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GENETIC TYPOLOGIES OF TALUS DEPOSITS DERIVED FROM GPR MEASUREMENTS IN THE ALPINE ENVIRONMENT OF THE FĂGĂRAȘ MOUNTAINS

Alexandru ONACA, Adrian Cristian ARDELEAN, Petru URDEA, Florina ARDELEAN & Adriana SĂRĂȘAN

Department of Geography, West University of Timișoara, Blvd. V. Pârvan, no. 4, Timișoara, 300223, Romania, alexandru.onaca@e-uvt.ro

Abstract: The subsurface layering of 43 talus slopes in the central part of Făgăraș Mountains was investigated by means of ground penetrating radar (GPR) measurements. The aim of this approach was to delineate different types of internal stratification of talus slopes and to identify the dominant morphogenetic processes, which acted during the Holocene. GPR technique proved to be suitable to detect the thickness of the talus deposits and their internal stratification. Rockfalls and debris flows contributed significantly to the formation of talus deposits and their activity was highly controlled by the Holocene climatic oscillations. Three different genetic types of talus deposits were identified: stratified slope deposits with alternating periods of intense rockfalls and intermediate storage depletion; post-depositional sediment redistribution by surficial debris flows and weak layering interrupted by high-magnitude rockfalls.

Keywords: talus slopes, stratified deposits, GPR technique, rockfalls, debris flows, Făgăraș Mountains

1. INTRODUCTION

Within the alpine environments talus slopes represent outstanding formations of sediment storage (Otto, 2006). They are widespread especially in glacial cirques and troughs, where the fluvial erosion can be neglected (Sass, 2006) and the dominant transfer processes are rockfalls, debris-flows, solifluction and snow avalanches. In high mountain environments talus slopes are considered sediment traps since they collect most of the detached material from adjacent rock walls and steep slopes (Saas & Kraublatter, 2007). In a simplified manner the alpine sediment cascade looks as follows: rock wall/steep slope → rockfall/debris flow →talus slope (Müller et al., 2014). If permafrost occurs then rock glaciers represent the ultimate stage of the sediment cascade of a periglacial slope (Müller et al., 2014).

In glaciated environments talus deposits act as natural sediment archives, allowing calculation of the post-glacial weathering rates based on the estimation of scree volumes (Rapp, 1960; Douglas, 1980; André, 1997). However this estimation is very rough since the contact between the talus and the bedrock is normally unknown. Due to the lack of information regarding the internal structure of talus slopes the current weathering rates are generally overestimated, since the authors assume a continuous production of scree during the entire Holocene (Sass & Wollny, 2001). Previous approaches revealed not only that talus deposits are very complex sediment storage formations, but also that after the deglaciation important fluctuation occurred regarding the dominant transfer process (Sass & Wollny, 2001; Sass & Kraublatter, 2007; Kraublatter & Moser, 2009). In Făgăraș Mountains, Urdea (1995) revealed for the first time the existence of stratified slope deposits in case of several talus slopes in Văiuga glacial cirque. More recent studies confirmed the presence of stratified deposits in Făgăraș Mountains using geophysical measurements (Onaca et al., 2013).

To gain insight into the internal structure of talus slopes and to elucidate the nature of the dominant morphogenetic processes, geophysical techniques have become the most promising approach in the last years (Sass, 2006). Of these techniques, ground penetrating radar turned out to be the best option for the determination of the thickness of the talus deposits and delineation of different types of stratification within talus deposits (Otto & Sass, 2006; Schrott & Sass, 2008).

Investigating the sediment structures of talus deposits in the alpine environment of Făgăraș Mountains by means of GPR and delineating different types of internal stratification of talus slopes we aim to identify the dominant morphogenetic processes, which acted during the Holocene.

2. STUDY AREA

The study was conducted in the central part of the Făgăraș Mountains (45°37’ N; 24°36’ E), the highest mountain unit of the Romanian Carpathians (Fig. 1).

The GPR profiles were undertaken in the Bâlea and Capra cirques and Doamnei glacial valley. The highest peaks in the investigation area exceed 2300 m in elevation (Vânătoarea lui Buteanu – 2507m; Văiuga 2443 m; Iezeru Caprei – 2417m; Paltinu – 2398m; Laița – 2397m). The lithology consists of micaschists, paragneisses, amphibolitic schists, quartz-sericite schists, limestones and crystalline dolomite, belonging to the Suru Formation of the Făgăraș Subgroup (Gridan et al., 1986).

