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Full Length Research Paper

The dynamics of slopes affected by avalanches in Piatra Craiului Massif – Southern Carpathians

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This paper aims to present the results of a complex analysis of the morphodynamics of slopes affected by avalanches in Piatra Craiului Massif. The study of avalanches is a current issue of dynamic geomorphology and very little is discussed in the Romanian geographical literature. Although the presence of avalanches has been reported in the Carpathian area for centuries, geomorphological analyses were performed only in the context of regional studies. In recent years, approaches to nivation as an extreme or morphodynamic event increased. In this context, the present paper focuses on analyzing the relationship between factors leading to avalanches, geological structure, slopes, exhibition, climate and biological triggers, the characteristics of the landscape as a whole, the micro landforms of avalanche corridors, slope dynamics and avalanche activity on the entire area where there is potential for occurrence. Its purpose is to gather knowledge on useful resources that the informational systems operating on spatial data can provide to dynamic geomorphology or extreme events.

Key words: Morphodynamics of slopes, avalanches, decisive factors, micro landforms, avalanche corridors, Piatra Craiului Massif.

INTRODUCTION

The study of avalanches is a less approached dynamic geomorphology issue in Romanian geographic literature. Snow avalanches have been noted in the alpine Carpathian area centuries ago but their explanation has preoccupied geomorphologists only in the context of regional studies, through descriptive-explanatory and less analytical approaches. At the level of Romania, the experience in the field increased in the last decade, but few cases have integrated informational sources (Urdea, 2000; Voiculescu, 2002 ; Nedelea, 2006; Constantinescu, 2006; Moțoiu, 2008). The research in the present paper focuses on analyzing the relationship between factors leading to the occurence of avalanche conditions, geological structure, slope, aspect, climate and biological triggers, the characteristics of the landscape as a whole, micro landforms of avalanche corridors, slope dynamics and modeling activities of avalanches. The purpose is the knowledge of useful resources that informational systems that operate with spatial data can provide to dynamic geomorphology, extreme events analysis or the development of mountain area.

The study area is one where avalanches occur annually. It is situated in Piatra Craiului Massif, on the Eastern part of the Southern Carpathians (Figure 1). It is bordered by Bârsa Mare valley to the North, Bârsa Tămaşului to the North West, Dambovita valley to the South West, Dambovicioara valley to the South East and Prăpăstiile Zărneştilor (Precipices of Zărneşti) to the North East. Here, avalanches can be considered the most important current processes, next to the gelifraction - karstification and torrentiality complex (Constantinescu, 2006). The action exerted is complex, of erosion both on the higher area of river origins and along transport corridors, from the sediment origins to the accumulation of materials in deposit areas. The consequences are visible in the overall landscape, providing a special feature to the morphology (Constantinescu and Pițigoi, 2003).

Objectives

The objectives of this paper are: investigating the factors

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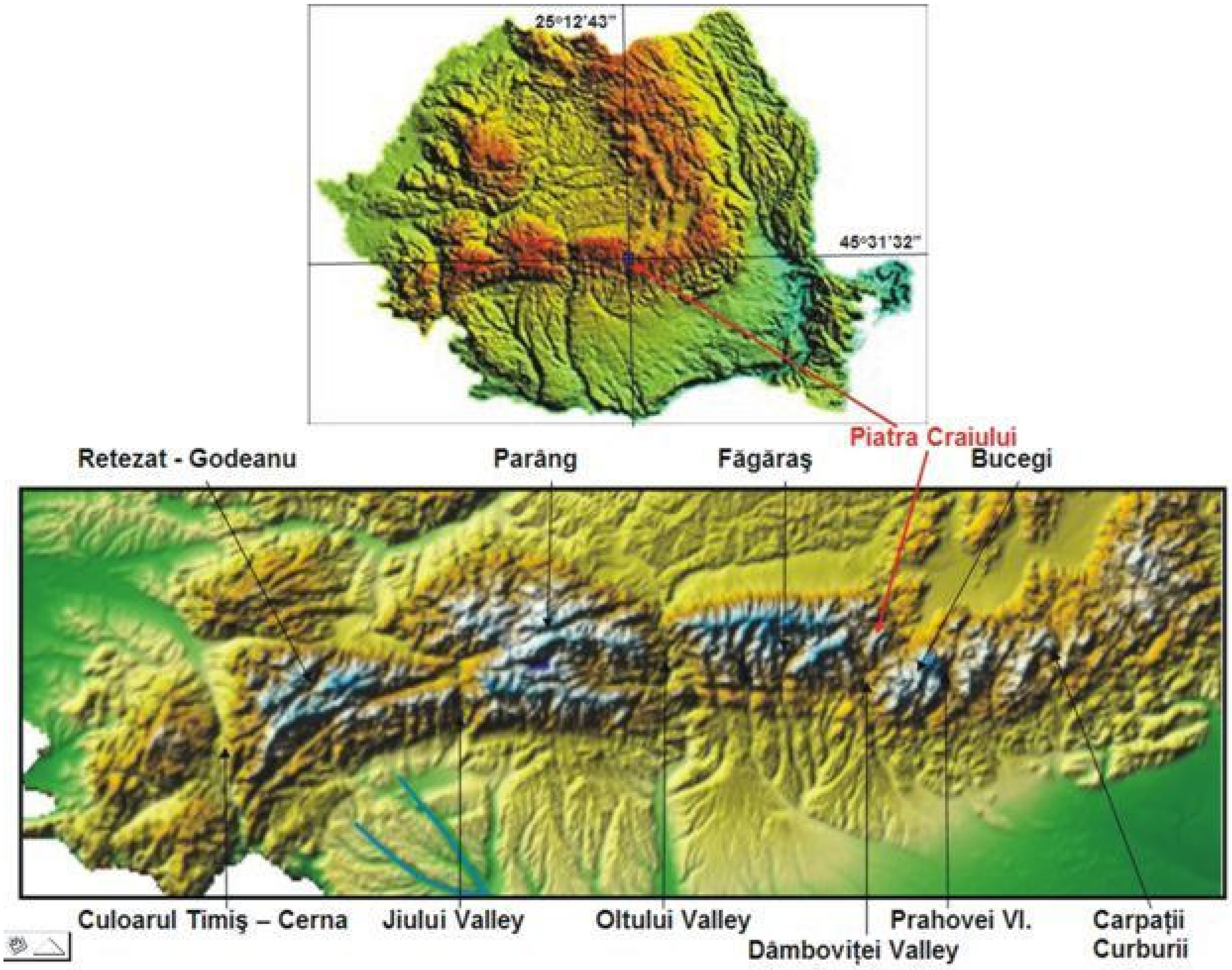

Figure 1. The geographical position of the Piatra Craiului Massif within Romania's and Carpathian's territory (original).

that determine the formation of favourable conditions for avalanches to occur, identifying the areas within which avalanches can occur, analyzing the way avalanches affect the dynamics of slopes and how they interact with different natural phenomena. Each of these objectives will be presented, according to their characteristics, their way of manifestation and their role in the mountain slopes dynamics.

