Karstification Dynamics and Development of the Deep Caves on the North Velebit Mt. - Croatia

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Abstract

In an area of approx. 25 km^2 on North Velebit Mt. in the last 10 years more than 200 caves were discovered and explored. The system Lukina jama - Trojama (-1392 m) and Slovačka jama (-1301 m) are the deepest caves in Croatia and the 12th i.e., 18th cave of the world. Furthermore, significant depth was reached at Patkov gušt (-553 m), Ledena jama (-536 m) and Jama Olimp (-531 m).
The development of large caves was analysed in respect to the geology, hydrogeological relations, karstification processes and paleoclimatic conditions. Neotectonic movements with summary amplitudes of about 1600 m, the Bakovac fault and its interruption of the Velebit complex barrier extension, as well as the concentrated recharge during interglacial stages of Pleistocene are recognised as the main factors contributing the speleogenesis.

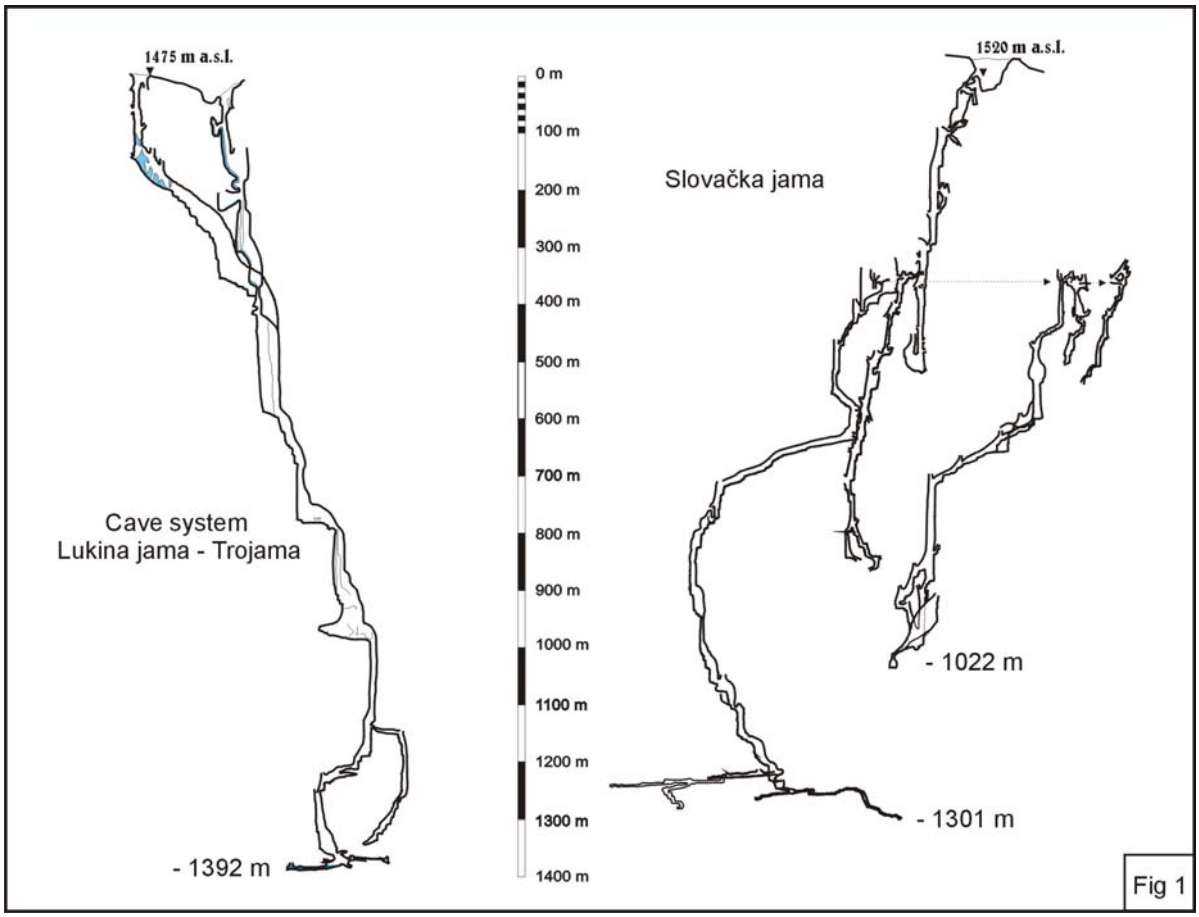
Introduction

Velebit Mt. is the longest (145 km), and according to many, the most beautiful mountain of Croatia. Its strike is NW-SE direction, and it spreads over three Croatian regions: Lika, Dalmacija and Hrvatsko primorje. North Velebit is the mountain region between Adriatic sea and Ličko-Gacko polje. It begins at Vratnik saddle in the north and spreads over to Veliki Alan saddle on the south, with the length of 30 km. The wideness of the massif in the area above 1000 m is also 30 km. The middle parts of the massif reach the heights of almost 1700 m (Mali Rajinac, 1699 m). Although the distance from the sea is only several km, the region of Velebit Mt. is in the mountain climate type. Medium annual precipitation on the north Velebit is in the range from 1500 to 2000 mm. In the highest parts of the massif, the snow stays on the ground over 100 days per year. The medium annual temperature is around 4°C.
