SPELEOLOGICAL FEATURES (CAVES AND PITS) AND THE KARSTIFICATION PROCESS OF THE MESOZOIC ROCKS IN THE CLASSICAL KARST OF CROATIA

SPELEOLOŠKE OBLIKE (JAME IN BREZNA) IN ZAKRASEVANJE MEZOZOJSKIH KAMNIN NA KLASIČNEM KRASU HRVATSKE

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Mladen Garašić: Speleološke oblike (jame in brezna) in zakrasevanje mezozojskih kamnin na klasičnem krasu Hrvatske

Analiza in računalniška obdelava preko 7300 speleoloških objektov na Hrvaškem (JV Evropa) kažeta, da je tako veliko število objektov tudi odraz kraških procesov. Predvidoma je na Hrvaškem okoli 17000 jam, kar je veliko število, glede na relativno majhno ozemlje. Hidrogeološki vidiki zakrasevanja kažejo na medsebojno odvisnost med talno vodo in intenzivnostjo zakrasevanja. Meritve kažejo na neotektonsko aktivnost, ki sega vsaj nekaj km globoko v mezozojske kamnine. To dokazujejo tako geofizični poizkusi kot tudi običajna vrtanja. Čeprav je zakrasevanje proces, ki zahteva dolgotrajne raziskave, že predhodne raziskave, predstavljene v tem prispevku, kažejo, da je zakrasevanje na teh območjih tako intenzivno, kot redkokje drugod na svetu.

Ključne besede: speleologija, zakrasevanje, jame, brezna, mezozojske kamnine, klasični kras, Hrvaška.

Abstract UDC 551.44:551.49(497.13)

Mladen Garašić: Speleological features (caves and pits) and the karstification process of the Mesozoic rocks in the Classical Karst of Croatia

The analysis and computer data processing for over 6500 speleological structures found in Croatia (southeast Europe) shows that the formation of a great number of caves and pits discovered in this area is also due to the process of karstification. It is assumed that there are about 17000 caves in Croatia which is a great number considering the relatively limited area in which they have been formed. Hydrogeological aspects of the karstification process point to the dependency between the ground water occurrence and the intensity of karstification. The measurements show neotectonic activity in the Croatian karst which spreads at least several kilometers into the depth of the Mesozoic rocks. This has been proven through geophysical testing, but also through trial boring. Although the karstification process is a phenomenon which will have to be investigated over a long period of time, the initial investigations presented in this paper already show that the karstification in this area is of intensity rarely found in other regions of the world.

Key words: Speleology, Karstification, Caves, Pits, Mesozoic Rocks, Classical Karst, Croatia

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INTRODUCTION

The karstification process has been observed in the speleological structures of Croatia in many localities (Garašić, 1993), but it is most marked in the Mesozoic rocks of the carbonate facies. These rocks are mostly limestones, dolomitic limestones, lime dolomites of the Trias, Jurassic and Cretaceous with all their varieties, from both lithologic and stratigraphic aspects. Among the over 7300 speleological structures that have been explored to this date, about 77% are vertical structures (pits), 22% are horizontal (caves), while the remaining 1% are combined speleological structures (Garašić, 1986,1991). Results obtained by trial boring in the Adriatic karst of Croatia show that karstification processes occur even at depths of over 4 km. Speleothems formations have been found in the Jurassic limestones. It should be noted that the thickness of Mesozoic rocks found in that area amounts to approx. 8 km. However, the best observations of karstification processes have been made in the course of speleological investigations.

