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The influence of nivation and cryofraction on periglacial relief formation on Velebit Mt. (Croatia)

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ABSTRACT

The peak areas of the Velebit mountain range display an interesting periglacial geomorphology. The appearance of forms is the result of the interdependent geological, geomorphologic, climatic, vegetational and pedological characteristics of the area. The structural and lithological properties of the rock complex, and the inclination of the slope, play a significant role in periglacial relief modelling. Climatic elements are also important, as they influence the intensity and duration of the processes. Low temperatures and relatively high precipitation during the last ice age (Würm III), served to intensify the activity of periglacial processes and relief modelling of the entire Velebit area. Nivation and cryofraction are the predominant periglacial processes which are represented by snow avalanches and stone streams. Air temperatures and soil temperatures (at 30, 60, 90 cm depth) were measured, presented and reviewed, together with other attributes and the slope inclination of the area. The interactions between ground temperature, snow cover and wind patterns play important roles in frost action. In addition to slope inclination, the penetration of warm winds (*jugo*) and warming of snow on the NE slopes are also important factors in destabilizing the snow cover and triggering avalanches. Snow avalanches are most intensive on slopes with declinations from 35° up to 50°, especially on the parts without vegetation cover.

Keywords: nivation, cryofraction, periglacial relief, Velebit Mt., Croatia

1. INTRODUCTION

The Velebit Mountain range extends along the Adriatic coast in a NW-SE direction. With its surface area of 2 359 km2 and length of 145 km, it is the longest mountain range of the Dinaric mountain belt in Croatia (Figure 1).

In the peak areas of the Velebit range (higher than 1400 m), beside karstic and slope processes, periglacial processes have also played a great role in shaping the relief. Their appearance is the result of the interdependent geological, geomorphological, climatic, vegetational and pedological characteristics of the area. Due to the specificity of the microclimate, predominantly marked by thermal inversions, periglacial processes can sporadically occur at altitudes of about 1000 m. Relief forms created by the influence of snow and cryogenic processes can be singled out. During the Pleis-

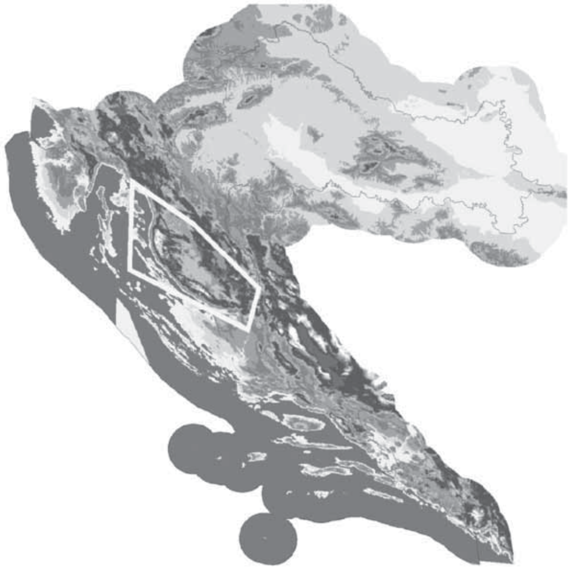

Figure 1: Position of Velebit Mt. (Croatia).

tocene, cryogenic processes influenced relief modelling in the middle and lower parts of the slopes. In the shaping of relief by periglacial processes, anthropogenic and zoogenic influences have had a significant role, especially evident in peak areas where *Pinus mugo* dominates.

2. PREVIOUS RESEARCH

Though the Velebit range had already attracted naturalists studying landforms in the late 18th century (HACQUET, 1785), it was not until the mid 20th century that POLJAK (1947) and ROGIĆ (1958) pointed out the issues of periglacial relief formation on Mt. Velebit. However, these scientists focused their studies on the deglaciation of Velebit (or its non-existence, (POLJAK, 1947) and regional issues (ROGIĆ, 1958), while periglacial processes and their modelling were only considered superficially. The first person to study recent and Pleistocene periglacial relief formation in the Velebit region was BELIJ (1985). Within regional geomorphologic researches, BOGNAR (1992, 1995) and BOGNAR & BLAZEK (1986) identified the significance of periglacial relief formation in the peak regions of Velebit. PERICA et al. (2002) also studied the Pleistocene and recent periglacial influence on relief modelling. MARJANAC & MARJANAC (date) examined the glacial history of the Croatian Adriatic and coastal Dinarides, including Velebit Mt. A number of papers deal with the glacial history of the Mediterranean mountains, the results of which can be applied to Velebit (HUGHES & WOODWARD, 2008; HUGHES et al., 2007; HUGHER et al., 2006; FEDERICI, 1980; KOTARBA et al., 2001; DRAMIS & KOTARBA, 1994; VIERA et al., 2003). Finally, there are some relevant works on modern glacial environments in Slovenia (the Triglav glacier, GABROVEC (1998)) and Montenegro (the Debeli Namet glacier, HUGHES (2007; 2008)).

Geobotanical (HORVAT, 1949), pedological and climatological papers had a significant impact on the research of recent periglacial processes and relief modelling in the Velebit Mt. region. Among the authors studying climate characteristics on Velebit which had significant impacts on research into periglacial relief formation, the following must be noted: ROGIĆ (1958), KIRIGIN (1967), BERTOVIĆ (1975, 1980), and PERICA & OREŠIĆ (1997).

3. METHODOLOGY

Given the topic of this paper, the research was based on field work, with supplementary quantitative geomorphologic methods. During fieldwork, consideration was given to the impact of snow, ice and wind on slopes of varying exposition and steepness, and to the differences in microforms created as a result of the interdependence of these factors. Climatological data (air temperature, precipitation and wind) of the State Hydrological and Meteorological Institute were used for the period from 1981−2000. Microclimatic measurements of soil temperature were performed between December 2003 to August 2005, near the Zavižan meteorological station. Soil temperature was measured with bimetal geothermometers at depths of 30, 60 and 90 cm below ground. GIS analysis of slope of the area in question (peak areas of southern Velebit) was applied during quantitative geomorphological analysis.