The Velebit region is the part of Dinaric karst region, which covers southern half of Croatian territory. The distinct carbonate geology was favourable for development of surface and underground karst geomorphologic phenomena. Although the data of first speleologic investigations of north Velebit mountain region dates from the beginning of 20th century, the systematic investigations did not begun until seventies. Because of the geomorphologic characteristics of surface relief, the area around Hajdučki, Rožanski and Begovački kukovi, the middle, the highest part of north Velebit massif respectively, was considered especially attractive. Extremely hard passability of this area is probably the reason of poor results of these investigations. Up to 1990 only dozen objects with max. depth of 143 m were investigated. At the beginning of the nineties this region was visited by Slovakian speleologists (Student University Club from Bratislava). Lukina jama (Manual) in which they descended up to depth of 195 m was among the first found objects. In summer of 1993 Croatian speleologists, gathered in Commission for Speleology of Croatian Mountaineering Association, organized the first major expedition in that area. At this time Lukina jama was investigated up to unexpected depth of 1355 m. This result initiated numerous investigations in the next few years in which Slovakian speleologists took part together with Croatian speleologists. The last results are very impressive. More than 200 speleogic objects were investigated on the detailed area of around 25 km^2, and the pit system Lukina jama - Trojama and Slovačka jama is ranked among the deepest pits in the world. Up to these investigations the deepest pit in Croatia was the pit Stara škola on Biokovo Mt. 576 m deep, and the deepest pit on Velebit region was ponor on Bunovac (south Velebit) 534 m deep.
In regard to the results achieved up to now, the discussed area of north Velebit is speleologicaly most important area of Dinaric karst region. In the following text the most important natural elements, contributing to the development of such intense karstification processes and genesis of extremely deep speleologic objects in this area are presented.