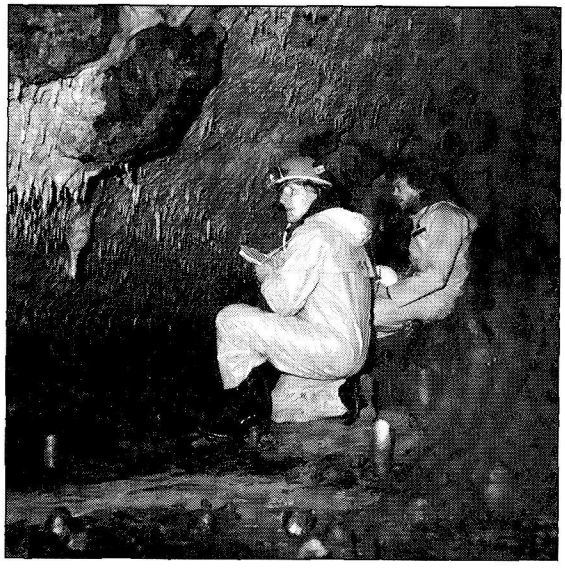
THE INFLUENCE OF THE PRECIPITATION, TEMPERATURE AND ALTITUDE ON THE FORMATION OF SPELEOLOGICAL STRUCTURES IN CROATIA

The mean annual (present-day) quantity of precipitation in Croatian karst amounts to approx. 1500 mm/year. The areas of Gorski kotar, Velebit, Biokovo and the region in the hinterland of the Adriatic have over 2000 mm/year of annual precipitation. The coastal area has the Mediterranean precipitation regimen so that it has up to 50% less precipitation in the hot half of the year and is thus characterized by an irregular annual distribution of rainfall. The analysis of speleological structures and the precipitation rate show that speleological structures are more frequent in regions with greater rainfall (annual precipitation from 2500 to 3500 mm) such as in the Delnice area and at the north side of Velebit (Pavić, 1975). This is due to the greater oportunity for the carbonate rock dissolution. There are however some areas (e.g. in Istria) with an average present-day precipitation rate (from 1000 to 2000 mm/year) where the speleological structures are also quite frequent (Rogić, 1975). The reason for that may be sought in an intensive tectonic

activity although it is most probably due to paleoclimatic conditions. The analysis shows that some very intensely karstified terrains have been formed in regions that currently do not abound in rainfall, such as in Istria and on the island of Brač (Friganović, 1975), but the precipitation rate in such areas was certainly intensive in the period of primary karstification. It may generally be stated that the majority of speleological structures now at the main or even initial stage of formation are situated on the mountain massifs characterized by high precipitation (Velebit, Dinara, Mosor, Velika Kapela, Mala Kapela, etc.). The present-day precipitation rate on the ground surface does not necessarily constitute the basis for the formation of speleological structures because the paleoclimatic conditions are the most significant factor. These conditions have significantly changed in some areas.

The air temperatures in Croatian karst are quite variable, i.e. on the Adriatic coast the winters are mild with the mean January temperatures ranging from +5.5 to +9.6 C, while the summers are warm so that the mean air temperature in July varies from +22.8 to +26.2 C. In the mountainous regions of the Croatian karst the winters are cold - the mean temperatures in January range from -1.9 to -4 C, while the summers are fresh - with the mean temperatures varying from +14.9 to +20.3 C. The relative humidity of air falls when going from north towards the south, i.e. from 85% in Gorski kotar to 65% in southernmost areas of the Croatian littoral (Dubrovnik) (Šarin, 1983).

Speleological structures situated at higher altitudes in areas with low mean annual temperatures and characterized by specific cave shapes and a particular orientation of cave channels and entrances may have snow and ice on their



entrances throughout the year. Such structures are called ice caves and snow caves. They can be found on Velebit (Garašić, 1981), in the region of Gorski kotar, on Biokovo and Dinara. Channel volumes of such structures are much greater than those of nearby structures not containing snow and ice. This is due to the fact that snow and ice mechanically (by dilatation, breaking) wear the rocks thus widening the spelological structures. This is a specific process of karstification. A former action of ice and snow has been observed in some speleological structures, while today such action is negligible, e.g. in the cave near Bačić kuk in Crni Dabar, and in Lukina jama near Hajdučki kukovi and Veliki Lom on Velebit Mt. This is due to paleoclimatic conditions which were earlier much different than they are today, e.g. in Istria or in the central part of Velebit, where visible traces of the former action of glaciers and moraine materials were discovered in the investigated speleological structures.

The possible relationship between latitude and the occurrence of speleological structures has not been established in the Croatian dinaric karst as the karst area is too small when compared to some greater karst areas situated in other parts of the world.