4. RESULTS AND DISCUSSION

The structural properties of the rock complex, i.e. the density of primary and secondary fissures and hollows, and the inclination of the slope, play a significant role in periglacial relief modelling. Though carbonates (limestones and dolomites), with layers dipping seawards (to the SW) are frequent throughout the Velebit range, these dominate in the peak regions (higher than 1200 m). The frequency of appearance of primary fissures is exceptionally high in "clastic" carbonate deposits of Tertiary age known as breccia in the highest parts of Velebit. In layered rocks (limestones and dolomites) with primary fissures, which include the highly significant diastromic (or interlayer) cracks, tectonic movements have created numerous smaller secondary fissures. The existence of these fissures has helped strong cryogenic destruction of the rock complex in the peak areas of Velebit, and also on the lower slopes. In the colder months (below freezing point), ice in the fissures acts on the rock surface, creating mechanical wear.

4.1. The influence of climate on periglacial formation of the relief

Climatic elements are important, as they influence the intensity and duration of periglacial processes. The boundary position of Velebit between the coast and the interior is best seen in the climatic properties of the upper ridges. The Velebit Mountains prevent the mixing of the lowest layers of air on either side to an altitude of 1000 m. The southwestern (coastal) slope is subjected to maritime influences, while the northeast is subjected to continental conditions, thereby creating significant differences in temperature, relative humidity, wind (amount and speed), cloud cover and precipitation (PENZAR & PENZAR, 1995).

The thermal maritime influence is limited to a narrow coastal band, and the central parts of the southwest Velebit slopes (up to approximately 900 m in altitude), which is best seen in the vegetation cover. This belt is virtually completely dominated by submediterranean vegetation. In the coastal regions, the mean annual temperature fluctuates around 15ºC. The winters are mild, with an approximate temperature of about 6.5ºC in the coldest month (January). Due to the exceptionally small number of cold (around 18) and icy (around 2) days, the influences of cryogenic processes are negligible. Furthermore, cold and icy days in the coastal regions primarily appear during periods of the strong northern wind *bora*, which brings rapid drying and evaporation of the bare carbonate surfaces that dominate on the southwestern slopes, thereby preventing the possible creation of ice in rock fissures and its mechanical action.

With increasing altitude, the air temperature drops rapidly on the south-western slope. During the colder part of the year, cold, icy and chilly days are common in the higher regions of Velebit (above 900 m), which causes freezing of water in rock fissures and the appearance of cryogenic processes.

Heavy orographic precipitation is characteristic of this region due to the exposure of Velebit to the warm and moist south-westerly air currents from the sea. The lowest amount of precipitation is recorded in the coastal areas (about 1200 mm annually). Precipitation increases with increasing altitude, though this is uneven. The lowest precipitation occurs on the SW slopes of northern Velebit, where the precipitation isoline of 2000 mm is at altitudes of about 1400 m. In the area of central Velebit, annual precipitation is markedly higher, with the precipitation isoline of 2000 mm, gradually dropping to an altitude of 900 m on the NW slope, i.e. to the very bottom of the poljes on the NE slope. The highest level of precipitation (greater than 2500 mm) is recorded in the peak areas of southern Velebit, particularly at its lee on the NE slope (Visočica 2883 mm; Bunovac 3419 mm). Furthermore, in southeastern Velebit, the quantity of precipitation drops to less than 2000 mm per year at 900 m altitude.

In the Velebit region, there is more precipitation in the colder part of the year. All rain measurement stations record the highest precipitation in the fall months, with a secondary maximum in the spring. Snow is least frequent along the coast (around 0.3 days) and on the lower parts of the SW slope, while the number of snow covered days increases with altitude. On the NE slope, the duration of snow cover is also lowest at the base of the slopes (71 days at altitudes up to 600 m), while areas between 700 - 1000 m (the peak areas of Velebit) are covered in snow up to 95 days. At the Zavižan meteorological station, snow cover of 1 cm or more was recorded for 166.8 days of the year, while a deeper snow layer of 50 cm or more was recorded for 97.8 days of the year. Snow retention is significantly longer in the forests than in the open areas, and also on the SW slopes rather than NE slopes, particularly at the bottom of deep depressions where it is carried by the wind, and at the base of avalanche areas. In areas with an inclination exceeding 50°, snow is not retained at all, but immediately falls to lower areas (ŠEGULA, 1986). Due to a lack of snow that would act as a thermal insulator, the peak areas are subjected to strong frost wear and periglacial relief modelling. In contrast, where the snow cover is retained for longer periods of time, its thermal insulation effect prevents a higher level of cryogenic processes in such areas.

The entire Velebit area is influenced by continental winds, of which the most important and strongest (up to 200 km/h) is the *bora*, a cold and dry northern wind, blowing mostly over the SW slope. In winter, the wind blows the snow cover away at saddles and cols in the ridge and on parts of the bare SW slope, thus creating snow deposits at more inclined and protected locations.

The *jugo* (southern wind from the sea), is the most important of the maritime winds. It collects much moisture during its passage over the Mediterranean and Adriatic Seas. Upon reaching the Dinaric mountain range, the wind is forced to rise, which is accompanied by a drop in temperature, increase in relative humidity, cloudiness and precipitation, while on the NE slopes, it frequently has the character of a warm and dry air stream (Makjanić, 1978). As a result, in the winter, the *jugo* causes sudden snow melt followed by snow avalanches, even in the peak areas of Velebit. Generally speaking, due to the specific climatic position, the peak areas of Velebit are characterised by constant air currents, accompanied by relatively strong winds (Zavižan, 3.2 on the Beaufort scale). Thus, despite the significant snowfall, large areas in the peak region of Velebit are bare in winter, without snow cover, thereby stimulating frost weathering.

It is important to discover and determine the connections between air temperature, duration and amount of snow cover, soil temperature, and their impact on periglacial processes. Therefore,soil temperature was measured at depths of 30, 60 and 90 cm, between December 2003 and August 2005, near the Zavižan meteorological station. Daily readings were taken at 7:00 am, 2:00 pm and 9:00 pm for both air and soil temperatures.

Air temperatures in 2004 and 2005, from 1st January to 20th March, (Table 1) were below 0°C. Such temperatures produced soil freezing to a depth of 30 and 60 cm and there were evident differences between air and soil temperatures (Table 1, 2; Figure 2, 3). Such values are connected with snow maintenance and depth of cover (snow cover as a thermal insulator, Table 3, 4; Figure 4, 5). However, **in** areas where the *bora* wind carried the snow away, and removed its thermal insulation properties, more pronounced frost processes operated.