Morphology of the deepest objects

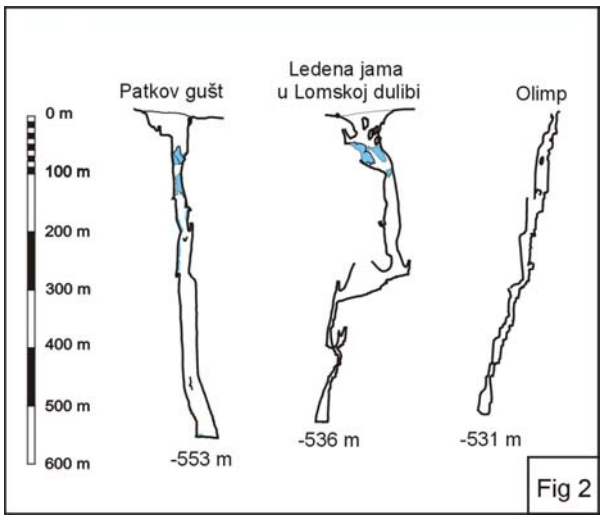
Pit system Lukina jama - Trojama with the depth of 1392 m is the deepest pit in Croatia. The entrance of Lukina jama is at 1438 m above sea level and the entrance of Trojama is placed at 1475 m above sea level. They were investigated in the period from 1992 to 1994. Lukina jama is almost vertical from the entrance up to the depth of 550 m with one inclined snow shelf at the depth of 320 m. From 50 to 320 m, the deposits of snow and ice are on the walls, so the pit temperature in this part is 0°C. At the depth of 520 m there is the connection with Trojama. The continuation of pit is distinctly vertical and there are only 2 places suitable for camping - in the meander at the depth of 743 m and in the great hall with dimension 85×70 m at the depth of 950 m. At the bottom of the pit there is the hall with dimensions 20×5 m with two syphons. Southeast syphon was dived in the length of 57 m ant it continues further. In deeper parts of the pit the air temperature is from 2 to 4°C, and the water temperature in the syphon is 4°C. The bottom of the pit system, reached up to now, is at only 83 m above sea level, with the distance from the sea of around 10.5 km. The length of the system is 1078 m.

Slovačka jama is at 1520 m above sea level. The pit is 1301 m deep and its investigation began in 1995. As opposed to majority of pits in north Velebit, in Slovačka jama there are no snow and ice, what is the consequence of horizontal entering part of the pit. The pits morphology is complex and it can be divided in several entireties. The old part of the pit is stretching up to -514 m. At the depth of -350 m the fossil horizontal canal was found, from which numerous vertical canals are separated. The deepest one, hydrogeologically active, is Velebni canal on whose bottom there is the combination of horizontal canals whose investigations have



not finished yet. The characteristics of the pit are narrow, hardly passable meanders, especially between the depths from 600 to 700 m. The air temperature in upper parts of the pit is from 3 to 5°C, and at the bottom it is from 6 to 8°C. The length of this object is 2414 m.

Pit Patkov gušt is 553 m deep and completely vertical, and was investigated in year 1997. The opening of the pit is at 1450 m above sea level, in the slope of the sinkhole with dimensions 100×75 m. The aperture of the pit is around 65×30 m big. From the depth of 50 to 135 m on the walls there are thick deposits of snow and ice. At the depth of 105 m there is the narrowest place of the pit (2×1.5 m) that was filled with snow and ice in the year 2000. After the depth of 130 m the pit widens and with almost the same profile, it goes all the way down to the bottom.



The walls are completely or partially covered with ice coating up to 300 m depth. The ice breaking is constant danger, so, after the investigations in the year 1997, the pit was visited all the way to the bottom only once. The pit ends with the hall with dimensions 40×30 m.

Ledena jama (Ice pit) in Lomska duliba is 536 m deep. For the first time it was investigated in 1977, when the depth of only 62 m was reached. The further advancing was obstructed by thick layers of ice. Only in 1992 the passage was found through the ice cork 40 m thick. The melting of ice leads to creating the new passages so, up to now, there are three openings in the ice. Morphologically, the pit is simple. It consists of two vertical sections and great hall with dimensions 80×50×60 m in the middle part of the pit. After the narrow part, at the depth of 473 m, which was widened by carving, one comes into smaller hall. The bottom with ground plan of 10×5 m is covered with gravel through which the water is seeping. The pit investigation was finished in the year 1996.

Pit Olimp is 531 m deep. The investigations were carried from 1998 to 2000. Although the pit is at the altitude of 1380 m, there are no snow and ice inside. The reason for that is relatively small aperture (6×3 m) in which the big stone block is fixed. The pit is of simple, knee-like morphology with numerous narrowings and shelves, which emerged mostly by fixing of rock blocks and debris in joints. The air temperature in the pit is 4°C and the water temperature is 5°C.