It may be assumed that the present-day altitude of cave entrances is not relevant for the genesis of speleological structures, as their formation is strongly influenced by the paleogeographic conditions.

In Croatia, most speleological structures are located at altitudes ranging from 450 to 850 m above the sea level. Some areas at these altitudes are characterized by a relatively high quantity of precipitation (Lika, Gorski kotar). Both horizontal (32%) and vertical (68%) speleological structures are found at these altitudes. It is interesting to note that the longest speleological structures in the Croatian karst have been found at altitudes ranging between 300 and 350 meters (Đulin ponor, Medvedica, Panjkova spilja (Garašić, 1991b), Muškinja, Jopičeva spilja) (Garašić, 1989). The deepest speleological structures have been found at altitudes ranging from 1100 to 1500 meters (Garašić, 1986a). The deepest cave in Croatian karst ares is Lukina jama near Hajdučki kukovi on North Velebit Mt. with depth -1355 meters.

The analyses of altitude and speleological structures do not always show the most realistic relationships (Maull, 1938; Gvozdeckij, 1981) with respect to the frequency of occurrence of speleological structures. This is due to the fact that many parts of the Croatian karst, particularly those situated at higher altitudes, have not as yet undergone speleological investigation and that most of the Croatian karst is situated at the higher altitudes. It is however certain that horizontal ground water displacement, and hence the greater number of horizontal speleological structures in Croatia, may today be expected on altitudes not exceeding 300 m (internal karst area), while vertical structures that have reached the main stage of their genesis may be expected on altitudes above 800 meters.

The analysis of the present-time quantity of precipitation, temperature and

altitude shows certain regularity in the occurrence of speleological structures. But this analysis does have some limitations which are primarily due to the fact that paleogeographical and paleoclimatic conditions have at some locations been significantly changed since the time of initial formation of speleological structures.

LITHOSTRATIGRAPHICAL DATA SIGNIFICANT FOR KARSTIFICATION

Lithostratigraphical properties of the rocks in which speleological structures may develop are of great significance for the formation and development of speleological structures. These properties have been analyzed in a number of published papers (Swinnerton, 1982; Ford, 1972; Kempe, 1972), and for Croatian karst (Poljak, 1914, 1925; Garašić, 1977; Božičević, 1985).

The karstification is a relatively regular process so that the rocks in which speleological structures are found may be determined through stratigraphic and lithologic analysis. The principal karstification in Croatia occurred in Mesozoic limestones, dolomitic limestones, lime dolomites and dolomites.

About 6% of all speleological structures found in Croatia are situated in the Trias dolomites, dolomitic limestones, lime dolomites and limestones. These structures are of fractured nature, although there is also a number of caves and pits that are quite developed so that some of them are characterized by greater dimensions, such as Veternica, Ponor on Bunjevac (southern part of Velebit), etc. Most structures formed in Trias dolomites are characterized by the constant presence of ground water which can be explained by the relative impermeability of Trias formations with respect to some other formations, such as chalky limestones. In the case of dolomites, which are the most frequently encountered, the rocks are of massive structure, they are characterized by sugary fractures, the bedding is not marked, the shape of caves and pits is fractured, and the access to some parts is often impossible as the channels become too narrow. In areas at the stage of neotectonic elevation, the channels of speleological structures have a specific shape of an elongated letter "I".

Trias limestones are less often encountered in Croatia and the channels of speleological structures found in such formations are wider and more voluminous when compared to channels found in the Trias dolomites. They are usually very fissured and weakly to moderately bedded. On Velebit, we have a number of structures that were formed in the Trias limestones containing chert (Danina pećina, the cave above Bukova glava).

