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The Dynamics of Tectonic Modelling of Some Caves in the Karst Region (Croatia)

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Key words: Tectonics, Stress, Caves, Compression, Extension, Karst Dinarides.

Abstract

Deformational processes resulted in the formation of certain caves in the carbonate rocks of the karst area are analysed. Some of the caves were formed by deformational processes connected to extension of the area, while others were formed by processes that followed compression during structural formation of the Dinarides. In the first case, the caves were infilled by calcite material and/or by debris from the surrounding rocks mixed with terra rossa. The second group is mostly represented by caves forming open spelaeological objects.

1. INTRODUCTION

In the karst region of the Republic of Croatia, the carbonate rocks are partly characterised by the occurrence of large and small caves. According to the statistical data of GARAŠIĆ (1991) the "proper caves" form approximately 29% of spelaeological objects, and the remaining of 69% are vertical caves and sinkholes. GARAŠIĆ (1991 p. 30) also observes that "… horizontal and vertical cave systems are located in the zones of marked tectonic activity …". POLAK (1955, p. 66) realised that there must be a causal connection between the fracture systems and formation of horizontal and vertical caves because "… some kind of cavity must already exist in order to enable the chemical action of water …". FRITZ et al. (1981) also observed the direct genetic connection between the faults and spelaeological objects.

Only a few characteristic areas have been analysed structurally in order to prove the tectonic connection with cave formation.

However, the variety of spelaeological objects in the karst region of the Dinarides indicates the need for wider structural analyses of this region.

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2. RESULTS AND DISCUSSION

The studied caves are located on the island of Krk, near the Maslenica strait and in the Paklenica nature reserve, all in the contact zone between the palaeodynamic units of the Dinarides (HERAK, 1986), and also in the Zeleni Vir area.

Formation by **extensional** tectonic processes is characteristic for some caves on Krk island, in the region of Omišalj (Tenka peninsula). The half-opened caves found there were formed by extensional deformation processes during the Pliocene and Quaternary (JAMIČIĆ et al., 1995). The caves are connected to joint systems that were formed under the influence of the NE-SW regional stress. This happened during the Late Palaeogene - Neogene period of tectonic activity, when the Cretaceous-Eocene sediments were folded into a sequence of parallel linear folds - symmetric anticlines and synclines. The fold axes have a NW-SE strike, which is the structural characteristic of the Dinarides. During reverse faulting and thrust faulting of the Cretaceous-Eocene limestones, conjugated shear joints were formed that with the long-lasting influence of stress gradually became the sinistral or dextral transcurrent faults. The prevailing faults are of NE-SW strike, and show dextral tectonic transport of the northwestern blocks. The more frequent occurrence of these faults is in connection with a clockwise rotation of the stress of approximately 30°, when the translation of the foraminiferal limestone rock masses also took place.

In this phase of kinematic formation of the structural fabric the extensional joint systems were also formed. They are found in the zone perpendicular to the regional fold axes and are limited by transcurrent faults. These joints are almost vertical, closely spaced and with rugged walls (Fig. 1), and are frequently encountered in the zones where there is no more than 20-60 cm between the joints. These joints are also present in the flysch deposits, but they are not as frequent. This is explained by the fact that flysch deposits have reduced susceptibility to break caused by their greater ductility index in relation to the Cretaceous and Eocene limestones which loose their elasticity very early in the deformational process. In the Pliocene and Quaternary, the structures that formed were influenced by the changed stress regime of approximately N-S orientation

Fig. 1 The closed fracture system of the zone perpendicular to the structure axis (Tenka peninsula, Omišalj, island of Krk).

Fig. 2 Separate fracture systems filled by calcite material. Formation of a half-opened cave (Tenka peninsula, Omišalj, island of Krk).

(RITSEMA, 1974; Del BEN et al., 1991). Previously formed structures were affected by the newly formed stress field, and were gently folded along the E-W axis. It is around this new axis that the already existing reverse fault planes and regional structural axes of NW-SE strike were folded.

The change in the stress field orientation caused the opening-up of the previously formed fracture systems (Fig. 2). The joints and faults were separated that were unfavourably oriented, i.e. the joints that were approximately at right angles to the new stress direction. Concurrently with this process, the old structures were uplifted and came under the influence of ground water. The opened fracture systems were then filled in by the impure calcite in the stalactite and stalagmite forms that cemented most of the opened joints.

The C^{14} radiometric analysis gave the age of calcite forms of approximately 40 ka. The continuation of opening has been determined at some joints (Fig. 3) followed by formation of vertical caves that reach width of up to 2 m on the surface. These opened joints are filled with loose fragments of surrounding Cretaceous and foraminiferal limestones mixed with terra rossa. The aforementioned clearly confirms the recent activity of extensional processes.