The landscape was shaped by the Pleistocene glaciers showing a typical alpine morphology with deep glacial cirques and troughs, well preserved glacial steps and âretes with very steep walls (Urdea, 2004).

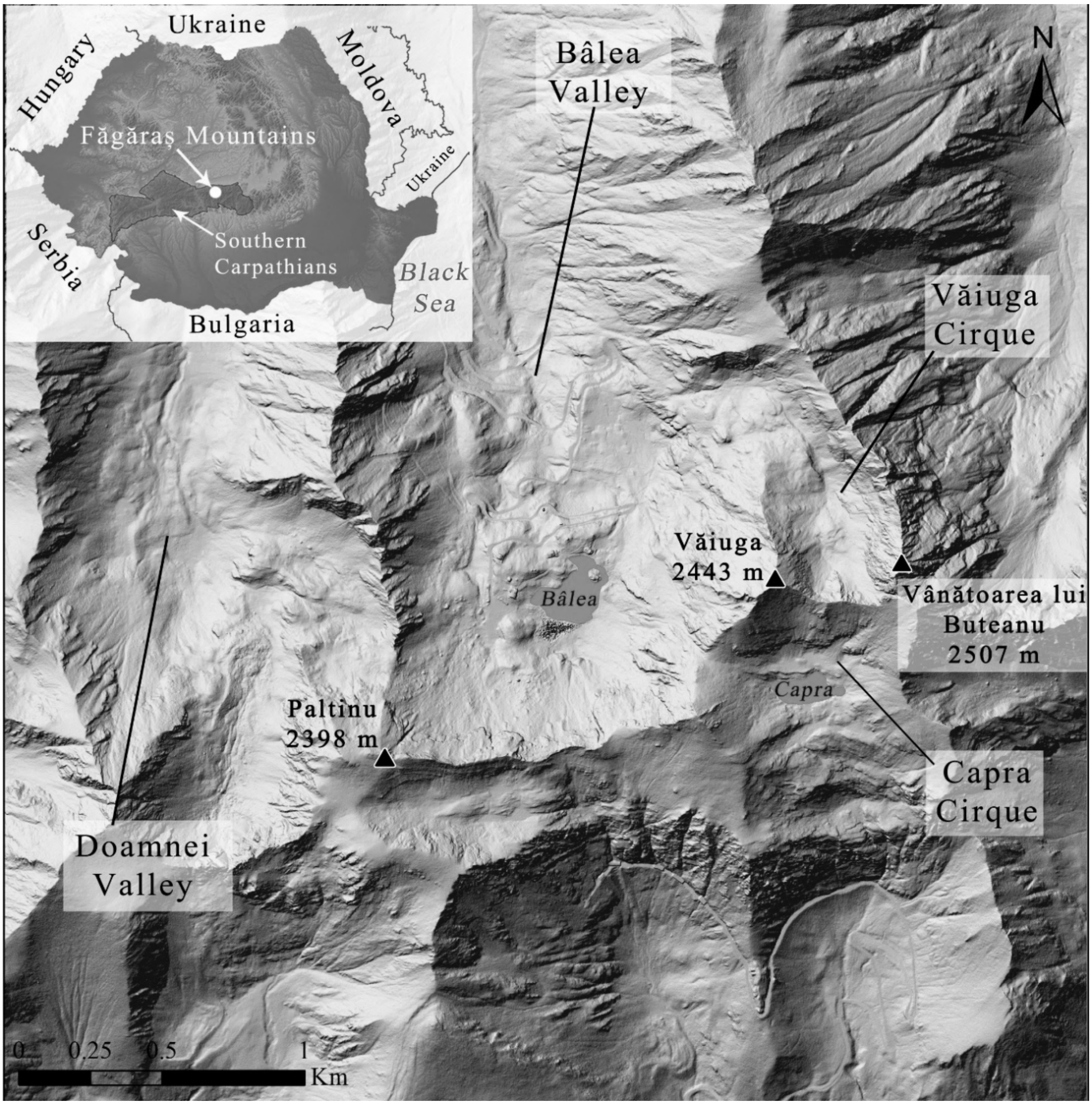

Figure 1. Location of the investigation area (central part of Făgăraș Mountains).