About 14% of all speleological structures found in Croatia are situated in the Jurassic limestones. Despite the fact that the area characterized by the Jurassic limestones and dolomites has undergone a relatively limited speleological investigation, it is interesting to note that a great number of speleo-

logical structures has been found precisely in this area comprising a part of Gorski kotar (Garašić,1992), the massif of Velika and Mala Kapela, Velebit and Biokovo. The reason for that should be sought in the great density of occurrence of speleological structures (up to 24 structures per square kilometer), for instance in the area called Samarske stijene and Bijele stijene. In the well bedded Jurassic limestones, the vertical speleological structures are more developed that the horizontal ones, but the presence of water has been registered in only 20% of structures, which is a relatively low percentage. The exceptions are structures formed in the Jurassic dolomites or dolomitic limestones containing cherts where water flows are almost always encountered (e.g. cave near Kučinić selo, Ponor). However, their shape is not so typical if compared to that of structures formed in the Trias dolomites.

From the speleological standpoint, the Cretaceous limestones and dolomites contain the greatest number of structures. Over 65% of all known structures in the Croatian karst have been recorded in these formations. The analysis of Cretaceous formations in speleological structures shows that the most frequent ones are well bedded limestones of the Upper Cretaceous (Senonian). The limestones and dolomites of the Lower Cretaceous are also well represented (approx. 30% of speleological structures found in the Cretaceous formations) as an environment where speleological structures have been formed. Vertical and horizontal structures are almost equally represented in the Cretaceous formations (with respect to their total number) and the water courses are present in such structures in approx. 20% of all cases, which is similar to the water presence information for the Jurassic formations, the only difference being that a much greater number of structures has been found in the Cretaceous limestones and dolomites. Horizontal structures formed in the Cretaceous formations characterized by the neotectonic elevation have a typical "V" shaped cave channel profile.

THE SIZE AND ORIENTATION OF ENTRANCES, THE DIRECTION OF MAIN CHANNELS AND THEIR RELATIONSHIP TO STRUCTURAL TYPES AND KARSTIFICATION

The tectonic predisposition is certainly one of dominant factors in the formation of speleological structures (Garašić, 1984). The practical investigation of a great number of structures has shown that, in their interior, they have rock layers, folds, ruptures, faults and even nappes (overturned folds). M. Herak (1984) provides a geotectonical framework of speleogenesis for the area of Croatian karst which coincides with the results of speleological investigations in the regional sense.

The rock layers may be monitored in almost all speleological structures, but they can best be observed in vertical structures. Limestones are characterized by the most marked bedding and are, in that sense, followed by dolomitic

limestones. In most cases, speleological structures follow the orientation and inclination of layers. In such cases, the orientation and inclination of layers corresponds to the orientation and inclination of the main channel of a speleological structure. In addition, speleological structures develop through the process of widening the interstitial fractures in thick-bedded limestones from the Cretaceous or Jurassic period. In structures formed in rocks whose layers are horizontal and not marked (massive dolomites and limestones), the level of rock fracturing dominantly influences orientation of speleological structures.

In speleological structures, it is easier to observe folds in caves than in pits. It has been established that vertical structures most often develop in the crests of anticlines, while horizontal ones usually develop in synclines. The micro-folds have also been discovered but also the wings of some large forms. It may be stated that the formation of speleological structures is sometimes not directly related to the folding of layers as can for instance be seen in the area of Mala Kapela. Here we have a synclinal shape, but the vertical structures are much more frequent that the horizontal ones. This is due to karstification, i.e. to the fracturing of layers, particularly of the Jurassic and Cretaceous limestones.

Ruptures or fractures occur in all speleological structures. They differ in size, orientation, fill, roughness, etc.

The faults are fractures along which there has been displacement of the sides and of individual rock blocks. In addition to fractures, these are the most common phenomena we find in speleological structures, since almost 90% of all structures in Croatia are located in fault zones. The faults that divide different lithostratigraphical members can more easily be observed, but those situated in the same lithologic environment may also be detected quite readily because of the striae and the smooth paraclases. The occurrence of smooth paraclases is more frequent than on the ground surface. The inclination of speleological structures regularly coincides with the inclination of paraclase, while the horizontal displacement or heave of the fault may be determined through differences among several different levels in a structure.

Nappes are in fact overturned folds and, in Croatia, they are one of the causes of genesis of speleological structures and constitute therefore an important part of karstification. The examples of such phenomena have been observed in the Trias formations of Gorski kotar.