Cave formation under the influence of **compression** is characteristic for the following exploration objects. In the area of the Maslenica anticlinal structure (PRELOGOVIĆ et al., 1995), lies a sequence of smaller and some larger caves that were formed during the modelling of this structure. They are more abundant in the southern limb (Fig. 4) on the western part of the Maslenica asymmetric anticline.

In the initial phases of formation of the Maslenica structure, the Cretaceous limestones were folded into an uplifted anticline of Dinaric strike (NW-SE). The folding commenced in the Late Palaeogene under the influence of the regional stress oriented approximately NE-SW. Joints and faults are the main structural characteristics that follow the folding in this phase of structural formation. A set of fracture systems and fold elements show a symmetric arrangement that suggests that the fractures formed as a direct consequence of folding influenced by a NE-SW directed contraction of the area and its NW-SE extension.

Along with compression of the area and continuation of deformational processes, tectonic transport occurred on the bedding planes towards the crestal part of anticline. This transport is documented by preserved striation marks that are found on the bedding planes. The azimuth of the greatest principal stress axis ($\sigma 1$) based on direct measurements of the striation marks lies in the range of 30-60°. A set of conjugated joints simultaneously formed that would be transformed into sinistral and dextral transcurrent faults in later phases of structural development. An important role in the final shaping of the Maslenica structure was played by NE-SW oriented joint systems, i.e. the joints perpendicularly oriented to the regional B axis. In the later phase of deformation, the Novsko Ždrilo strait was formed by subsidence of tectonic blocks along these joints that are encountered at distance of approximately 20-30 m apart.

The kinematic act of folding was accompanied by the formation of fracture systems parallel to the region-

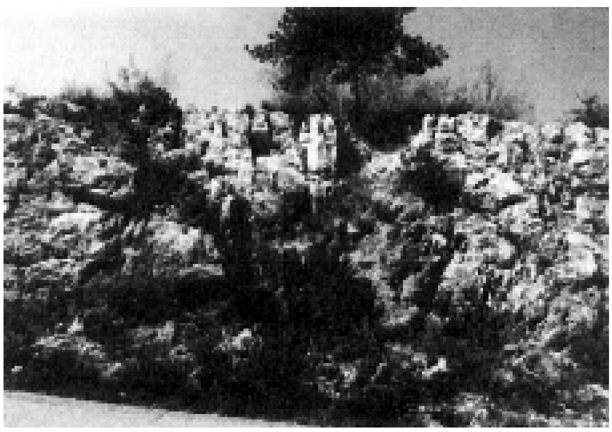


Fig. 3 The cave filled by terra rossa and rock fragments (Tenka peninsula, Omišalj, island of Krk).

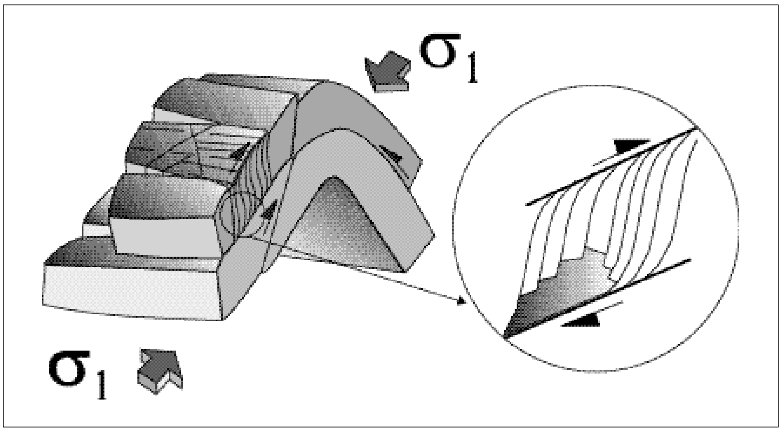


Fig. 4 The formation of caves on the Maslenica structure, along intersections of the bedding planes with the sigmoidal joints of the axial plane cleavage zone.

al B axis; in other words the joints pertaining to the axial plane cleavage zone were formed. These joints have a sigmoidal bend and never crosstransect the bedding planes. The caves were opened by brecciation of rocks at intersections of these discontinuity surfaces with the bedding planes (Figs. 5 and 6). The longitudinal axes of caves follow the regional axis of the Maslenica structure. The caves were, during the Quaternary, mostly filled with deluvial-proluvial deposits, and some remained opened. In most of the caves, stalactites and stalagmites occur, some of them up to 3 m in thickness (Fig. 7), which indicates that the relaxation phase started after the Maslenica structure was uplifted to the level of ground water influence.