The climatic characteristics of Velebit during the last ice age (Würm III) also had a great role and effects on periglacial relief modelling. Some authors consider that traces of the last glaciation in the Velebit region date back exclusively to the Würm glaciation, which was quite extensive (BELIJ, 1985; BOGNAR et al., 1992, 1997; NIKLER, 1973, PERICA & OREŠIĆ, 1997). MARJANAC & MARJANAC (2004.)

Table 1: The middle monthly air temperature and soil temperature by date and depth – December 2003 to May 2004 on Zavižan (1594 m).

PERIOD	DECEMBER 2003			JANUARY 2004			FEBRUARY 2004			MARCH 2004			APRIL 2004			MAY 2004		
SOIL Depth cm	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31
30	2.0	1.0	0.1	-0.7	-0.2	0.0	0.0	0.0	0.0	-0.2	-1.0	0.0	0.0	0.0	0.7	1.0	1.2	5.8
60	2.8	2.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-1.0	0.0	0.0	0.0	0.0	0.2	4.0
90	4.0	4.0	3.4	3.0	3.3	3.0	3.0	2.6	2.0	2.0	1.0	1.0	1.0	1.0	0.3	0.0	0.0	3.3
Air temp°C	-1.9	-2.2	-4.6	-7.1	-2.3	-12.3	2.7	-6.5	-4.1	-7.5	-2.1	-2.1	1.7	0.9	2.4	2.3	4.2	4.8

Table 2: The middle monthly air temperature and soil temperature by date and depth – December 2004 to May 2005 on Zavižan (1594 m).

PERIOD	DECEMBER 2004			JANUARY 2005			FEBRUARY 2005			MARCH 2005			APRIL 2005			MAY 2005		
SOIL Depth cm	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31
30	3.0	3.4	1.0	1.0	1.0	0.3	0.0	-0.4	-1.0	-1.8	-1.9	-1.3	3.0	4.4	6.7	11.5	16.2	17.6
60	2.0	2.0	2.0	2.0	2.0	1.5	1.0	1.0	0.0	-0.4	-1.0	-1.0	-0.1	0.4	2.3	3.2	4.0	5.6
90	4.0	3.7	3.0	3.0	3.0	2.8	2.0	1.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5	2.8	3.7
Air temp°C	2.8	-1.4	-4.9	-1.1	-4.6	-15.1	-8.9	-6.9	-8.1	-11.4	-0.7	2.0	0.2	-0.2	2.4	5.1	4.6	11.3

suggests that the most extensive glaciation was much older than the Würm and reached low altitudes on the piedmont and even below sea level. They noted that the Würm glaciation was restricted to the higher valleys and cirques. Elsewhere in the Balkans, it also appears that the most extensive glaciations occurred during the Middle Pleistocene, which would have had a big impact on periglacial processes and landform development in the Velebit (HUGHES et al., 2006, 2007). Some discussion on the age of glaciations from Montenegro also suggests a Middle Pleistocene age for the oldest and most extensive glacial deposits in this region (HUGHES & WOODWARD, 2008). According to some authors, the most extensive glaciations in the Italian Apennines also occurred during the Middle Pleistocene and were bigger and more severe than that during the Würm (FEDERICI, 1980, KOTARBA et al., 2000).

Many authors studying climate during the last ice age consider that the air temperature was lower by 10 to 15ºC.

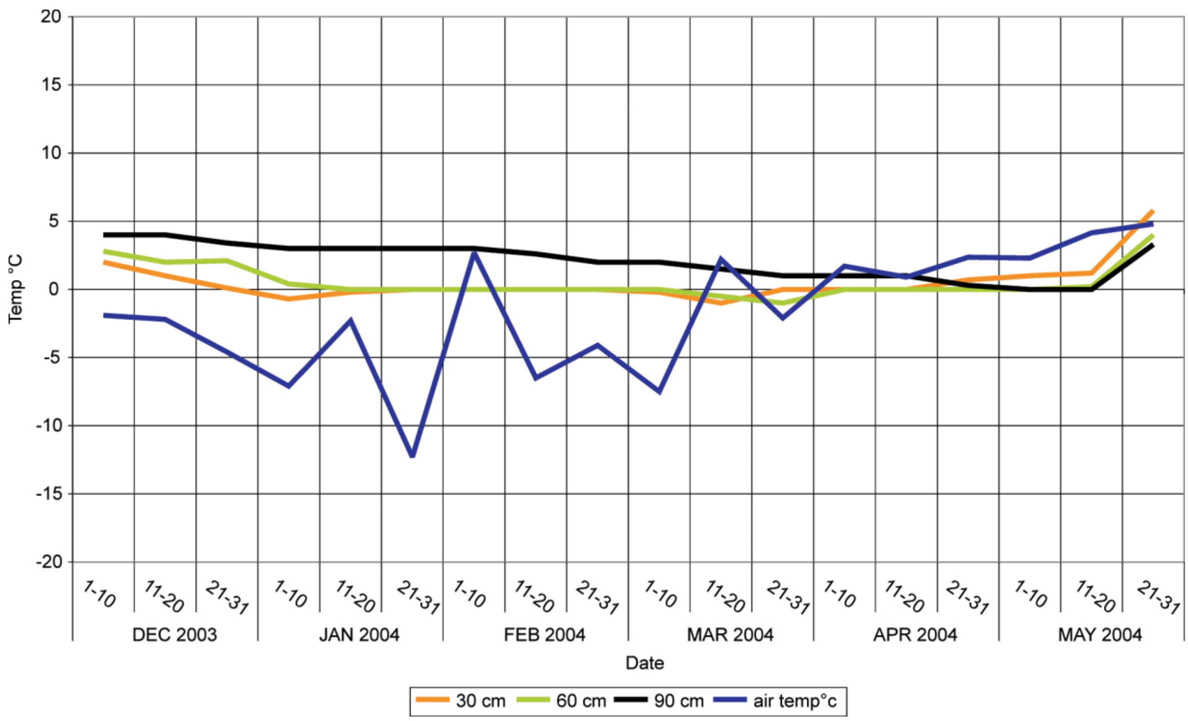

Figure 2: Comparation of air and soil temperature from December 2003 to May 2004 on Zavižan (1594 m).