The entrances of speleological structures provide in most cases the explanation of the paleo or recent function of a structure (Bögli, 1980). This is due to the fact that they may point to the spring caves and pits, sinkhole caves and pits, intensity of karstification, the way of formation (caving from above, caving from below, inverse karstification, solution from above, etc.).

The basic orientation of the entrance does not necessarily coincide (although that is very often the case) with the general direction of the main

channel of speleological structures found in the Croatian karst. Approximately 66% of speleological structures are of northwest - southeast direction or "Dinara spreading", 16% are oriented perpendicularly to that direction, i.e. they are of northeast - southwest spreading, while other speleological structures (18%) are of variable direction.

If we compare the orientation of entrance and main channels of speleological structures with the structural units of the lithosphere in the Croatian karst, we may conclude that direction of speleological structures coincides with that of faults, fold axes and nappes. This is an obvious proof that tectonics is a significant factor in the genesis or karstification of speleological structures.

HYDROGEOLOGICAL FUNCTIONS OF SPELEOLOGICAL STRUCTURES AS RELATED TO KARSTIFICATION

A firm link has been established between the rock karstification and the hydrogeological paleo and recent functions of speleological structures. With respect to hydrogeological function, we may observe in Croatia the presence of perennial and intermittent springs, permanent and occasional ponors, flow structures, estavelles and submarine springs. Their location, orientation, size, morphology and hydrogeological potential are directly dependent on the type and intensity of karstification. There would be no real karstification without the influence of ground water which has been found in approx. 18% of all speleological structures of Croatia. Cases of inverse karstification have been found in Istria, while karstification by direct gravity action has been observed on Velebit (Garašić, 1989,1991).

THE LONGEST AND THE DEEPEST SPELEOLOGICAL FEATURES OF THE MESOZOIC ROCKS IN THE CROATIAN KARST

The longest caves in Croatia:

1. Đulin ponor (Đula) - Medvedica (sustav) ..... 16396 m
2. Muškinja - Panjkova spilja (sustav) ..... 12385 m
3. Špilja u kamenolomu Tounj ..... 8143 m
4. Veternica ..... 6804 m
5. Jopićeva spilja - Bent (sustav) ..... 6564 m
6. Donja Cerovačka spilja ..... 2510 m
7. Klementina I ..... 2403 m
8. Mandelaja ..... 2326 m
9. Munižaba ..... 2300 m
10. Spilja za Gromačkom vlakom ..... 2171 m

The deepest pits (shafts) in Croatia:

1. Lukina jama ..... 1359 m

2. Stara škola ..... 576 m
3. Vilimova jama (A - 2) ..... 572 m
4. Ponor na Bunjevcu (Bunovcu) ..... 534 m
5. Jama pod Kamenitim vratima ..... 520 m
6. Fantomska jama ..... 477 m
7. Munižaba ..... 448 m
8. Nova velika jama ..... 380 m
9. Jama kod Rašpora ..... 361 m
10. Biokovka ..... 359 m

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Povzetek

Analiza in računalniška obdelava preko 7300 speleoloških objektov na Hrvaškem (JV Evropa) (med njimi je 77 % brezen in 22 % jam) kažeta, da je tako veliko število objektov tudi odraz kraških procesov. Predvidoma je na Hrvaškem okoli 17000 jam, kar je veliko število, glede na relativno majhno ozemlje. Hidrogeološki vidiki zakrasevanja kažejo na medsebojno odvisnost med talno vodo in intenzivnostjo zakrasevanja. Meritve kažejo na neotektonsko aktivnost, ki sega vsaj nekaj km (tudi preko 4 km) globoko v mezozojske kamnine, ki na tem področju dosegajo debelino približno 8 km. To dokazujejo tako geofizični poizkusi kot tudi običajna vrtanja. Čeprav je zakrasevanje proces, ki zahteva dolgotrajne raziskave, že predhodne raziskave, predstavljene v tem prispevku, kažejo, da je zakrasevanje na teh območjih tako intenzivno, kot redkokje drugod na svetu.