METHODOLOGY

The paper is based on a series of studies on avalanches, on identifying areas where these can occur and the way they affect the dynamics of the slopes. In this regard, analyses have been conducted on avalanche corridors, on the dynamics of debris on the corridors, on the effects they have on the environment components. The research base consisted of field mapping, measurements, observations and cartographic analysis - topographic and tourist maps, orthophotoplans, satellite images, photographs. Data processing was done digitally, using GIS software, according to existing literature (McClung and Schaerer, 1993; Pietri, 1993; Hervas, 2003; Voiculescu, 2002; Ludkvist 2005). Very useful data were also provided by Piatra Craiului National Park Administration, members of Zărneşti and Câmpulung Mountain Rescue teams, the forestry districts, chalet administrators and members of NGO operating in the area.

Avalanche corridors were identified in the field and on the cartographic material. For the most important of them, morphometric measurements were made on dynamics and the substrate. The data were interpreted and analysed by the standards of literature (Ancey and Charlier, 1996; Keylock, 1997; Raczkowska, 1997; Ancey, 1998; Kotarba and Pech, 2002; Voiculescu and Vuia, 2004; Alexa, 2005). Subsequently, the map of areas prone to avalanches was made.

Through observations and measurements repeated during 2004-2010, there were made connections with the dynamics of slopes. Thus, the effects of avalanches were determined and how they act on the dynamics of slopes.

RESULTS AND DISCUSSION

The triggers of avalanches

The dynamics of slopes in Piatra Craiului Massif is strongly influenced by a number of geological and physical-geographical factors. First, the geological substratum is represented by a Mesozoic blanket (composed of kimmeridgian-tithonic and neocomienee