A large variety of periglacial landforms occur between the tree line and the highest peaks such as: rock glaciers, debris cones, scree slopes, block streams, patterned ground, solifluction, earth hummocks etc. Specific landforms and deposits suggest the current activity of mass wasting processes (e.g. rockfalls, debris flows, solifluction, snow avalanches, and frost creep). The tree-line is located at 1600-1700 m, whereas above this elevation the slopes are covered by alpine herbs and sub-alpine shrub species (*Pinus mugo, Juniperus nana, Rhododendron kotschy, Vaccinium myrtillus*).

According to the data from the high altitude Bâlea-Lac meteorological station (2038 m; 45°36’20″ N; 24°36′45″ E) the climatic conditions specific for the alpine domain of the Făgăraș Mountains, are cold with moderate precipitation. In table 1 the main characteristics of the regional climate are highlighted.

3. METHDOLOGY

The GPR technique was used in the investigation of alpine deposits since the last century (Haeberli, 1985). Lately there has been an increase in studies concerning GPR investigation of slope deposits (Sass & Wollny, 2001; Otto & Sass, 2006; Sass, 2006; Sass & Krautblatter, 2007).

GPR investigations are based on transmitting high frequency electromagnetic (EM) pulses into the ground (Reynolds, 1997; Hauck & Kneisel, 2008; Jol, 2009). When the transmitted signal encounters a single object or a continuous contact between two layers of different relative dielectric constant, the signal changes its path, thus part of it is reflected back to the receiver and part of it is redirected further in the substratum (Telford et al., 1990; Bristow & Jol, 2003; Milsom, 2003). By knowing the velocity of the EM signal, the two-way travel-time (m/ns) can be converted to depth (m) of the investigated environment (Kearey et al., 2002; Milsom, 2003). Typical values of radar parameters for most common materials are presented in table 2.

The investigations were performed using a RAMAC GPR system made by MalåGeoSciences, equipped with 25, 50 and 100 MHz center frequency Rough Terrain Antennas (RTA) and unshielded antennas. The choice of antennae frequency dictates maximum investigation depth and resolution, thus while low frequency surveys (25 Mhz) offer a greater penetration depth, high frequency investigations offer a better resolution of the investigated environment, at the cost of a reduced penetration depth. A total number of 68 longitudinal and cross profiles were performed between 2011 and 2015 on several talus deposits situated within the Bâlea, Capra and Văiuga valleys. Data was acquired by continuous measurements, applying a sampling interval of 0.5 s and sample frequencies of 250 and 500 MHz. The built in auto-stacking option, provided by the manufacturer was applied for trace stacking. Due to the fact that the RTA antennas are of compact type, no Common Midpoint (CMP) or Wide Angle Reflection and Refraction (WARR) measurements were performed, thus an overall wave velocity of 0.12 m/ns was used for the depth conversion of the radar signal (Otto & Sass, 2006). Processing of GPR data was performed using Reflexw 7.6, based on processing sequences exemplified in similar studies (Schrott & Sass, 2008).

4. RESULTS

Between 2011 and 2015 we investigated the internal sediment structure of 43 talus slopes in the Văiuga, Bâlea, Doamnei and Capra glacial cirques and their corresponding glacial troughs (Fig. 3).

Table 1. Climatic characteristics of the Bâlea-Lac meteorological station.

	MAAT (°C)	Precipitations (mm)	Days with $AT_{min} \leq 0$	Days with $AT_{max} \leq 0$	Days with $AT_{min} \leq -10$	Days with snow cover	AMinAT (°C)
Bâlea Lac	0.4	1220.3	207	119.5	69	221	-27.4

MAAT – mean annual air temperature, AT – air temperature, AMinAT – absolute minimum air temperature.

Table 2. Typical values of radar parameters for several materials (Milsom, 2003).