Lithostratigraphy and hydrogeological properties of the rock units

The studied area of Velebit Mt. is composed of lithostratigraphic units in range from Middle Triassic to the Paleogene age. The

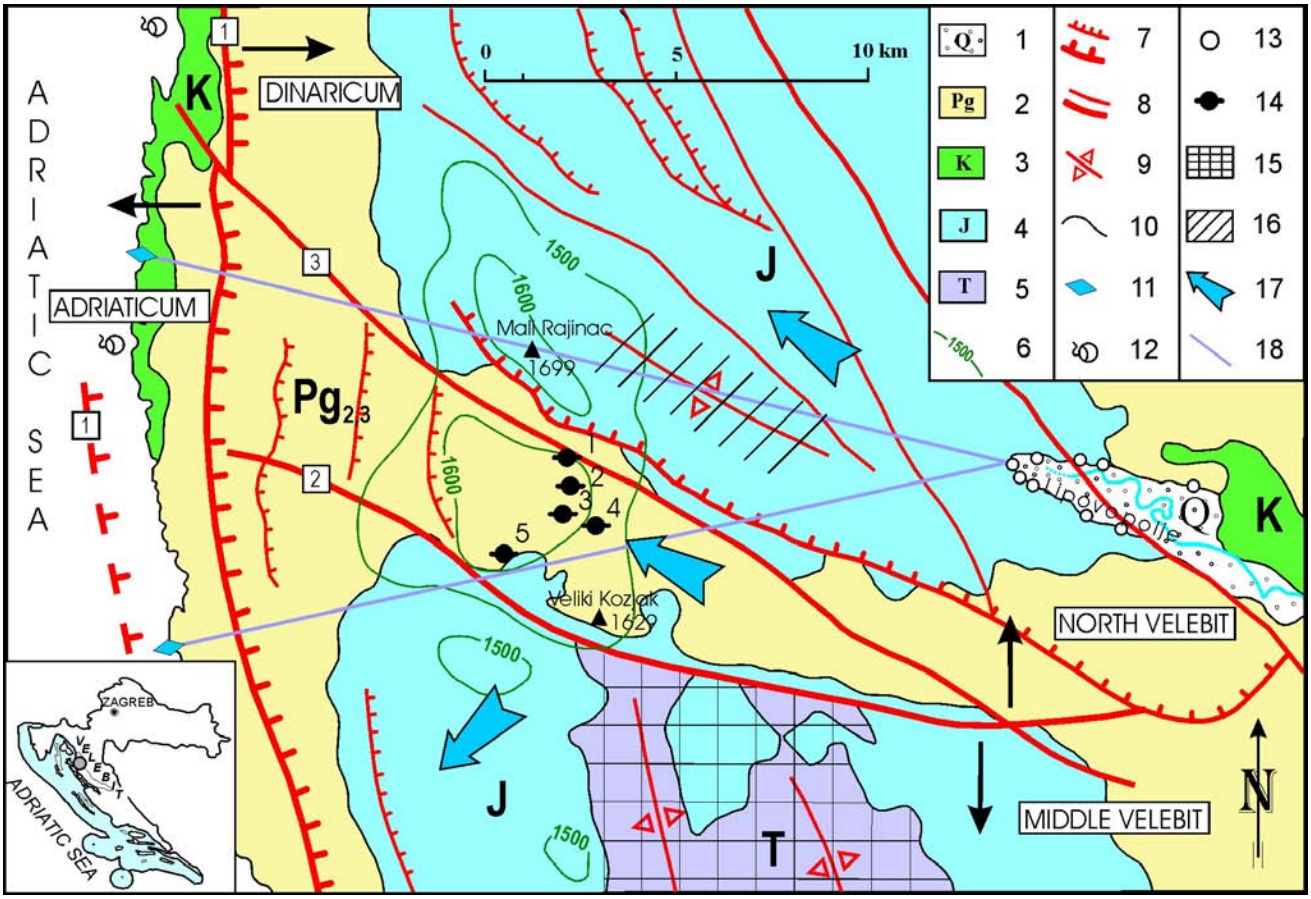


Fig. 3 Simplified geological map of the North Velebit area. Legend: 1) alluvium deposits; 2) calcareous breccias of Upper Paleogene; 3) Cretaceous carbonate rocks; 4) Jurasic carbonate rocks; 5) Triassic carbonate and clastic rocks; 6) summary amplitudes of vertical neotectonic movements (in metres); 7) reverse faults, (1) Velebit fault; 8) normal faults, (2) Bakovac fault, (3) Lomska duliba fault; 9) anticline axis; 10) geological boundary; 11) coastal spring; 12) submarine spring (vrulja); 13) sinkhole; 14) deep caves, (1) Ledena jama, (2) Lukina jama-Trojama, (3) Patkov gušt, (4) Olimp, (5) Slovačka jama; 15) area of Velebit complex barrier; 16) relative barrier; 17) general groundwater flow direction; 18) groundwater flow direction tested by tracing.