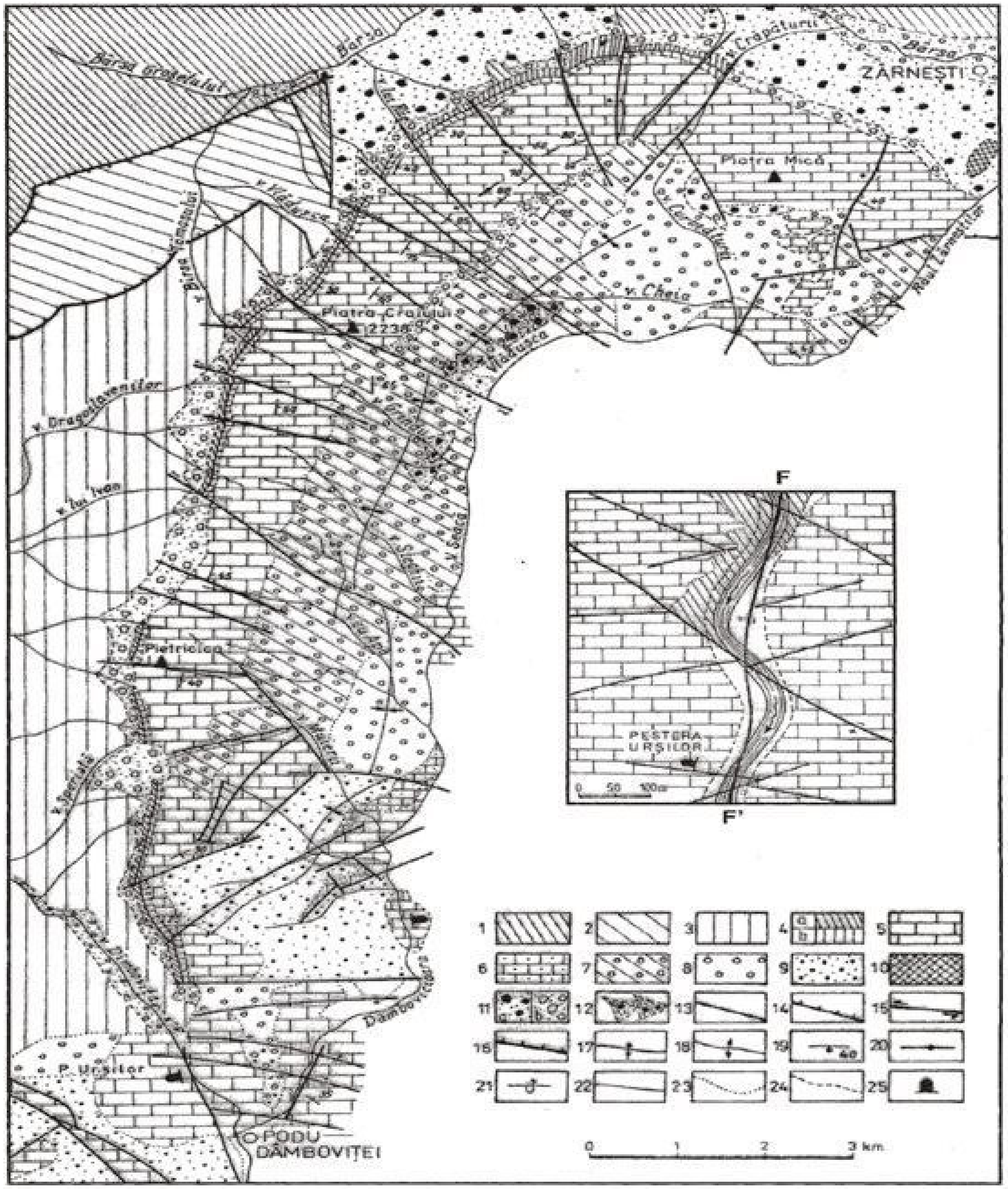

Figure 2. Geological section in Piatra Craiului Massif – Geologic Map. 1-crystalline schists (Cumpăna Formation); 2-crystalline schists (Leaota Formation); 3-crystalline schists (Căluşu Formation); 4.a- sandy limestones (Dogger); 4.b-red limestones, radiolarites (Dogger); 5- kimmeridgian-tithonic limestones; 6-neocomian limestones; 7-upper aptian conglometares; 8-vracono-cenomanien conglomerates; 9- vracono-cenomanien sandstones; 10-eocene sandstones; 11.a-fixed debris; 11.b-mobile debris; 12- fixed debris fans; 13-normal fault; 14-reverse fault; 15-strike slip fault; 16-Şariaj; 17-Axes of syncline; 18-Axes of anticline; 19-direction and value of inclination angle of layers; 20-vertical layers; 21-overturned layers; 22-geologic limit; 23-transgression limit; 24-limit of quaternary debris; 25-cave (Constantinescu ,1994).

limestones and aptian sup. and vracono-cenomaniene conglomerates) that covers the crystalline pedestal that determines the characteristics of rocks. This substratum is structured as a ridge (at 2,000 m altitude) on the Western flank of a trough, with strong layers rebuilt in the form of a hogback, oriented NE-SW (Constantinescu, 1994), (Figure 2). The two slopes thus appear irregular, the western one-predominantly limestone, very steep (over 45°, often vertical), the Eastern one-limestone at the top and conglomerate in the rest, being less steep (20-40°) (Figure 3A).

Structural and petrology aspects led to the formation of specific landforms, with torrential valleys that fragment the slopes and that in winter operate as avalanche corridors. The morphology of slopes and valleys contributes in a different way to the preservation and gliding of the snow. A particularly important role is played by the presence of tectonic alignments - faults, which causes the formation of the valleys, on which avalanche corridors are channeled or steep slopes with fractures that produce imbalances in the structure of snow (Constantinescu, 1992). The layout and narrowness of the ridge determines the formation of cornices that by breaking leads to avalanches (Mititeanu and Mititean, 20011). The basins located in the area of springs provide favourable conditions for the storage of large quantities of snow (Cristea, 1984). Also, at streams confluences, other basins are formed that can stop or reduce the power of small avalanches. Areas on the Eastern slope, less fragmented, convex or concave, longer, with exposed rocks, but especially the grass-covered slopes cause a lot of snow accumulation in the Grind, Vlăduşca, Mărtoiu, Funduri areas. Narrow valleys, in the form of 'V', on the Western slopes are more prone to spontaneous avalanches coming from the ridge (Munteanu, 2009). The corridors of the valleys impose the route of avalanches and the thalweg width determines their amplitude. At the base of petrological steep slopes lie the quaternary deposits covered by material transported by avalanches. Altitudes between where avalanches take place may vary between 2,000-2,200 m in the trigger area and between 1,200-1,300 m where deposits can reach (Moțoiu and Munteanu, 2006).

In gorges, where slopes are fragmented by torrential streams or structural treads, there is the possibility of forming avalanches, especially when snow is recent or in large amounts. In the limestone pits in Piatra Mica or along the Dambovita and Dambovicioara rivers, as well as along wood transport channels, there is a favorable morphology for producing avalanches (Munteanu and Moțoiu, 2006).

The degree of inclination of the terrain is one of the factors needed to produce mass movements of snow. In conjunction with other factors (weather, roughness) the optimal inclination of slopes for avalanches slopes is considered between 25-50°, with a maximum for those between 35-45°. Theoretically, on slopes exceeding 45-50°, snow accumulation is insufficient to start an avalanche in the true sense of the word (Voiculescu, 2002). However, in Piatra Craiului, avalanches occur even where slopes exceed these values, the tread morphology allowing the triggering in the higher sector of 30-40° and passing through areas with steep lithological slopes, where slopes are often more than 50°. Also, due to the instability of snow immediately after snowfall, avalanches run on all slopes with gradients exceeding 45° (Munteanu, 2009) (Figure 3A).

The most common avalanches are triggered on slopes with values of 20-55°, available on most slopes. Slopes less than 20° can also be dangerous when followed from higher slopes or when located at the bottom of highly inclined valleys. Depending on the strength of avalanches (snow quantity, speed), even areas with low slopes, or opposed inclination slopes, may be covered or 'swept' by the avalanches produced upstream (Constantinescu and Munteanu, 2006; Munteanu, 2006).

Different exposure to direct solar radiation determines the temperature of the snow layer and indirectly its cohesion. Northern slopes and in general shaded, receive a lesser amount of heat and lose caloric energy by long wave radiation. The snow layer remains cold and stabilizes slowly, as far as air temperatures rise in spring. Therefore, in most northern, northwestern valleys most powerful avalanches are the bottom ones, occurring in spring when all the snow layers are heated enough to cause the movement of the base layer. In contrast, eastern slopes, south-eastern and in general sunny, allow faster melting of snow and avalanches are more numerous during the entire winter. The largest avalanches are recorded in Padinile Frumoase – Mărtoiu – Vlăduşca – Piscul Baciului – Grind – Funduri area, where eastern and south-eastern aspect causes the heating and softening of snow, over a large area and in depth, especially when the trigger basin is less fragmented (Figure 3B). In spring, the increase of temperature and degree of insolation will increase the rapidly melting of snow and the instability of snow layer (Moțoiu, 2008; Munteanu, 2004, 2008).

The typical climate of mountainous regions involves rainfall (1000-1200 mm / year), of which large quantities fall in winter (16.5%). The influence of snow layer is particularly important in producing avalanches. Date of occurrence, formation, duration and date of disappearance of this layer are directly influenced by several factors: the altitude of 0°C isotherm (located at 2050 m altitude on short portions of the ridge), the frequency of snowfall, the aspect and exposure to prevailing winds (northern) and the existence of vegetation cover (Voiculescu, 2002).