With formation of the new regional stress field, oriented N-S, the Maslenica structure experienced new tectonic changes during the Pliocene and Quaternary. The change in orientation of stress caused a gentle bending of the structure around a vertical axis in such a way that its eastern parts rotated counter-clockwise for some 40°. The N-S oriented compression also resulted in the folding of the northern limb of the anticline around a horizontal axis oriented E-W. In consequence, this limb became more inclined thus making the anticline asymmetrical, with the axial plane vergence towards the N-NE. The steepening up of the anticlines northern limb was, in the southern-southwestern limb followed by reverse faulting and displacement of the hanging wall blocks in N-NE direction (Fig. 8a). The reverse faults cut through all the previously formed structural elements. The presumption that these deformation processes are very recent was confirmed by observations made on the Quaternary sediments filling one of the caves, which also has stalactite and stalagmite build-ups. The Quaternary deposits are foliated parallel to the reverse fault planes, and the stalactites are cut and displaced in lengths of 11 cm (Fig. 8b) along the joints parallel to the reverse fault. The age of stalactite formation was determined by C^{14} radiometric dating to be approximately 36 ka, which implies that deformational processes must have been even younger. These faults do not exhibit big relative displacements. Based on the direct measurements of the linear elements they are in the range of 3-11 cm.

The reverse faulting on the southern limb of the Maslenica structure was immediately followed by extensional processes conditioned by rotation of its eastern part. These processes are also recently active, which has been ascertained by the finding of the recent gastropods *Helix pullmonata* fossilised in the material that filled one of the previously opened joints (Fig. 9). This joint, 80 cm wide, belongs to the older deforma-

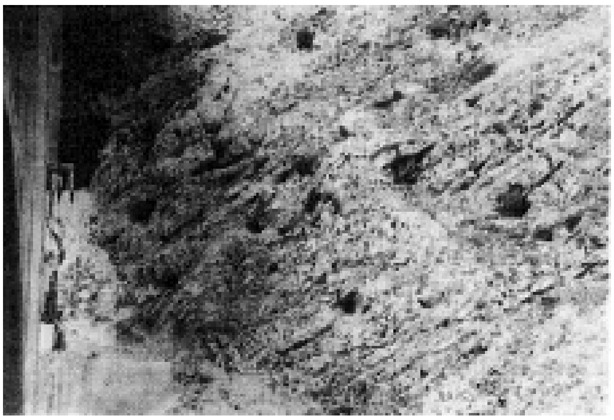


Fig. 5 Minor caves on the southern limb of the Maslenica anticline (western bank of the Novsko Ždrilo channel).

Fig. 6 The cave formed on the intersection of a bedding plane with sigmoidal joints of the axial plane zone (detail of Fig. 5).

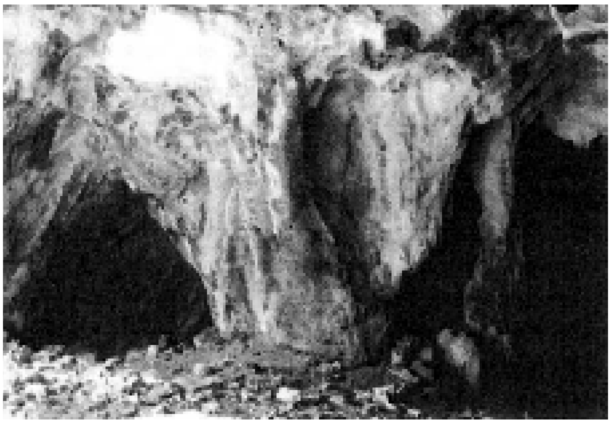


Fig. 7 The cave on the northern limb of the Maslenica structure. The broken stalactite is approximately 3 m in diameter.

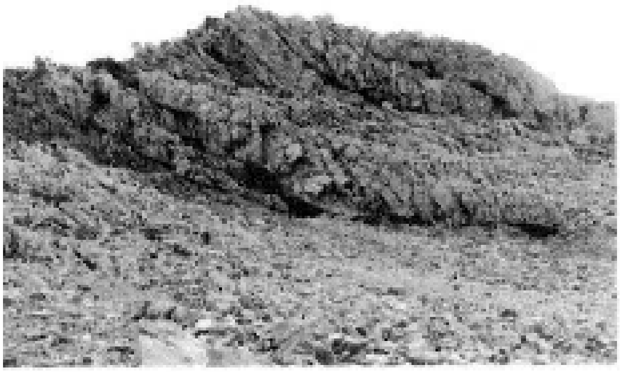
tional phase system, and is filled by fragments of surrounding rocks mixed with terra rossa.