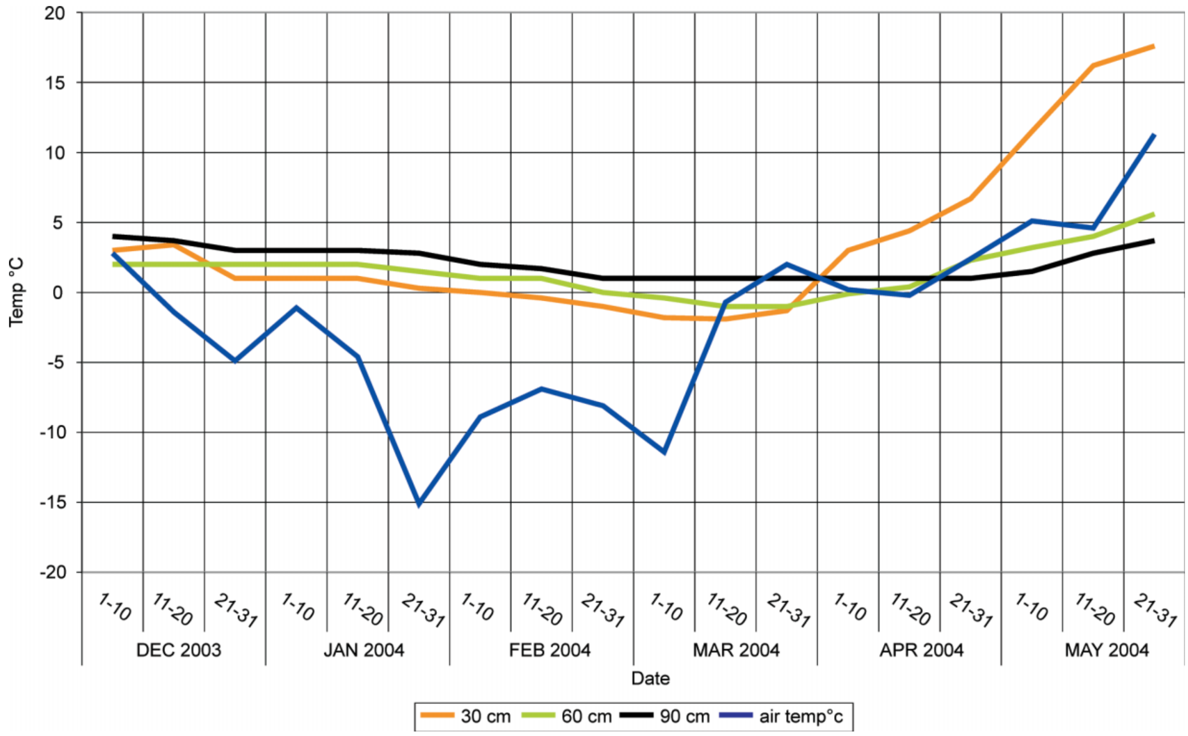

Figure 3: Comparation of air and soil temperature from December 2004 to May 2005 on Zavižan (1594 m).

ŠEGOTA (1963) assessed that mean air temperatures in July during the peak of glaciation were lower by 10–12ºC, RIĐANOVIĆ (1963) by 10ºC, and GATES (1976) by 14–15ºC. Based on studies of periglacial processes and forms in the Pannonian lowland, POSER (1947) stated a mean annual temperature of -2ºC. Therefore, the mean July temperatures obtained here correspond with those of the map created by GATES (1976).

According to ŠEGOTA (1982), increased atmospheric circulation at the start of glaciation caused a reduction in precipitation by at least 20%, with solid precipitation being dominant. Later, due to reduced evaporation of the sea caused by low temperatures and expansion of the ice shield, the quantity of precipitation decreased to its minimum at the period of maximum glaciation (ŠEGOTA, 1963; ŠEGOTA & FILIPČIĆ, 1996). Due to the proximity to the sea and fa-

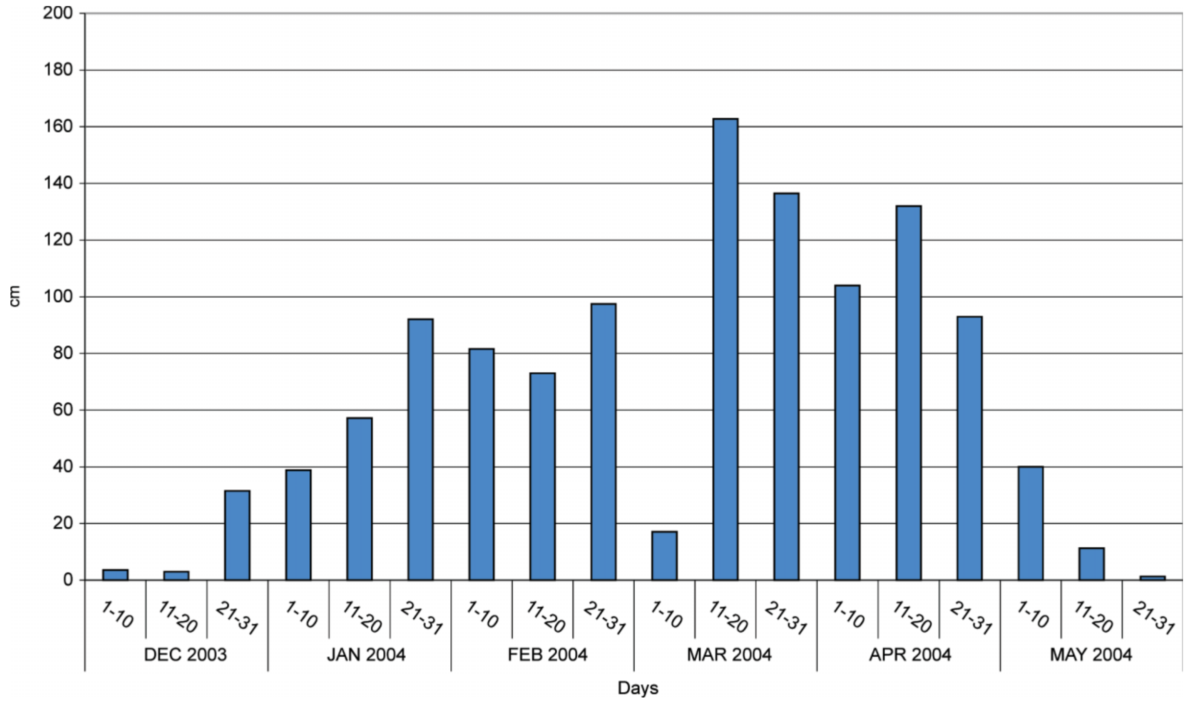

Figure 4: Amount of snow from December 2003 to May 2004 on Zavižan (1594 m).