Precipitations under the form of snow fall between November-April with a maximum between January-February, when it is registred the highest thickness of the snow stratum. Territorial distribution of snow layer is uneven and varies depending on the active surface features (especially on the presence or absence of heterogeneous elements) and wind (because of the intensity and direction). The snow layer presents large thickness, especially in the negative landforms, while on convex surfaces is much lower. The average amount of snow in winter is at the highest altitudes of over 70 mm, reaching at the periphery of the massif 40 mm (Teodoreanu, 2006). The average number of days with

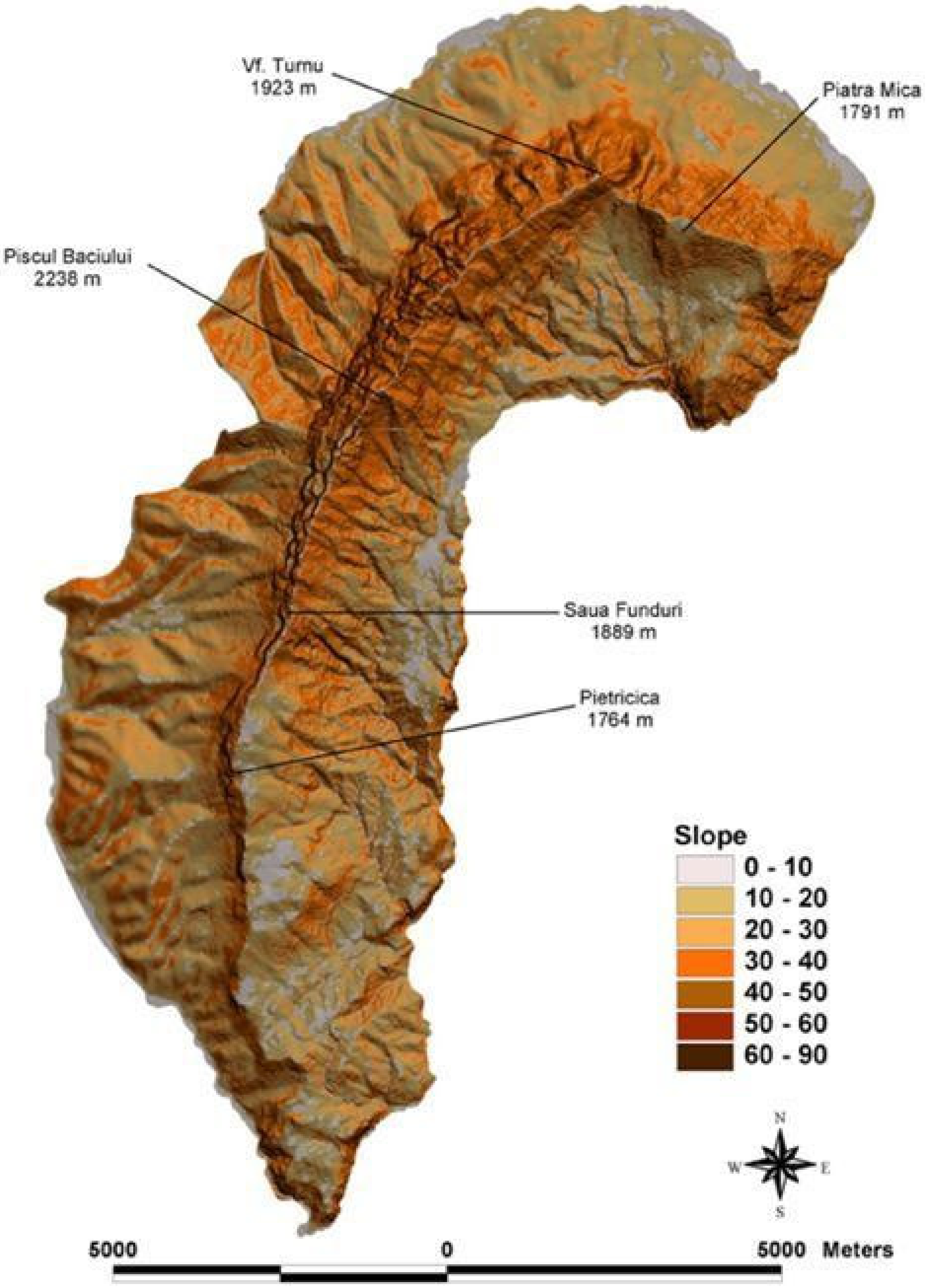

Figure 3A. The slopes map (Munteanu, 2009).

snow reaches 170-180 cm, at altitudes of over 2000 m, while at lower altitudes reaches only 90-95 cm. (Constantinescu, 1994, Table 1). Depending on altitude, in January there are between 20-29 days with snow layer (Teodoreanu, 2006).

In the ridge area and on the two macroslopes snow is present in most months from September, sometimes even from late August until May-June, even July in shady areas on the northwestern slope. There could be times when snow, in avalanche deposits especially, continues from one season to another (Teodoreanu, 2006). This snow plays a particularly important role in present dynamics, particularly of debris, many of which are involved in avalanche deposits.

The air temperature represents one of the most important factors in determining the characteristics, as well as the time and space dynamics of the snow stratum, due to the fact that they directly influence the metamorphism of the snow and the launch of the avalanches. In January, in Piatra Craiului, in areas of