Material	ε_r	*σ (mS/m)*	*V (m/ns)*	*α (dB/m)*
Air	1	0	0.3	0
Ice	3-4	0.01	0.16	0.01
Fresh water	80	0.05	0.033	0.1
Dry sand	3-5	0.01	0.15	0.01
Wet sand	20-30	0.01-1	0.06	0.03-0,3
Shales and clays	5-20	1-1000	0.08	1-100
Limestone	4-8	0.5-2	0.12	0.4-1
Granite	4-6	0.01-1	0.13	0.01-1

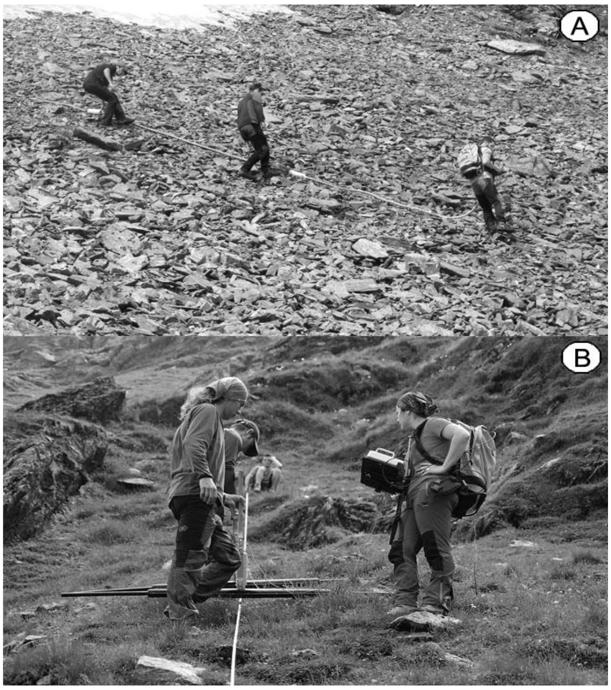

Figure 2. GPR investigatioans performed with RTA (A) and unshielded antennas (B)

In 25% of cases, additional geophysical investigations consisting in DC resistivity measurements were performed to compare the contrasts in specifical physical properties of the subsurface. The combination of GPR and DC resistivity techinques allowed a more sophisticated geomorphological interpretation, but for the detection of the talus deposits thickness and internal stratification, the GPR method proved to be highly suitable and in this paper we will refer only to these data.

Dry and coarse talus deposits, but also consolidated deposits, where finer sizes materials and vegetation prevail at the surface were investigated (Fig. 3). In most of the GPR profiles, the bedrock surface was clearly recognizable from the radargrams. All the profiles reveal a very similar reflection pattern and radar wave propagation velocities, with clear signals returning from more than 15 m below the investigated surface. The thickness of the debris deposits vary from site to site, but generally range between few meters and more than 10 m in the lower parts of the slopes. In several cases the bedrock was intercepted at more than 15 m depth.

Analysing the internal structure of all the investigated talus slopes we observed three main types of layered structures, which are described in detail in the following lines through the most representative GPR profiles situated in the Doamnei Valley:

Type 1: Stratified slope deposits with alternating periods of intense rockfalls and intermediate storage depletion

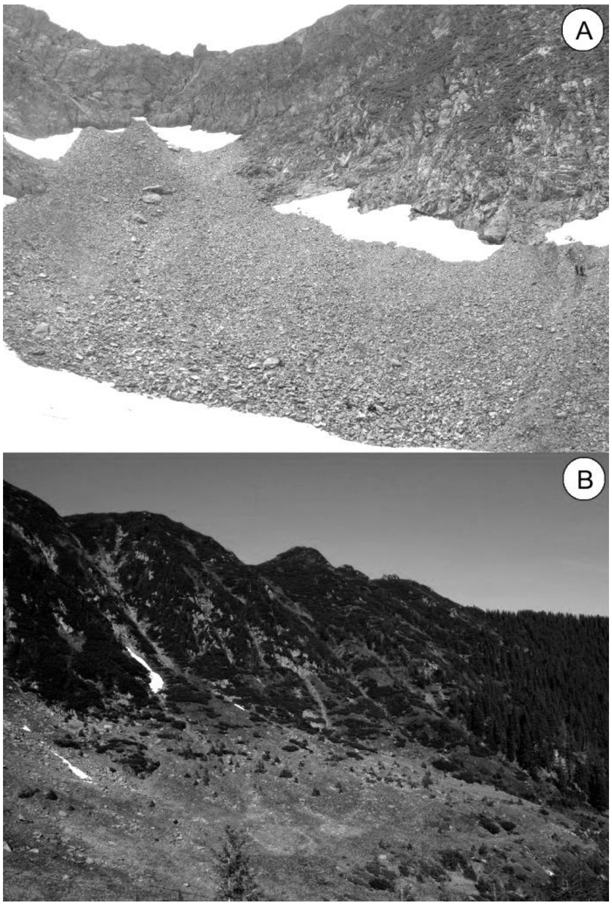

Figure 3. Active (A) and relict (B) investigated talus slopes in the Văiuga Cirque (A) and Doamnei Valley (B).