MiddleTriassic deposits are mostly composed of limestones. In the uppermost part laterally, the tuff and tuffite occur. The lower part of Upper Triassic is characterised with the sequence of clastic rocks up to 200 m thick represented by shale and sandstones. Carbonate sedimentation proceeded with 250 m thick dolomite deposits. Due to a lower permeability as the consequence of lithological composition (clastic and dolomites), and structural position in the central part of an anticline structure, the Triassic sediments form the complex hydrogeological barrier of Velebit Mt. The largest part of Velebit Mt. is composed of Jurassic sediments, which have been continuously deposited under almost the same conditions and contain carbonate rocks only. In the composition of deposits the limestones prevail but the dolomites are present too. Generally, the Jurassic sediments are very permeable unit but on some locations dolomite retards the groundwater flow and acts as the relative barrier (Apatišan area). The thickness of Jurassic deposits is approximately 2850 m.

In the investigated area, the well permeable Cretaceous sediments have not greater importance. At a narrow belt along Adriatic coast they are represented by limstone-dolomite alteration. In the Lika region on the other side of Velebit Mt. (Lipovo polje) deposits are composed of limestones intercalated by dolomite and calcareous breccias.

The significant part of the area concerned is covered by Jelar formation of Upper Paleogene age. Its origin is closely related on strong tectonic movements, which effected the area during that time. In the hinterland (Lika region) they are partly permeable but on higher positions at Velebit Mt. calcareous breccias are highly permeable. The best prove for the mentioned is the spectacular landscape of Hajdučki and Rožanski kukovi area, as well as the numerous karstic phenomena and the deepest caves of Croatia among them. The thickness of calcareous breccias is up to 300 m.

Tectonic basis of karstification processes

Conceptual basis of geotectonics of the Dinarides established HERAK (1986) in the view of mobilistic theory i.e., the plate tectonic. In the structural pattern of the main body of the Dinarides four dynamic and paleogeographic units are differentiated. The investigated area, as well as the whole Velebit Mt., is situated within structural complex of the Dinaric carbonate platform (Dinaricum), along its contact zone with Adriatic carbonate platform (Adraticum).

The geological structure is the consequence of two main periods of tectonic activity. During the Tertiary tectonic cycle, which lasted from Eocene to the end of Miocene, compressive movements oriented NE-SW reached their cumulative maximum with orogenesis of the Dinarides. As the consequence of mentioned regional tangential stress, the deep nappa structures, folds and regional faults of Dinaric strike (NW-SI) have been formed. During the later, Neotectonic period, the main stress changed to N-S, resulting in further uplift and transpressive deformation of older structures, which were broken in the smaller structural units and tectonic blocks.

On the basis of geology of the studied area and the basic tectonics involved, distinctive areas, structural units and faults that influence the hydrogeology of the terrain and karstification

processes development are presented on Fig. 3. The map was prepared in accordance with data from previous studies BAHUN (1974), PRELOGOVIĆ (1989) and PAVIČIĆ (1997). Numbers mark the most important faults that effected the development of numerous deep caves in the investigated area.

- The regional longitudinal reversal Velebit fault (1) located in the coastal area, on the surface manifested as 4-6 km wide faulting zone, represents the boundary between Dinaricum and Adriaticum megastructural units. The tangential movement is estimated on 6-8 km.
- The Bakovac fault (2) is very strong normal fault. The horizontal movements along it are not observed but the vertical displacement is estimated on about 1500 m (PRELOGOVIĆ, 1989). The fault interrupted extension of
- the Velebit complex barrier and significantly effected the hydrogeological relations in the area. In geomorphologic sense, the Bakovac fault represents the boundary between Middle and North Velebit.
- The Lomska Duliba fault (3) is located on the northern boundary of the investigated area. The vertical displacement is estimated on 150 m.

