karst water appears in the speleological objects with the following hydrogeological functions: periodical springs (caves or pits) 3,5% (193), permanent springs (caves or pits) 0,7% (37), periodical sink holes (caves or pits) 5% (258), permanent sink holes (caves or pits) 1% (55), estavelas 7,5% (387), vruljas 0,3% (9) and percolating speleological objects 17% (903).

The percentage maybe slightly changes the relations among occasional classes, but it is quite certain that all the morphological and hydrogeological classifications will be the basis for further and more precise divisions. Using these classifications every speleological object in the Croatian karst, indisputably, will be defined morphologically and hydrogeologically.

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