Figure 4 presents a 70 m longitudinal profile executed on a talus cone located on the western slope, within the lower sector of the Doamnei Valley. The current profile has a W - E general orientation, stretching in elevation from 1790 to 1740 m. Within the first 30 m, at a depth of 7 – 11 m, the radargram exhibits a clear and continuous reflection interpreted as the contact between the talus body and the underlying bedrock (Otto, 2006). For the rest of the profile the talus/bedrock contact is not given as a sharp reflection, but rather as an area without reflections, several studies pointing out that the internal structure is more pronounced than the underlying bedrock and could cause difficulties in clearly identifying the bedrock contact (Otto & Sass, 2006, Sass & Krautblatter, 2007, Sass & Wollny, 2001). This situation is mainly due to a low dielectric contrast between the debris body and the underlying bedrock, thus, it can be concluded that in this case the debris/bedrock contact is characterized by a considerable decrease in reflections.

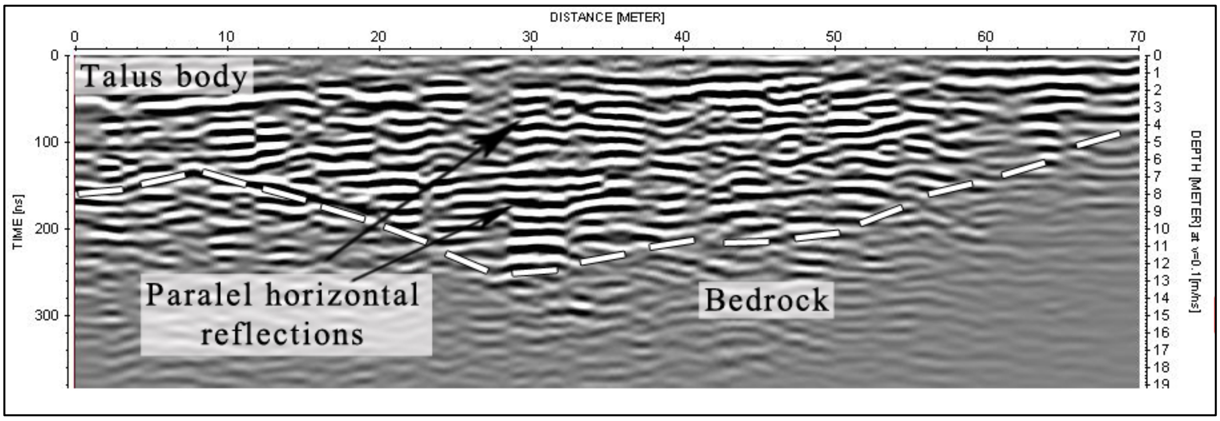

Figure 4. Radargram on a talus slope within the Doamney Valley, dominated by the alternating rockfall activity.