Table 3: Amount of snow in cm - December 2003 to May 2004 on Zavižan (1594 m).

DECEMBER 2003			JANUARY 2004			FEBRUARY 2004			MARCH 2004			APRIL 2004			MAY 2004		
1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31
4	3	32	39	57	92	82	73	98	17	163	137	104	132	93	40	11	1

Source: Croatian Meteorological and Hydrological Service Archives

Table 4: Amount of snow in cm - December 2003 to May 2005 on Zavižan (1594 m).

DECEMBER 2004			JANUARY 2005			FEBRUARY 2005			MARCH 2005			APRIL 2005			MAY 2005		
1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31	1-10	11-20	21-31
0	5	27	37	26	97	123	122	163	188	163	88	30	55	20	0	0	0

Source: Croatian Meteorological and Hydrological Service Archives

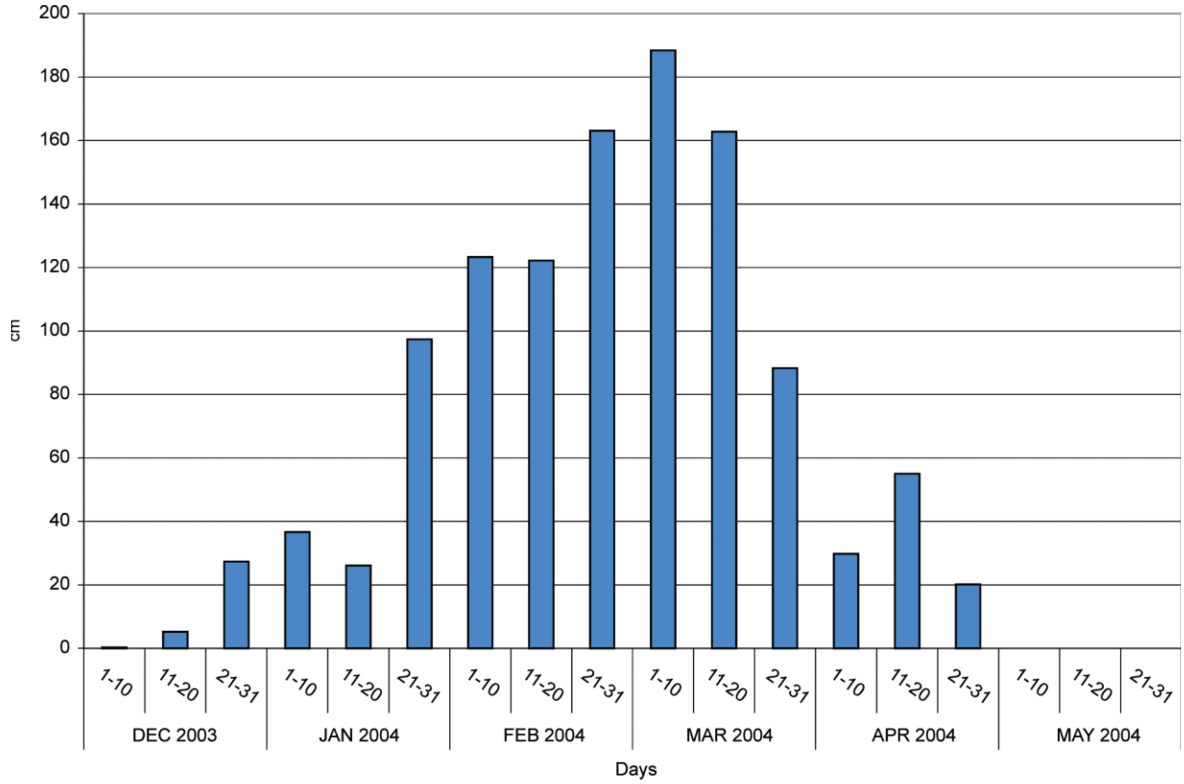

Figure 5: Amount of snow from December 2004 to May 2005 on Zavižan (1594 m).

vourable air currents, Velebit received a relatively large amount of snow. According to KLEIN (1953), during the coldest period of the Würm glaciation, there was 20% less snow on the southern Velebit and 40% less snow on the northern Velebit.

Low air temperatures and relatively high quantities of precipitation during the Würm glaciation were suitable for maintaining glaciers at higher altitudes and snow cover at lower altitudes, resulting in intensive periglacial processes throughout the Velebit area. According to BOGNAR (1992), intense frost damage is particularly evident in the destruction of early created karst microrelief forms (karren) in the central and lower parts of the SW and NE slopes.

4.2. The influence of slope inclination on periglacial formation of the relief

As a quantitative geomorphologic parameter, slope inclination has an important role in periglacial formation of the relief (Figure 6.). The characteristics of slope inclination enable estimation of the character, volume and intensity of periglacial processes. Snow avalanches are most intense on slopes with inclinations from 35° up to 60°, as on the NE slopes of the highest areas of Velebit, especially on those without vegetation cover. Alternatively, in the areas with inclinations between 15 and 35°, the snow glides and forests partly prevent the development of snow avalanches. Slopes with inclinations over 50° comprise a small part of the research area but on these slopes the snow is instantly blown away and cryogenic processes are more significant (due to the absence of snow as a thermal insulator).

Sometimes where slopes are below 15°, the fragmented materials formed by nival and cryogenic processes, move more slowly. On steeper slopes, (with inclinations over 35°) rock collapse is present. Collapse processes are most significant on slopes with inclinations over 50°, such as on the sides of the canyons of Velika and Mala Paklenica, the Golovrh area (1368 m) and the area southeast of M. Visočica (1545 m), Veliki Orljak (1324 m), the southwest slope of Kozjak (1572 m), northeast slope of Šiljevača (1449 m), Badanj (1638 m, no. 10, Fig. 6, 7), northwest area of Vaganski vrh (between Štirovac and Vaganski vrh, no. 8, Fig. 6, 7), the area south and southwest of Debelo Brdo (1632 m) and Vaganski vrh (1757 m): Buljma, Brezimenjača, Jerkovac, the area north of Jelovi tavani (1223 m), north slope of Jelov vrh (1227 m), a small part of northeast canyon of Mala Paklenica, Tulove grede area (1120 m), and several smaller areas.

4.3. The influence of nivation and cryofraction on relief modelling

Periglacial processes have a significant impact on relief modelling of Velebit. They often appear in the highest altitudes but, due to specific microclimatic conditions (thermal inversion) these can sporadically appear at lower altitudes.