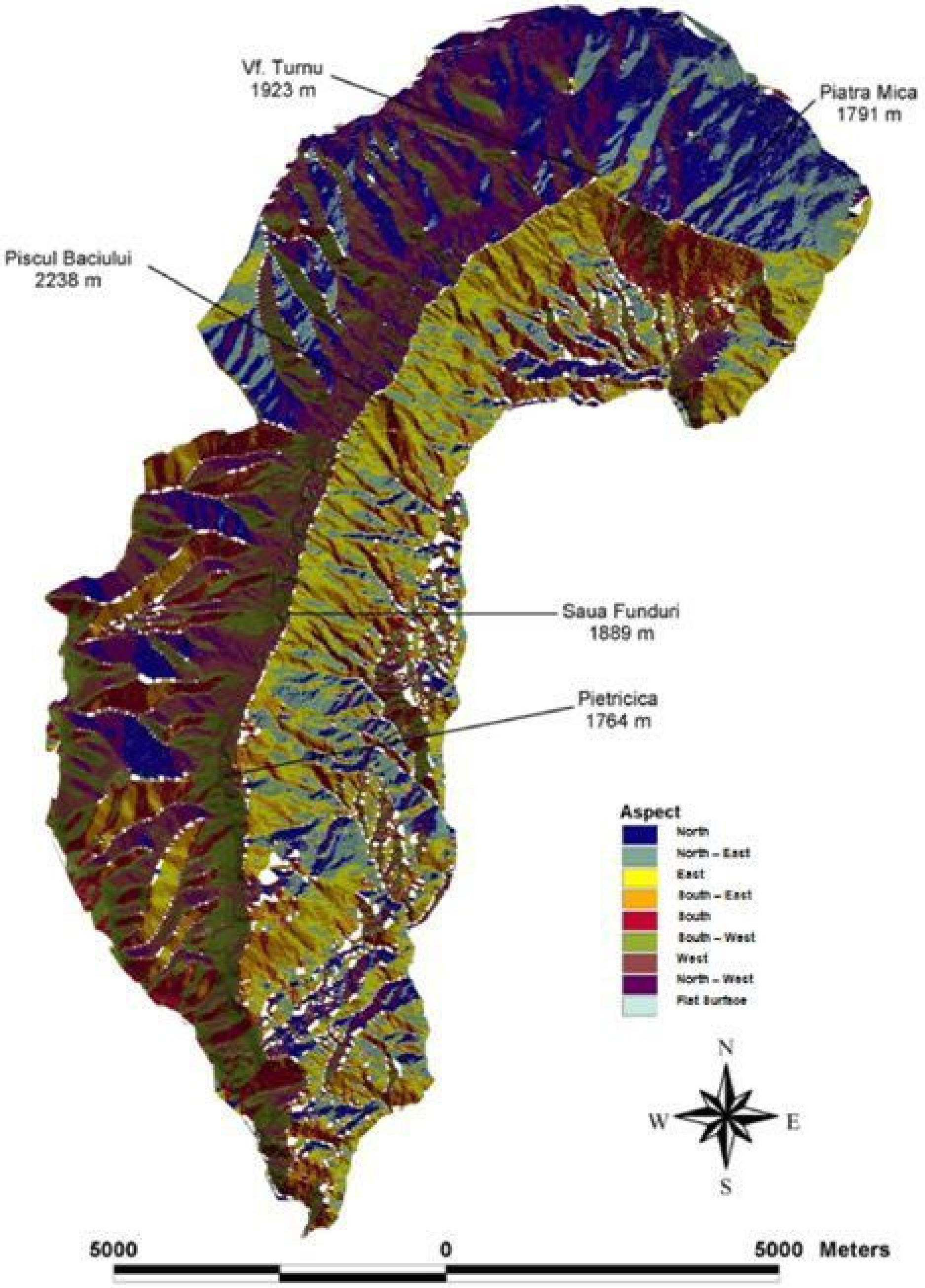

Figure 3B. The exposure slopes map (Munteanu, 2009).

Table 1. Repartition of atmospheric precipitations depending on the altitude (after Constantinescu, 1994).

Absolute altitude (m)	Precipitations annual average (mm)	The average number of days with snow
800 – 1000	900 – 1000	90 -95
1000 – 1200	1000 – 1100	105 -110
1200 – 1500	1100 – 1150	125 – 135
1500 – 1800	1150 – 1250	145 – 155
1800 – 2000	1250 – 1350	155 – 165
> 2000	1150 – 1200	170 – 180

over 2,000 m, the temperatures are of -8°, whereas in average height areas the temperatures are of -6° and in peripheral areas they reach -4° (Teodoreanu, 2006), which provides favourable conditions for the preservation of snow and thus triggering avalanches (Munteanu, 2009).

The wind bears an effect over the unconsolidated snow, through the unequal spread of snow and the mechanical transformation of snow crystals, which determines the avalanche risk to occur. The air streams floating over the mountain peaks and ridges are forming into the predominant / altitude wind. In Piatra Craiului, in the ridge area, this wind has a West, North-West, South-West direction (65%) (Teodoreanu, 2006). This determines a contribution in humidity and snow to deposit in the small basins upstream the avalanche corridors. The snow accumulates in valleys and in concave areas, while on ridges and convex areas there are snowstorms (Moțoiu, 2005).

The biological factors influence the way snow quantity deposits and glides. Certain characteristics of the vegetation (type, afforestation degree, density of the vegetation carpet, type of plant associations and grazing intensity, as well as the length of the grass blade) may favour or limit the production of avalanches, while the fauna elements can contribute to triggering avalanches. The vegetal wrapping has an important role in the current morphodynamics, being an indirect factor in emphasizing or diminishing the amplitude of the shaping processes, such as: detritus dynamics, triggering or diminishing the avalanches etc. The examination of the vegetation in areas affected by avalanches provides essential indication regarding their frequency (Moțoiu, 2005).

Favourable conditions to snow gliding can be found in areas where the mountain slopes are covered with alpine and sub-alpine dwarf vegetation (grazelands), such as: dwarf juniper tree, bilberry bush, rhododendron etc. On the other hand, the mountain slopes on which there is subalpine vegetation like the juniper tree or forest trees are less predisposed to avalanches, due to the fact that their presence fragments and retains snow. Sometimes, when these juniper trees are covered with snow or leveled by older snow, they can become an avalanche bed for the new snow stratum (Mititeanu and Mititean, 2011). These situations are present in the Northern and Southern extremities of the Western slope, where large areas are covered by juniper trees. On the avalanche corridors, the vegetation has an indicating role which can lead to the reconstruction of the avalanche dimensions. Production areas and avalanche ciclicity can also be identified depending on the vegetation that can be observed. The avalanche areas have certain morphological and soil conditions, as well as long persistant snow layers (due to the avalanache deposits) which prevent the natural reforestation (Munteanu, 2006, 2009).

The effects of the avalanches, together with the other geomorphological processes (gravitational, crionival, errosional) are reflected in the descent of the forest natural boundary, especially in the reception basins. This determines the existence of some corridors through the woods, which favour the avalanches to channel and to advance in their forestry areas. These are also very well reflected, especially on the Eastern slope, where these are visible from a big distance. But even here, the corridors in the forestry area continue (Munteanu, 2008).