Another cave formed by compressional deformation processes is in the Paklenica natural reserve, where several caves with almost horizontal entrances are found. One of them, illustrated in Fig. 10, is also located in the Cretaceous limestones that were exposed to strong tectonic deformation in the course of folding and structural formation of this part of Mt Velebit.

The cave is genetically related to the zone of extensive crushing of limestones between the two semi-parallel reverse faults positioned 270/46°. The fault planes are at a distance of little bit more than 2 m, and it is in this space that the relatively closely-spaced sigmoidal fracture systems were developed during the displacement on the fault planes. These sigmoidal fracture systems increased the brecciation of rocks and made it possible for certain separate blocks to become loose. The reverse displacement is defined by the linear striation marks with a sinistral angle of 75° on the fault planes (Fig. 11) and by the sigmoidal shapes of joints between the faults. The calculated azimuth of stress ($\sigma1 = 259/5°$), that conditioned the formation of structures lies along the E-W axis, with a vergence of structures in an eastern direction.

A similar tectonically induced situation of cave formation is encountered in the vicinity of the entrance to the newly discovered Slovakia cave (Fig. 12) in the Rožanski kukovi area of the central part of Mt. Velebit. It is also here, like in the case of the Paklenica cave, that several parallel reverse faults are observed. They have a 50° dip and satellite sigmoidal fracture systems. The Slovakia cave "… has an atypical, horizontal entrance that mostly resembles a cave, rather than a vertical hole." (KOZARČANIN et al., 1996). According to the personal communication of D. BAKŠIĆ, one of the cave explorers, the reverse faults have a Dinaric strike, i.e. NW-SE.

The fracture systems that led to opening of this caves entrance are surely connected with strong com-



a

b

Fig. 8 a) The sigmoidal joint systems formed by reverse displacement on bedding planes. b) The stalagmite intersected by a reverse fault (eastern side of the Novsko Ždrilo strait).

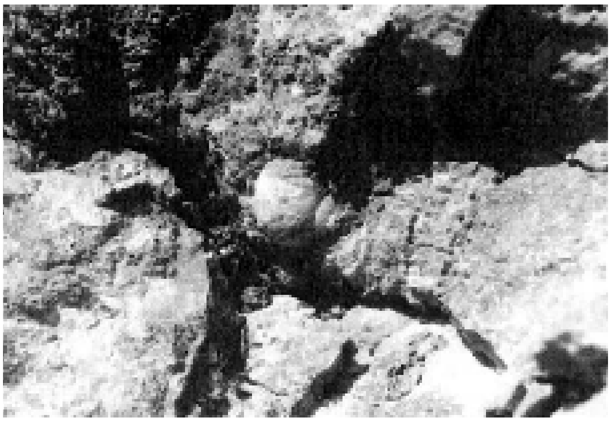


Fig. 9 Detail of the cave filled by crystallised calcite material and Quaternary deposits with fossilized gastropod *Helix pullmonata.*

pression of the area, and influenced by the greater deformation index of the Jelar deposits, not only by their reverse faulting. According to the same explorer (D. BAKŠIĆ) the cave has some 10-15 meters of horizontal length, and after a few steps it passes into a vertical hole of the Slovakia cave. This information points to the existence of transcurrent faults that are normally connected to this kind of structural formation in the course of strong folding in an area.

Another example of a studied spelaeological object that can be interpreted to have been conditioned by tectonic events is the Muževa hiža cave. The cave (Fig. 13) is located on the right bank of the Curak brook, in the end of the Vražji prolaz canyon that is in the immediate vicinity of the Zeleni Vir near Skrad.

In contrast to the two previously described spelaeological objects, the Muževa hiža cave was formed by structural deformation between the bedding planes that occurred during the folding and reverse faulting of Jurassic limestones. It was formed by tectonic processes comparable to those observed at the Maslenica structure. Namely, the reverse displacement along the bedding planes formed relatively closely spaced joint systems of the axial plane zone, that have with development of deformational processes obtained sigmoidal shapes. The narrowing of joints close to their contact with bedding planes caused a stronger fragmentation of rock and thus enabled cave formation. The cave was formed in the lower part of the arch-shaped sigmoidal joint systems, rather then in their upper part. This is due to the fact that in this zone the blocks are more easily separated under the influence of gravity, thus making the place for the next blocks to fall out. The approximately 40 m long cave has a Dinaric strike which implies that the structural elements that caused its for-