Movement of the snow cover is seen on the slopes of the peak regions. On slopes covered with forest vegetation, and on bare slopes with an inclination of less than 35°, the snow cover usually creeps. Where such slopes have forest vegetation, the tree trunks bend at their base (BERTOVIĆ, 1975; 1980). This is particularly evident in the beech forests (*Fagus sylvatica*) in the foothills. Due to the long period of snow retention and its depth, low forest vegetation (*Pinus mugo*) dominates in the highest altitudes of the southern part of Velebit. The average monthly number of days with snow on the ground at ≥ 1 cm depth is 166.8 days, and for depths ≥ 50 cm it is 97.8 (as measured at Zavižan meteorological station between 1981 and 2000).

On unforested slopes with an inclination > 35°, snow avalanches are common. Avalanche processes occur in two ways: the first is related to linear snow movements from the slope, which form avalanche trenches (corridors), while the second appears when the snow avalanche covers a large part of the slope (surface avalanche). Snow falling on steep and shaded slopes in peak regions with an inclination greater than 60° instantly moves downslope (ŠEGULA, 1986). This is often directed into the somewhat gentler, trenches and valleys where the snow accumulates (Figure 8) and, due to the large inclination (between 35° and 60°), this moves in the form of a snow avalanche to the base of slope regions.

There are many such corridors and valleys in the peak regions of the NE slopes, among which the following are particularly significant: the trench between Vaganski Vrh (1757 m) and the point 1723 m towards basins Vaganj (Figure 9) from Vaganski vrh to the fold on the NE slope above the Vaganac sinkhole and from the direction of Dolina Cesarova and the NE slopes of Malovan (1709 m) to the Bunovac basin. On the SW slope, the most prominent are the steep valley (former glaciated valley) between Crljeno (1616 m) and Babin kuk (1435 m). Smaller avalanches also appear in the gullies on the steep, shady slopes of Badanj (1638 m),

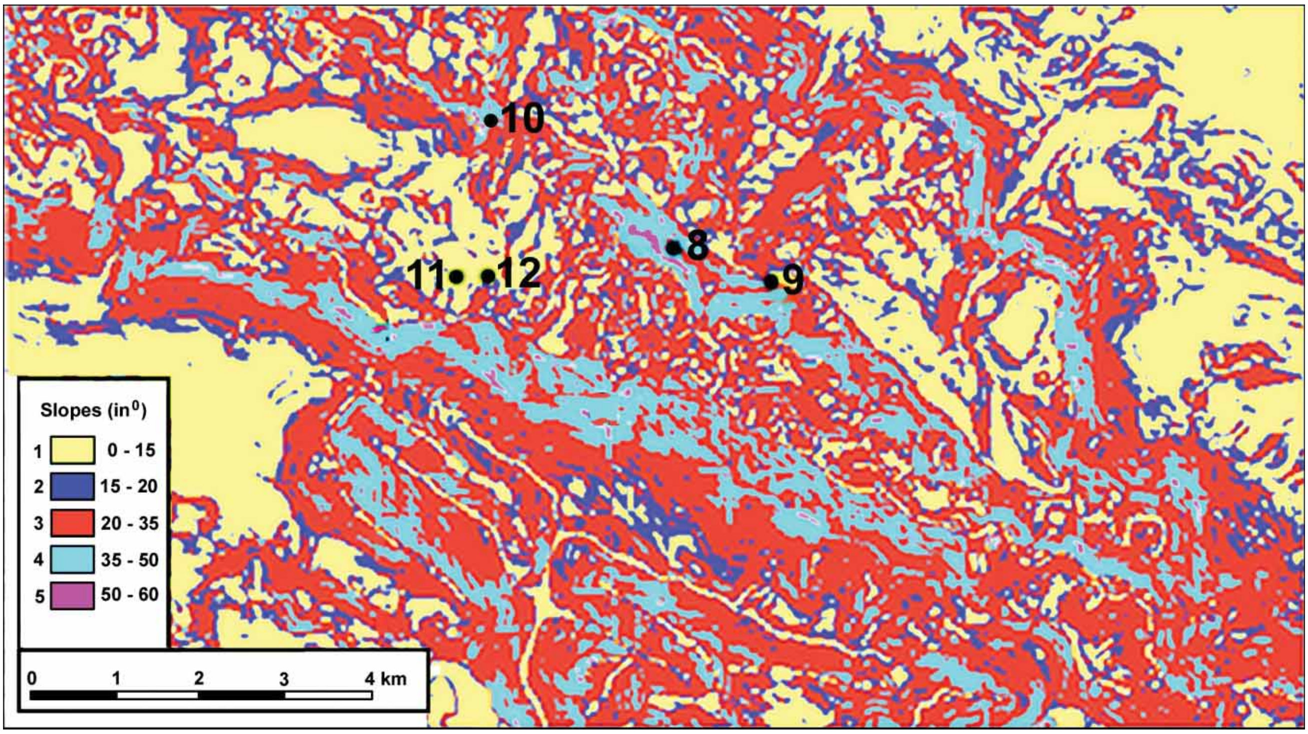

Figure 6: Inclination map of researched area (Velebit Mt., Croatia) with locations of figures 8-12.