The identification of areas where avalanches can occur

Areas where the conditions for avalanches to occurr are met are located on two large macro-slopes of Piatra Mareand Pietricica, Piatra Mica (North, West, Southwest, East) and along Prăpăstii Gorges, Dâmbovicioara, Dâmbovița, but also where the anthropic activities led to such conditions, as well as on the forest exploatation channels and quarries. The largest surfaces affected by avalanches can be found on the Western (10.5 km^2) and Eastern slope (9 km^2), while on Pietricica (3.1 km^2) and Piatra Mică (2.1 km^2) these areas are much more reduced (Figure 4) (Munteanu, 2009).

The avalanche corridors are the most important, being located on each side of the ridge, on the slopes of Piatra Mare, Piatra Mică şi Pietricica. The differences which arise between them are based on morphology, slope, exhibition, location on the slope. The inclination of the corridor follows the slope relief, the deposits generally being located where the slope drops below 20°. Certain features are determined by the location. On the Western slope (Figure 5A, B), there are significant differences between the Northern and Southern sectors, as follows (Munteanu, 2008):

i) South of Baciului Peak: Where the average slope exceeds 40° and the valleys are less deep in the origin area (as it is at Marele Grohotiş), avalanches do not usually channel only on thalweg valleys. Snow transportation mainly manifests as a tumble-fall from the ridge zone to the basis of the limestone slope, where it accumulates and can continue on valleys in the forestry sector. Although they have a high frequency (higher than in the North), their moulding action is lower. Surface avalanches are clearly dominant, because large amounts of snow do not accumulate in reception basins. This affects the superficial limestone layer, and particularly the debris deposits, contributing to the dynamics and accumulation of transported material.

ii) North of Baciului Peak: The valleys are greatly deepened, with many very narrow sectors, the avalanches being triggered at the level of the reception basins. The snow in motion is channeling on valleys, but in most cases it is stopped by the small basins located above the very narrow sectors existing along the valleys

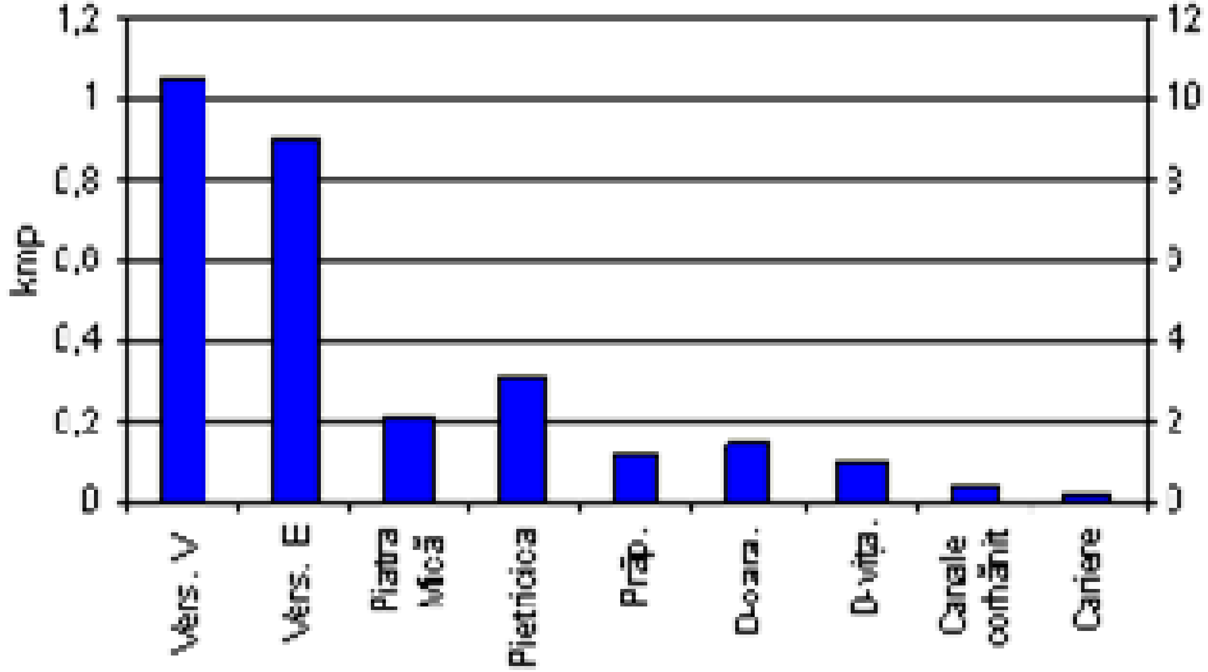

Figure 4. Surface of areas vulnerable to avalanches (Prăp. - Prăpastiile Zărneştilor Gorges, D-oara. – Dâmbovicioara Valley, D-ița. Dâmbovița Valley).