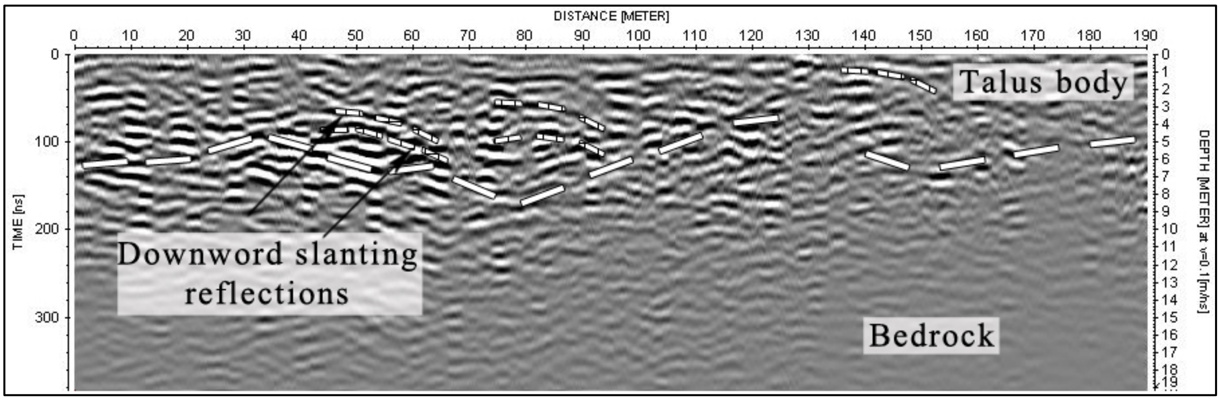

Figure 5. Radargram on a talus slope dominated by the debris-flow activity.

The current profile reveals a rather dense reflection pattern which stretches mainly over the entire length of the radargrams. This dense pattern of mostly parallel and continuous reflections is characteristic to a stratified internal structure determined, most likely, by the alternation of compact layers, composed of different sized boulders (Sass, 2006). The sedimentation process which lead to the input and deposition of debris have acted mainly within the specific climatic conditions of the Late Pleistocene, with a probable maximum of debris input within the Tardiglacial period and a minimum of debris accumulation within the middle and late Holocene (Urdea, 1995). Therefore, based on the fact that the complex mechanism of debris production and storage is strongly influenced by environmental changes - in the cold periods debris input is dominated by coarse-grained rockfalls, whereas in warmer periods the heavy rains activity release fine-grained secondary rockfalls from the intermediate storage, deposited during cold periods (Kraublatter & Moser, 2009) - it can be said that the presence of a dense, surface parallel, reflection pattern confirms the occurrence of internal stratification within the investigated talus body, composed by an alternation of coarse and fine debris layers.

Type 2: Post-depositional sediment redistribution by surficial debris flows

The second radargram shows a 190 m longitudinal profile performed on a talus cone located on the eastern slopes of the Doamnei Valley (Fig. 5), having a SW – NE general orientation and stretching from 1652 to 1573 m. Between the 30 and 60 m marks the bedrock/talus contact is characterized by a strong reflection and similar to the previous profile the rest of the radargram exhibits a bedrock/talus contact given as a diminution of reflections, ranging in thickness from a minimum of 4 m, to a maximum of 8 m.

In contrast to the previous profile the current radargram exhibits a series of rather weak reflection pattern, revealing both surface parallel and downward slanting structures (Fig. 5, 40 – 60 m; 140 – 150 m). The presence of surface parallel structures suggest that the investigated talus slopes share a similar genesis and are thus the result of a long term stratification process. Although the presence of several reflections with a dip angle different than the general angle of the scree slope, the identified reflections suggest that the main factors controlling redistribution and stratified sedimentation, at the current site, are debris flow events (Sass & Krautblatter, 2007). Similar reflection was intercepted in other places (Wilkinson & Schmid, 2003; Sass & Krautblatter, 2007) and the discordant layers, which generally are not extended over the entire length of the talus, were considered to be the result of large debris-flows activity.

Type 3: Weak layering interrupted by high-magnitude rockfalls

Figure 6 reveals the last profile presented in the current paper, having a length of over 250 m and revealing a third type of talus deposition within the investigated area. The current profile was performed on the largest debris cone investigated within the current paper, being located on the western slopes of the Doamnei Valley. Its general orientation is SW – NE, streching in elevation from over 1860 m to just under 1710 m. Similar to the previous profiles the talus/bedrock contact is revealed by a strong reflection only between the 140 and 200 m marks, while for the rest of the profile the maximum depth of the talus body is given as a diminution in reflection amplitudes. The thickness of the investigated talus ranges between 5 and 11 m.

Unlike the above profiles the current radargram reveals a rather weak stratification pattern, with numerous discontinuities given by several reflection hyperbolas (Fig. 6), which point out the presence of large blocks within the internal structure of the investigated slope deposit. This specific discontinuity of the preexistent stratification has been identified in previous studies from the European Alps (Sass & Krautblatter, 2007), being described as the result of large scale rockfall, events that have a major role in disturbing the previous stratification, although this situation could as well be caused by the alternation of continuous debris flows with episodic rockfall events (Sass & Krautblatter, 2007).