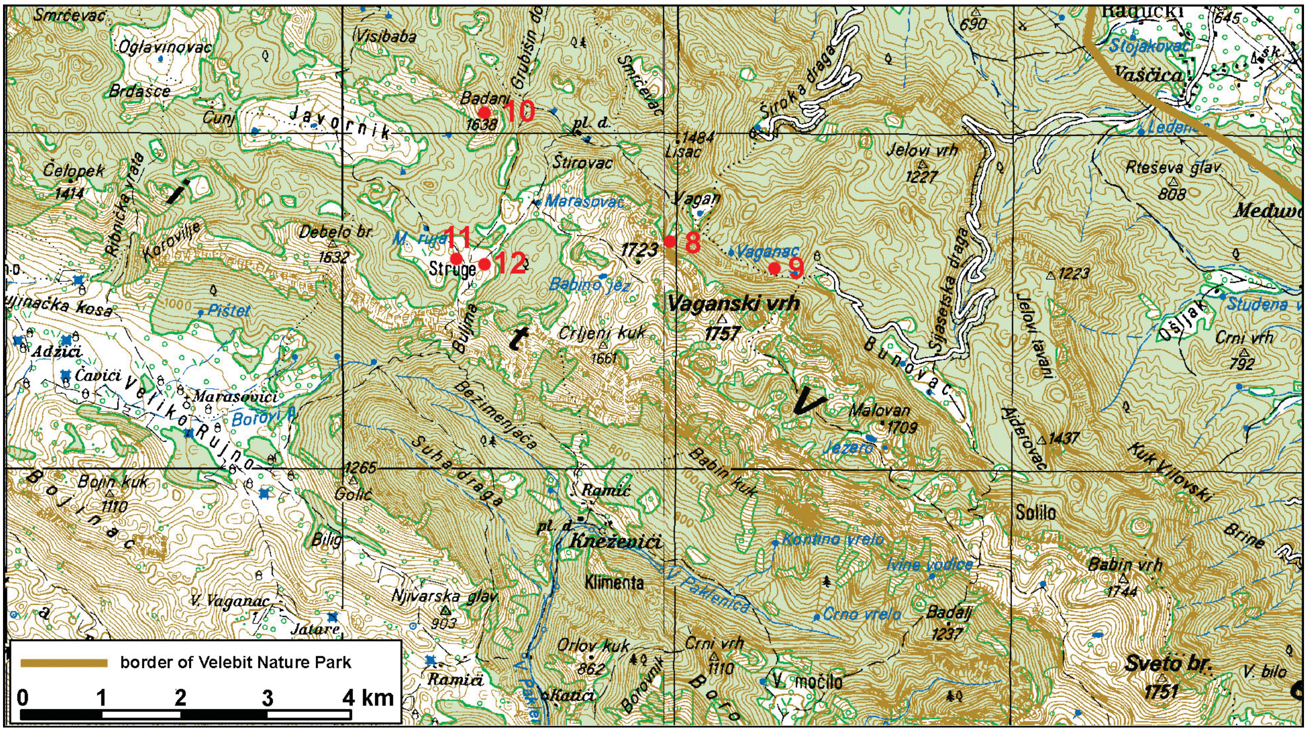

Figure 7: Topographic map of researched area (Velebit Mt., Croatia) with locations of figures 8–12.

Visočica (1616 m) and Golovrh (1584 m). These are avalanches with exceptionally important impacts. The avalanches move at high speed in the lower parts, encountering forests and destroying trees. Considering that many trenches can also act as funnels, carrying the karst rock and even rock slabs with a volume exceeding 1 m^3, they form *avalanche corridors* (Figure 9). At the base of steep NE slopes, avalanche deposits in the form of large compacted snow masses accumulate on gentler slopes (Figure 8).

Unlike the avalanches from trenches and valleys, surface avalanches covering a large area of the slope occur on the steep slopes of the peaks and on the sides of the deep sinkholes. These avalanches are the result of instability due to large accumulations of snow on gentle slopes that represent local denudation bases. Depending on the time of the critical point when, due to the effect of gravitation, the internal cohesion of the snow mass is lost, the mass either cracks or separates in line with its mass and the inclination of the slope and collapses down the face of the slope. Snow carried by such avalanches accumulates in the bottom of basins, deep sinkholes and in the foothills of the peak slopes. This kind of avalanche is most prevalent on the NE slope of Sveto Brdo (1751 m).

Figure 8: The avalanche accumulation.

In addition to inclination, the penetration of warm winds (*jugo*) and warming of snow on the NE slopes are also important factors in destabilizing the snow cover and triggering avalanches. An increase of snow temperature to 0°C causes weakening of internal cohesion within the snow mass, and results in its ultimate collapse down steep slopes (ŠEGULA, 1986). Such avalanches are common on the grass covered slopes of the peaks and the sides of sinkholes and basins (on the southern slopes of Sveto Brdo, Badanj and Debelo brdo, Fig. 10).

Due to the specific microclimatic conditions at the base of individual depressions, and in areas where avalanche snow is deposited, large snow masses (snowfields) form at the base of the NE slopes. The creation of large snow masses in sinkholes and basins is the result of wind removal of snow from the ridge and those exposed parts of the slope. The bases of sinkholes and basins are in shade virtually all year round due to their depth. This causes a strong thermal inversion and ensures snow retention until mid summer. The most pronounced example of an accumulation is in a sinkhole NW of Vaganski Vrh (1757 m) at an altitude of 1680 m. Such snow masses, formed by the mechanical and erosive? impacts of the snow, the water (from snow) and ice, acts to break down the soil substrate, both expanding and deepening the bottoms of the sinkholes and basins, creating nivation niches. Also, due to suffosion activity, the snow masses create niches with a semi-circular shape, arranged in step-wise sequences on the slope. Such forms are described by GUTIÉRREZ (2005). There are many such step-like indentations on the upper parts of southern Velebit, and these often appear at lower altitudes (about 1000 m, i.e. Sladovača) on the shaded and SW sides of the depressions.

Certainly, the most pronounced of all the periglacial processes is the cryogenic process, including cryofraction and cryoturbation (the stone sea near Struge, Fig. 11). These are very common in the peak areas of Velebit. The average air temperature of -3°C at Zavižan peak, during the winter period (December to March) maintains the periglacial processes. The very small fluctuation around 0°C in day and night temperatures during spring and fall causes the water in fissures to thaw and refreeze, thus resulting in powerful frost destruction of the rock complex. Microclimatic measurements of summer air temperatures 5 cm above the ground in the Modrić dolac sinkhole on northern Velebit near the Zavižan meteorological station (1594 m), and at a site 74 m lower, confirms that the temperature in the mat grass community is 10 to 12°C lower (dropping to -6°C) than at the meteorological station itself (KIRIGIN, 1967). It is important to mention that in many depressions, temperatures are often much below average. Such values are shown in the results of microclimatic measurements of air temperature performed in depressions of the Dinaric regions of Slovenia (at altitudes between 700 and 1000 m) where the minimum temperature measured was from -25°C to -30°C, as a result of thermal inversions (OGRIN et al., 2006).

Figure 9: The Veliki Vaganac uvala (South Velebit) with vegetational inversion (the consequence of the nival avalanches).

Figure 10: Badanj – talus slope.

As such, it can be concluded that cryogenic processes in the sinkholes and basins of the peak areas of southern Velebit, also overgrown with mat grass, are very prevalent in the summer months.