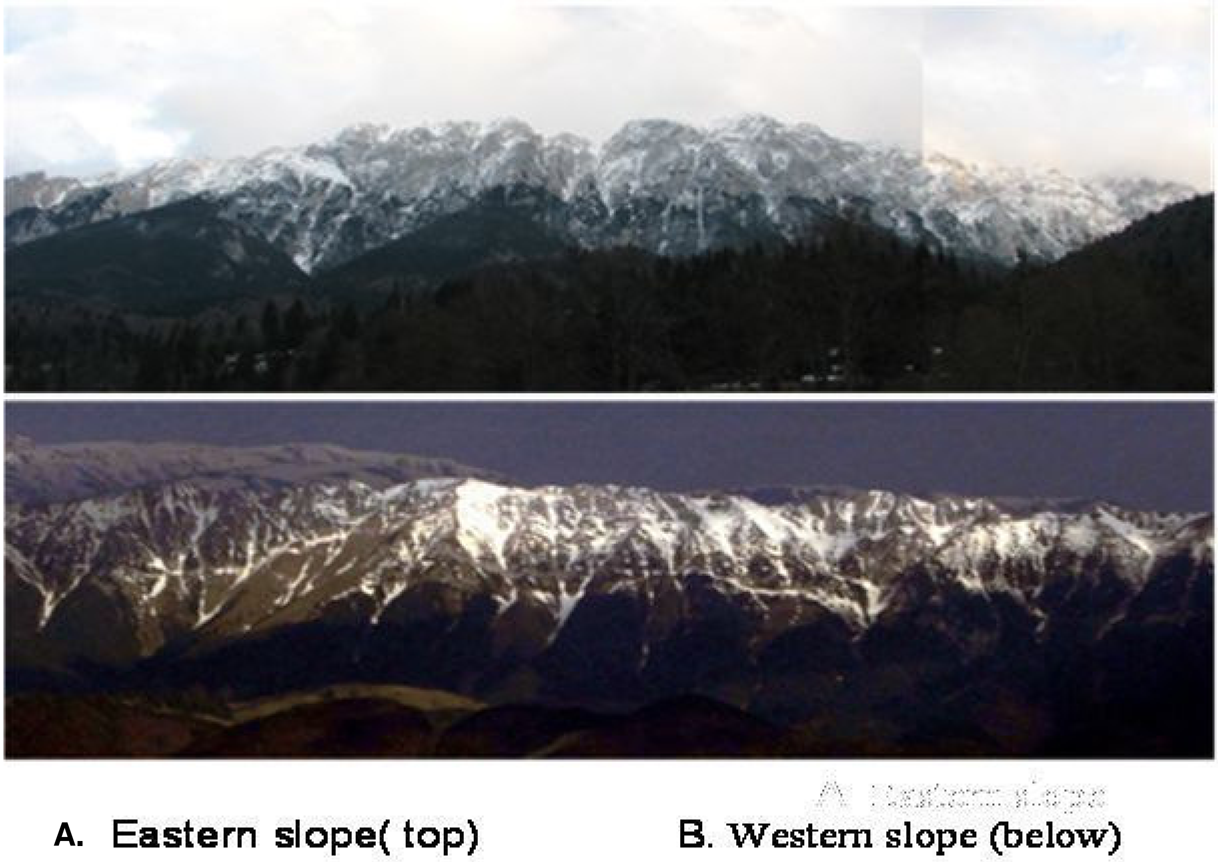

Figure 5. Avalanche corridors on the Eastern slope (A) top and (B) Western slope below.

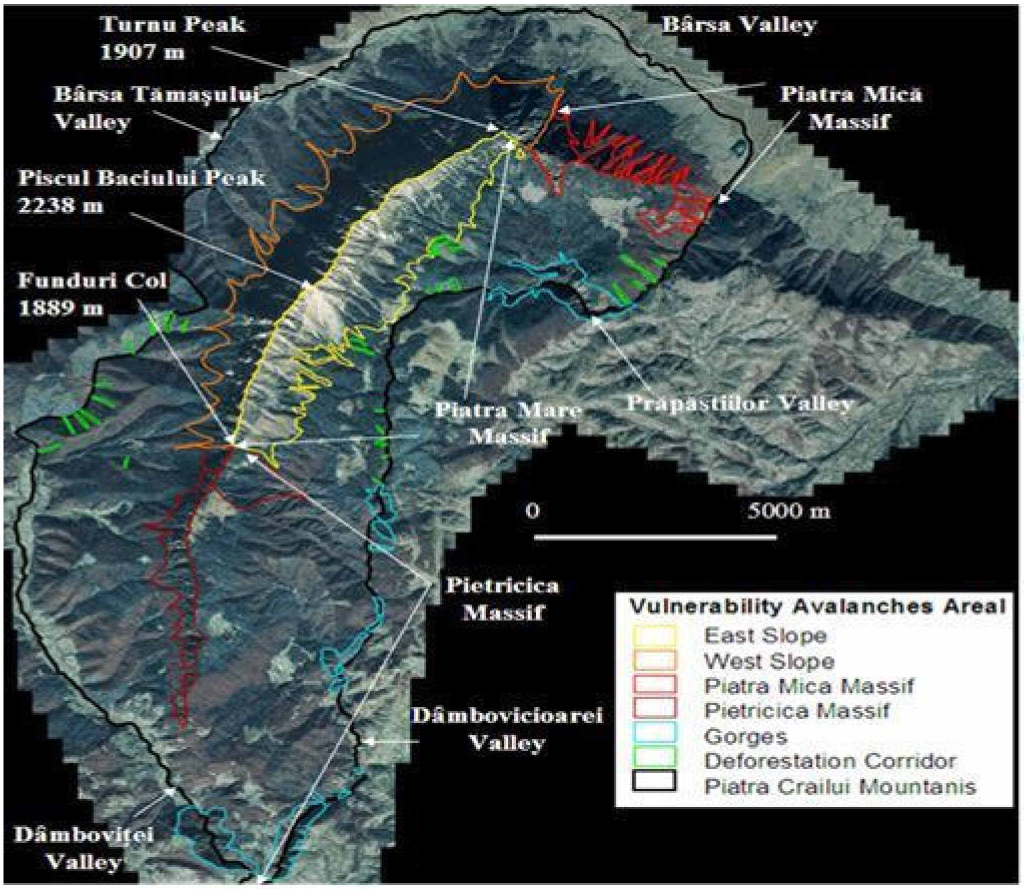

Figure 6. Areas in Piatra Craiului where avalanches can occur (Munteanu, 2009).

(Cristea, 1984). Usually, the small avalanches do not descend to the limestone slope basis (about 1,800 m, Padina lui Călineț). Only the very large avalanches, especially those in spring time, reach as far as the slope basis. These can affect the slopes of the valleys (especially in narrow sectors or above the thresholds), deploying material which is then transported along the corridor and deposited at the basis.

iii) The Eastern slope (Figure 5A, B) provides more favorable conditions for producing avalanches than the opposite side, because of the exhibition and morphology. These form in the small limestone valleys from the upper side, cross over the narrow sectors above the lithological contact and forest vegetation corridors, the deposits being particularly on conglomerates (Munteanu, 2004). It is here the blocks detached from the superior part, being transported and stored along variable distances. Limestone blocks prevail on most corridors, even if the substratum is conglomerate. The corridors are predominantly nivalo-torrentially modelled, with a narrow thalweg on limestone and another large one on conglomerates. This shows the erosion potential and transport dynamics of the slopes which the avalanches have and which manifest differently, as follows (Figure 6) (Munteanu and Moțoiu, 2006):

i) The central Southern, between Steghiei Valley to the South and Cheia Valley to the North is representative, as there occurs the largest number of typical avalanches, affecting about three quarters of the slope surface. Some may surpass 1000 m in length.