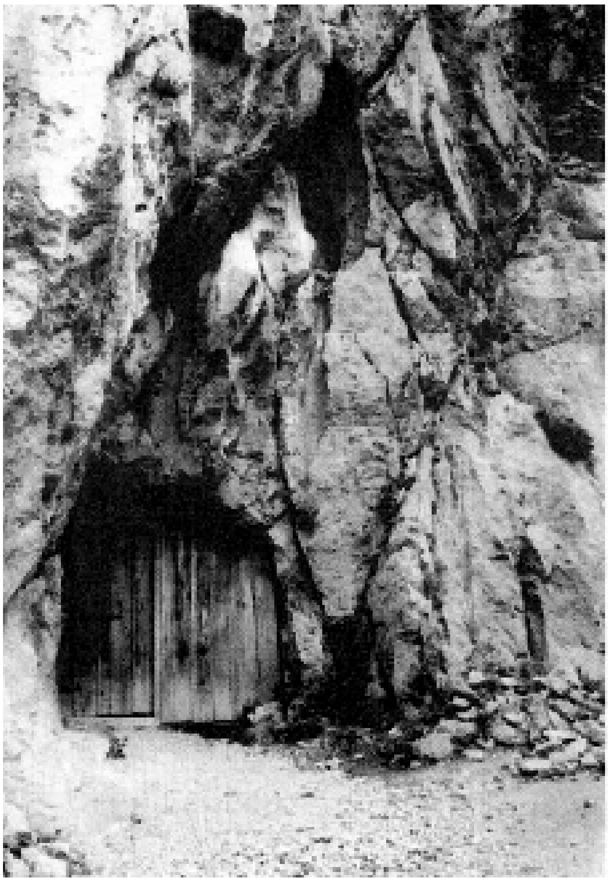


Fig. 10 The closed entrance to the cave in the Paklenica natural reserve.

Fig. 11 Linear striation marks on a reverse fault. Detail of Fig. 10.

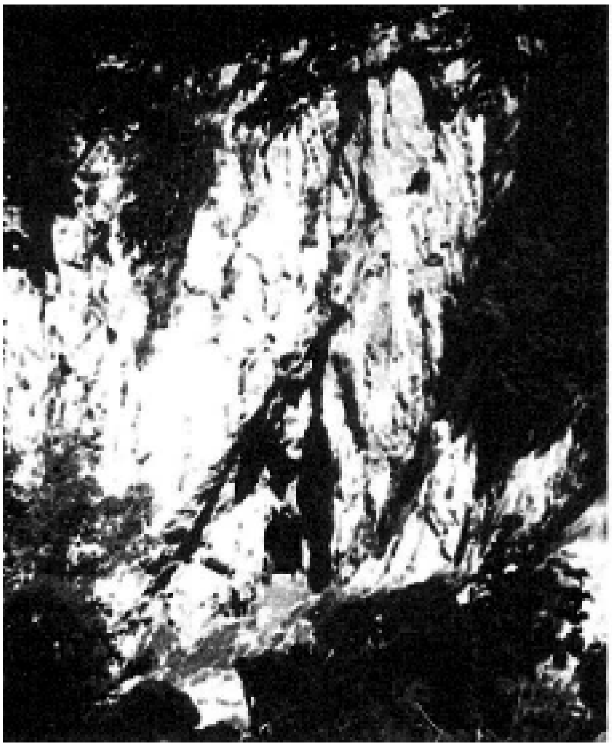


Fig. 12 The Slovakia cave entrance (photograph taken by D. Bakšić).

Fig. 13 The Muževa hiža cave in the Vražji prolaz canyon (Zeleni Vir).

mation also belong to the time of structural formation of the Dinarides.

3. CONCLUSION

The presented data draw the conclusion that the studied shapes of some caves within the carbonate rocks of the part of Dinarides were modelled by different tectonic processes. Some of them were connected with extension of the area, while other were found to result from the compressional activity during the folding in the phases of strong structural reorganisation of the Dinarides.

In the younger phase of tectonic activity, the extensional processes led mostly to opening of the previously formed fracture systems. The calcite build-ups were sedimented in these joints, and they were later filled with fragments of the surrounding rocks and terra rossa.

The caves that can be interpreted to have been formed due to compression of the area are more abundant in the carbonate rocks of the Dinaride area. They were formed either by rock fragmentation taking place at intersections between the reverse fault planes and the satellite joint systems, or by the reverse displacement along the bedding planes followed by the occurrence of closely-spaced sigmoidal joints of the axial plane zone.

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