According to BELIJ (1985) and BOGNAR & BLAZEK (1986), a large quantity of cemented slope material in the valleys of the Velika and Mala Paklenica Creeks, clearly indicate the intensive cryogenic processes that took place during the Pleistocene. According to BOGNAR (1992, 1995) in the dry-cool climate of the Pleistocene period, cryofraction and nival processes, and pronival solifluction (CHRISTIANSEN, 1998) played important roles in the shaping of soils in the Velebit area.

The fracturing of karst fragments, which continue to crumble as they fall, created colluvial talus and fans at the base of steep shady slopes. An exceptionally good example of frost destruction created by colluvial fans occurs on the SW slope of the peak part of the Velika Paklenica valley, and below the NE slope of the Badanj (1638 m; Figure 10) Babin vrh (1725 m), and Sveto Brdo (1751 m) peaks. On the steep sides of basins and sinkholes, and on the slopes of the highest peaks in southern Velebit, the karst fragments move slowly down slope due to alternative freeze – thaw processes, creating *rock streams*. Rock streams also fill the bottom of the funnel-like sinkholes. On gentler slopes, there are large areas covered with fragmented rock due to the lesser possibility of movement of frost-eroded karst and its further crumbling by frost action. These are known as *blockmere*, and one example is found on the Struge plateau (Figure 11).

Due to the seasonal freezing of water, on horizontal and slightly inclined terrain, there is an alternation of swelling and settling of the soil. If the soil contains fragmented rock

Figure 11: The stone sea near Struge.

material, then this is forced up to the surface, where it is further fragmented and sorted. The fragmented rock is forced to the surface, and rips the grass cover, creating new cracks. Further freezing and thawing causes these cracks to expand and fragments of the karst rock accumulate within, surrounded by individual clumps, thus creating polygonal soils (Struge area, uvala Javornik). On steeper slopes, the freeze-thaw results soil creep. If the terrain is covered with grass, the karst fragments forced into the ground and later forced to surface, break through the grass cover. The inclination of the terrain influences the collection on the lower part, simultaneously stretching in the upper part of the grass cover, thus creating gelisolifluction tongues which descend down the slope. On slopes with a higher inclination, growth of grass cover and the formation of vegetational terracotta is somewhat faster.

Following thermal inversions in depressions and the removal of snow by wind, polygonal soil, migrating grass hummocks and terracotta appear at a substantially lower altitude (in the area of Sladovača and kuk Stap at 1000 m).

Today, snow and ice are largely significant in the shaping of speleological objects in the peak areas of Velebit (approximately above 1000 m). It is common that dolines and caves, or their entry areas, in the higher altitudes of Velebit are filled with snow and ice year round due to the specific position of their entrances and channels, and the low temperatures within (Figure 12). The size and volume of these areas and the complete filling of these objects is, as a rule, larger than those without snow and ice. This is the result of intensive frost wear of the rock complex (GARAŠIĆ, 1986). Traces of frost action occurring during colder geological periods are evident in some speleological objects (Puhaljka pit, a sinkhole at Grgin brijeg, a cave near Bačić kuk and at Crni Dabar) (MALINAR, 1984, GARAŠIĆ, 1986).

During the Pleistocene, periglacial processes were dominant in relief modelling in those parts of Velebit that were not subjected to glacial modification. The formation of dry, hanging valleys and blind valleys in the Velebit area is primarily related to the complexes of partially permeable and partially impermeable rocks, in the conditions of the moister and colder periods of the Pleistocene. During the first half of the cooling phase, which marked an increase in precipitation levels, their formation was accelerated by the gradual increase of subterranean waters in the fissure systems and surface water flow. However, in the second phase of cooling, which was marked by a pronounced drop in air temperature and reduced precipitation levels, periglacial disintegration and the creation of permafrost became more dominant in the creation of dry valleys. Disintegration was most intense on the dolomite and dolomitic limestone, where a thick cover of relatively impermeable material resulted. This facilitated the formation of creeks, both intermitent and permanent (Babrovača in northern Velebit, or Stap–Sjauševac in southern Velebit). The presence of permafrost is particularly important in the modelling of valleys on permeable limestone complexes, as this prevented subterranean water drainage. However, upon warming, when a moderate dry and semi-dry climate began to predominate (at lower and middle altitudes), the permafrost melted. Both periglacial processes in relief modelling and valley formation ceased. Identical conditions also facilitated the formation of hanging and blind dry valleys. The lower ends of hanging valleys are usually cliffs (Lički doci), while blind valleys usually form sinkholes at their ends. During the period of maximum cooling, the exceptional domination of glacial and periglacial processes, resulted in numerous openings and channels of cave objects that served as sinkholes (i.e. at the end of blind valleys, sinkholes and uvalas), being filled with evacuated materials (BÖGLI, 1980; FORD & WILLIAMS, 2007). This is also seen by the glaciofluvial sediments discovered in the Puhaljka pit (MALINAR, 1984).

5. CONCLUSION

Periglacial processes are very important in relief formation of the highest parts of Velebit. Their appearance is controlled by the interdependence of physical and geographical features of the area, and it is the result of morphological formation and domination of carbonate rock complex. It is possible to isolate the relief forms that were modelled by the influence of nival and cryogenic processes.

Figure 12: Ice cave near Struge.

During the Pleistocene, cryogenic processes had an impact on the relief formation of the central and lower slopes of Velebit. Though they have been associated mostly with the higher parts of Velebit, due to specific microclimatic conditions (thermal inversion) they also occur sporadically in the lower parts (at about 1,000 m).

It is important to emphasize the long-term negative anthropogenic and zoogenic influences, which are particularly reflected in the destruction of primary vegetation cover. Consequently, these changes affected the modification of microclimate, so that contemporary periglacial processes are more prevalent.

Considering the length of Velebit (145 km), its surface (2359 km^2) and the complexity of periglacial processes, it is necessary to conduct further research concerning the geologic, geomorphologic, climatic, vegetational and pedological influences on relief formation.

Also, is necessary to emphasize the importance of quantitative geomorphologic analysis in studying periglacial process and relief forms. Knowing the quantitative geomorphologic features of the researched area (slope inclination, and other quantitative parameters, such as relative elevation, slope length, slope aspect etc.), enables us to evaluate the possible locations where nival and cryogenic processes may occur, as well as their characteristics, volume and intensity. Therefore, it is necessary to conduct further detailed research of the Velebit area, based on statistical analysis of a greater number of quantitative geomorphologic parameters, which would ultimately provide guidelines for further field research.

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