ii) In the Northern central part of the slope, between the Grindu valleys to the South and Padinile Frumoase to the north, the avalanches are traveling on distance of 1500 m along valleys, passing by the upper limit of the forest and all the way to the synclinal axis. A diphluence phenomenon may also occur, the avalanches crossing from one corridor to another, over the lower conglomerate interfluves (as it was in Vlăduşca, in March 2005) (Moțoiu and Munteanu, 2006).

iii) To the North, in Curmatura valley basin the avalanches occur on most of the small valleys which cut through the limestone area from Piatra Mare and Piatra Mica. The moving distance is small, of 100-300 m (Constantinescu and Munteanu, 2006; Munteanu, 2006).

iv) In South of Steghii Valley, up to Saua Funduri alignment, the avalanches are also of varying sizes with lengths reaching 1,000 m.

v) In Piatra Mică, avalanches occur on most of the valleys on the Northern slope, on distances of 1000 m, to the East they reach approx. 500 m and to the south-east 100-300 m from the launch area; while in Pietricica they reach 500 m to the East and between 100-700 m to the West (Munteanu, 2009).

The dynamics of the slopes hit by avalanches

The avalanches are one of the most important processes which contribute to the slope dynamics because they induce the detachment, transportation and storage of the blocks which are on slopes with exposed rock. This leads to a gradual reduction in limestone areas and also a slow but continuous withdrawal of the slopes (Munteanu, 2008). Erosion occurs differently along the corridors:

i) The avalanches lead the mobile debris towards the bottom of the corridor, detach parts of rock through the impact effect and erode especially convex sectors and the threshold edges, concave areas being relatively protected.

ii) The displacement effect of unstable material also occurs on the lateral of the corridor, but this effect diminishes towards the surface of the avalanche, where motion speed is more reduced and the tree vegetation initially carries a protective effect, then being most probably destroyed.

The deposits can be found at the basis of the majority of corridors, being the place where, due to the changing in slopes, the energy of the avalanches gradually diminishes, variable material quantities remaining behind (snow, stone, trees, soil). Its role here is one of accumulation, which leads to the apparition of some specific microforms, resembling the glacier morens. Several generations of such avalanche deposits can be met on the same slope (Constantinescu, 1973). Most of the times, limestone blocks of varying sizes are present, which were set in time by the debris material and, at their turn, have been affected by other avalanches. Avalanches do not always reach the same size in the same valley, therefore, successions of such microform deposits left by different avalanches can also be met there.

The analysis of the debris after the snow is melting points out the chaotic disposition of the material, without sorting the materials. Generally, the rocks are angular, and their dimensions vary from centimeters to millimeters (Munteanu, 2009).

The avalanches have a remarkable role in the dynamics of debris. By analyzing experimental polygons marked in the debris along more than 20 avalanche corridors, more than 20 morphodynamic effects were found, their morphodynamic effects being highlighted. Since the majority of the debris deposits are found along the corridors or at their bottom area, the motion exercised by snow also carries away the debris mass. This process is variable, depending on the location of the debris on the avalanche path, as well as its magnitude. Most easily to be retrieved and transported are the deposits in the convex sectors of the longitudinal profile of the corridor, or those located downstream the narrow sectors. On Valley number 10 of Padinile Frumoase, the avalanche in March 2005 carried downstream for about 200 m a stone marked in summer 2004 (Moțoiu and Munteanu, 2006, Figure 7).

Generally short avalanches occur in gorges, on the deposits at the basis of the steep slopes, when the snow destabilizes. Some can be on the whole length of the torrents which fragment the limestone slopes, especially on the sectors with Northern disposure from Prapastii and Dambovitei Gorges. Along the snow quantities, these also trigger the large rocks detached or found in the semi-fixed deluvio-coluviale deposits (Munteanu and Constantinescu, 2006).

The forest exploration channels have a major morphodynamic role, as many are formed on torrent organisms, some in an incipient forming stadium, with a convex aspect and accentuated slopes (over 25-30°). The avalanches producing on them are untypical, as they are due to antropic activities and not to initial natural conditions. These emphasize erosion on a land that was originally protected by forest vegetation, by destroying the soil and creating new transportation routes for snow and water, especially for torrent erosion, which occurs throughout the year. Note that when deforestation is halted and such a forest exploration channels is never used again, the vegetation can recover in time and the risk of avalanches to be gradually reduced, thus reducing the intensity of morphodynamic processes, especially erosion ones (Munteanu and Moțoiu, 2006).

Sporadically, reduced dimension avalanches can occur in limestone quarries, as well, when there are abundant snowfalls on steep slopes areas, situated above. For example, in the quarry upstream of Valea Prapastiilor (Precipice Valley) there were formed avalanche corridors due to the snow coming from Piatra Mica, among the pine alignments planted to stabilize the slope. These can determine a detachment and emphasis in dynamics of the superficial deposits (Munteanu and Moțoiu, 2006).

The data above represent the results of certain analyses which can explain the way the avalanches influence the evolution over time of the morphodynamic processes, of the way the environment, the society, man and his activities are affected. These data represent base resources which are used within the informatic systems for dynamic geomorphology, extreme phenomena analysis, the way to plan the mountain environment.

Conclusion

The avalanches represent one of the most important

Figure 7. Comparative evolution of avalanche corridor of Padinile Frumoase in (a) 2004 and (b) 2007. The picture is new (prelucrated).

morpho-dynamic processes in Piatra Craiului Mountains, through a large spread and a variety of manifestation types, influenced by the local morphology, morphometric characteristics, meteorological parameters, coverage degree and vegetation type, differentiated on the two macro-slopes. They have a seasonal periodicity, with major effects on the evolution of the slopes. They produce dynamic alterations on the detritus deposits, through the contribution of material coming from the slopes, by accelerating the dynamics of the mobile deposits, contributing to the continuous slope retraction. By destroying the vegetation, other deposits are reactivated, initially fixed. The impact of the avalanches on the dynamics of the slopes is evidenced through the differentiated aspect of the areas where they occur, the erroded material, transported and laid again, the aspect of the avalanche corridors and deposits, which remain as testimony in the landscape.

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