5. DISCUSSION

The analysis of GPR results allowed identifying the stratification characteristics of 43 talus slopes in the central part of the Făgăraș Mountains. Based on these findings we were able to recognize the geomorphologic processes responsible for the input and deposition of debris materials. We assume that rockfalls and debris flows contributed significantly to the formation of talus deposits and their activity was highly controlled by the climatic oscillations. The alternations of coarse-grained and fine-grained layers depicted in figure 4 support this assumption. During cold intervals, characterized by intense frost action the evolution of talus slopes was governed by enhanced rockfalls activity, whereas during warm and wet periods either debris flows processes or the release of finer materials due to secondary rockfalls from intermediate storage dominated (Kraublatter & Moser, 2009). Solifluction would have been also involved in the investigated stratification, but considering the current low activity of this frost-derived process in the Southern Carpathians (Onaca, 2013), we assume that the efficiency of this mechanism was high enough to generate distinct layers only in the Tadiglacial, after the deglaciation.

In some cases (Fig. 7) the internal sediment structures identified on the radargrams reveal clear evidences of post-depositional sediment redistribution by surficial debris flows. Here, we assume that the initial rockfalls deposits accumulated mainly at the end of Pleistocene were redistributed by intensive debris flows occurring during the wet periods of the Holocene (Wilkinson & Schmid, 2003). This situation is confirmed in many cases by the current surficial debris-flows activity frequently observed by the authors in the investigated area during summer rainstorms. In addition, the small-scale distinct morphology of debris flows deposits and paths, marked by the presence of several tens of centimeters height lateral levees and poor sorting of sediments is clearly recognizable in the field.

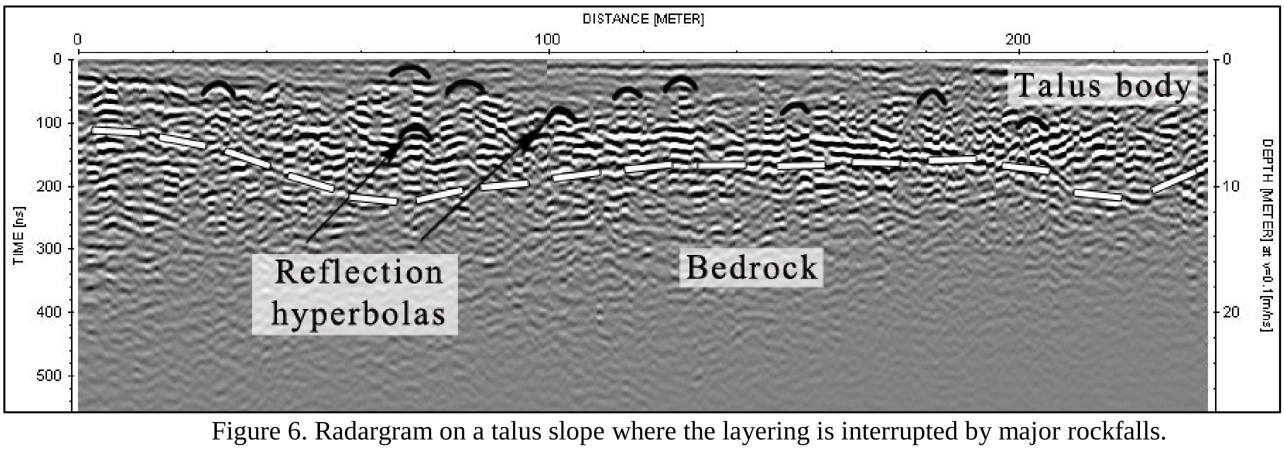

Figure 6. Radargram on a talus slope where the layering is interrupted by major rockfalls.