All mentioned faults have been very active during Neotectonic period. The vertical neotectonic movements were estimated on the basis of deformations of the Jelar formation, position of the Pliocene and Quaternary deposits, comparison with neighbouring areas and disposition and deformation of geomorphologic elements. In the area concerned, the summary amplitudes of these movements reach 1600 m.

Karstification dynamics

The first favourable conditions for karstification occurred in the Dinaride area after the Pyrenean orogeny, when large masses of carbonate rocks were exposed to exogenous processes. However, the Neotectonic movements, which commenced in Miocene and were intensified toward the end of Pliocene and the beginning of Pleistocene, played the major role in the reshaping of the landscape and the development of karstification. At that time, Velebit Mt. was uplifted together with other mountain ranges, while depressions developed as isolated karst plateaux and poljes. Recent studies performed in the Dinaric karst terrain indicate that the present landscape is very young. The majority of the most important and developed morphological features were created during the Lower Pleistocene and Holocene (FRITZ, 1992).

The investigated area is located at the highest (1250 - 1676 m above sea level), central part of Velebit Mt. The general karstification processes as well as the hydrogeological relations are directed by the position of erosion basis i.e., the lost rivers of the Lika region (550 - 480 m above sea level) on the east and the Adriatic Sea westward. The Velebit hydrogeological barrier has a very important role and controls the groundwater conditions and underground discharge from the Lika region toward sea.

The advanced karstification stage at the elaborated area is recognisable from the surface geomorphology, but in the underground the results are even more spectacular. In the last 10 years more than 200 caves were discovered and explored in the area of only 25 km^2. The system Lukina jama - Trojama (-1392 m) and Slovačka jama (-1301 m) are the deepest caves of Croatia and the 12th i.e., 18th. caves of the world. Furthermore, the significant depth was reached at Patkov gušt (-553 m), Ledena jama (-536 m) and Jama Olimp (-531 m). In some areas the density of caves is higher than 40 on one km^2 (Hajdučki kukovi 48, Vratarski kuk 42). Regarding the morphological characteristics the vertical caves (pits, jamas) are dominant and represent 98 % of all explored speleological features.

The development of so strong karstification processes at the studied area was contributed by several major factors.

Along the Bakovac fault the Triassic clastic and dolomite deposits, which built up about 75 km long complex hydrogeological barrier of Velebit are displaced. To the north of the Bakovac fault, the impermeable rocks lie significantly deeper beneath the surface, enabling deeper karstification and groundwater drainage from the Velebit karst hinterland (Lika region) towards the Adriatic sea.

On the other hand, the constant uplift of Velebit Mt. at all, during Neotectonic phase, was the most intensively expressed in the studied area (summary amplitude of the 1600 m). The karstification processes tended to compensate these movements and on the way toward erosion base they developed network of deep underground channels, the cave systems respectively.

The large number and density of caves is the consequence of favourable lithology. Namely, the uppermost part of terrain built up the massive calcareous breccias that are very liable to karstification. The mentioned fact is prooved with the results of cave exploration conducted in same deposits on the other parts of Velebit Mt. (LUKIĆ, 1991), as well as with always present exceptionally indented landscape of such areas.

As already mentioned, the underground discharge from the Lika region supported karstification inside the mountain massive, but the dominantly developed vertical caves indicate the very important role of vertical circulation through the deep unsaturated zone. During the latest geomorphological investigations the traces of Pleistocene glaciation have been established in the North Velebit region for the first time. According to BOGNAR et al., 1992, the cirque, valley and plateau glaciation types have been determined. Based on that, during interglacial periods of Pleistocene i.e. ice melting, the strong and concentrated recharge can be supposed on some locations. The concentrated recharge in the highly situated karst area significantly contributed to the development of the karstification processes and genesis of deep caves.

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