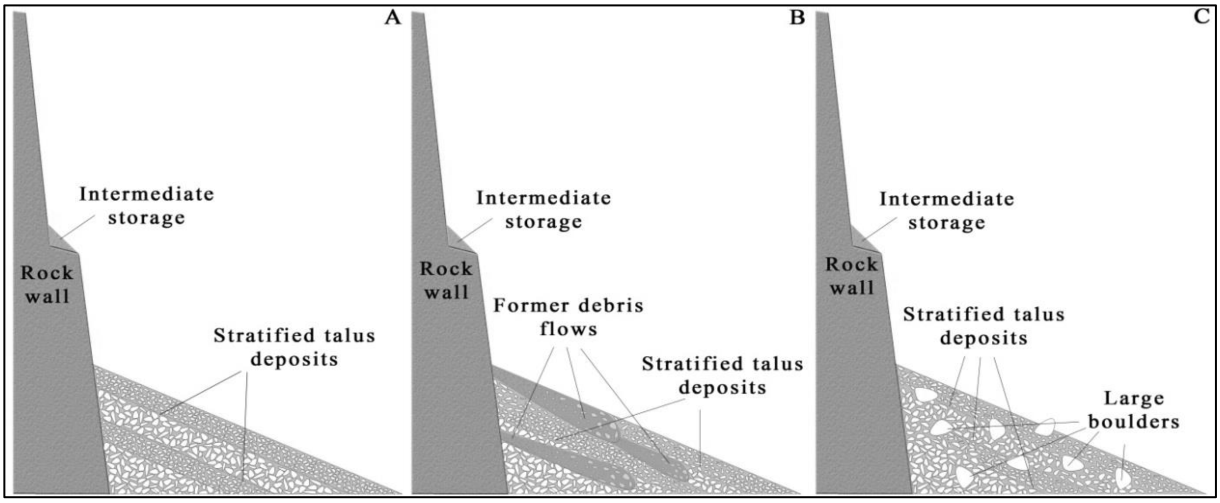

Figure 7. Genetic models of talus deposits in the Făgăraș Mountains (A. stratified slope deposits with alternating periods of intense rockfalls and intermediate storage depletion; B. post-depositional sediment redistribution by surficial debris flows; C. weak layering interrupted by high-magnitude rockfalls) (adapted after Kraublatter & Moser, 2009).

However, in case of high magnitude rockfall events, no stratification can be expected, since the impact energy and specific movement of fallen blocks is much too high to allow the formation of a continuous layer of boulders (Sass & Krautblatter, 2007). Very-large boulders, with a diameter exceeding few meters and widespread particularly in the hanging glacial cirques testify the activity of large slope failures in the past.

In all the investigated profiles we observed a stratification of the internal materials to a certain degree. In most of the cases the stratification is obvious only within specific sectors of the profiles and appears to be disturbed especially upslope by post-depositional processes (e.g. debris-flows, solifluction, large rockfalls). In other cases, the parallel layers of different grain-size materials were intercepted at few meters below the surface. Based on these we assume that the formation of clear distinct layers of rockfall deposits occurred probably in Tardiglacial or at the beginning of Holocene. Despite that in similar studies (Sass & Krautblatter, 2007; Kraublatter & Moser, 2009) the recent cold period, known as Little Ice Age was outlined as the uppermost layer of coarse-grained materials, we were not able to distinguish a clear distinct coarse-grained layer near the surface.

Based on our findings it appears that within most of the talus slopes the deposition of sediments was not continuous during the Holocene. The results seem to indicate that the deposition was interrupted when the amplitude of freeze-thaw activity was low and restarted several times when periods of intense freeze-thaw cycles or heavy rains occurred (Kraublatter & Moser, 2009). Between the cold periods with enhanced rockfalls, warmer phases characterized by sediment redistribution, finer-grained rockfalls and soil formation appear to dominate during the Holocene. However, several high-magnitude rockfall events were intercepted in the investigated talus slopes.

Analysing the 68 radargrams we identified three main types of layered structures. The models of the talus slopes development in the investigated area are showed in figure 7 pointing out the depositional and post-depositional processes which explain the stratification of the subsurface deposits.

6. CONCLUSIONS

The investigation of the internal structure of 43 talus slopes in the central part of Făgăraș Mountains, based on GPR results, led to 3 main conclusions:

- GPR technique proved to be a powerful tool to detect the thickness of the talus deposits and their internal stratification;
- Rockfalls and debris flows contributed significantly to the formation of talus deposits and their activity was highly controlled by the climatic oscillations;
- Three different genetic types of talus deposits were identified: stratified slope deposits with alternating periods of intense rockfalls and intermediate storage depletion; post-depositional sediment redistribution by surficial debris flows and weak layering interrupted by high-magnitude rockfalls.

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