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# ASSESSEMENT OF INTERNAL STRUCTURE OF PERIGLACIAL LANDFORMS FROM SOUTHERN CARPATHIANS (ROMANIA) USING DC RESISTIVITY TOMOGRAPHY

**Alexandru ONACA, Petru URDEA, Adrian ARDELEAN & Raul ȘERBAN**
*West University of Timișoara, Department of Geography, Blvd. V. Pârvan, no. 4, Timișoara, 300223, Romania, alexandru.onaca@cbg.uvt.ro*

**Abstract:** This study presents the use of DC resistivity tomography for the detection of periglacial landforms structure from Southern Carpathians. Direct-current (DC) resistivity tomography has been applied to six periglacial landforms from the alpine domain of Southern Carpathians for the first time in Romania. Due to important differences in the electrical resistivity of the subsurface materials it was possible to determine the internal structure and the thickness of the periglacial landforms. A rock glacier (Roșiile) from Parâng Mountains, two patterned ground sites from Țarcu Mountains, as well as two solifluction phenomena and a scree slope from the central part of Făgăraș Mountains were investigated by means of 2D resistivity imaging. The electrical resistivity measurements indicated the presence of sediments cemented by ice and ice lenses in Roșiile rock glacier. The large depth of the active layer and the low content of ice suggest that the permafrost exists in marginal condition and is not in equilibrium with the present climate. A chaotic structural pattern characteristic for the near-surface layer of the patterned ground was interpreted as the result of actual frost heaving. The solifluction lobe and terraces were analyzed comparatively displaying a relatively thin mixture of unconsolidated unfrozen sediments affected by seasonally frozen ground. One scree slope from Văiuga glacial cirque was investigated in a similar manner revealing a thick mantle of unconsolidated stratified periglacial deposits

**Keywords:** DC resistivity tomography, periglacial landforms, permafrost, rock glacier, patterned ground, solifluction lobe, solifluction teraccetes, scree slope, Southern Carpathians

## 1. INTRODUCTION

Interest in frost-related processes has increased in the last 20 years because researchers have become concerned to capture the modifications induced by a warming climate in sensitive cold environments. Furthermore, since the degradation of mountain permafrost generates slopes instability (Haeberli, 1992) and consequently significant economical losses this subject has become more attractive for scientists.

Because direct observations of the subsurface materials in periglacial environments are not an easy task and some time is extremely time consuming and expensive, the best alternative to drilling is to apply geophysical techniques. Owing that these equipments are able to provide fast information on the shallow substrate, a growing number of geomorphologists have begun to use intensively geophysical measurements to get more information on the physical properties of frozen ground. Due to a high contrast of resistivity between water and ice electrical methods are suitable for mapping subsurface frozen sediments (Hauck & Vonder Mühll, 2003).

In periglacial environments, geophysical measurements have been widely used to provide information on permafrost distribution and characteristics (Vonder Mühll et al., 2002). Only several researches have focused on the internal structure and paleoclimatic significance of periglacial landforms affected by seasonal frozen (Kneisel, 2006, Otto & Sass, 2006; Schrott & Sass, 2008). In the Southern Carpathians where a wide variety of periglacial landforms occur above the timberline these methods have been used since 2007 (Urdea et al., 2008a).

Despite the fact that frost-related processes are heavily involved in the recent transformation of the Southern Carpathians relief (Rączkowska, 2009), significant studies about this subject are missing almost totally. Between 2007 and present a small number of geophysical surveys were conducted on periglacial landforms in Făgăraș, Muntele Mic and Retezat Mountains (Urdea et al., 2008a, Urdea et al., 2008b, Onaca et al., 2011).

So far, the existence of sporadic permafrost in Southern Carpathian was shown by DC resistivity only for few rock glaciers from Retezat Mountains (Urdea et al., 2008b, Vespremeanu-Stroe et al., 2012). Regarding the internal structure of periglacial landforms from non-permafrost Southern Carpathians areas the contributions are conspicuously lacking.

This paper aims to examine the internal structure of different periglacial landforms from the alpine area of Southern Carpathians by means of DC resistivity in order to detect permanently frozen bodies and to understand the processes associated with freezing and thawing of unconsolidated periglacial deposits. A further intention of this study is to explore the advances, limitations and perspectives of 2D resistivity imaging applied in different types of periglacial landforms.

## 2. STUDY AREAS

The Southern Carpathians are the highest part of the Romanian Carpathians (Moldoveanu Peak – 2544 m a.s.l.). The climatic conditions specific for the high zone of the Southern Carpathians are cold, with mean annual air temperature (MAAT) of 0.3° C at Bâlea-Lake (2038 m a.s.l.), -0.5°C at Ţarcu (2180 m a.s.l.) and -2.4°C at Omu (2505 m a.s.l.) and with moderate precipitation (1220 mm at Bâlea-Lake, 959 mm at Ţarcu and 969 mm at Omu). Between the highest peaks and ridges situated above 2000 m a.s.l. and the timberline (1600-1800 m a.s.l.) a large variety of periglacial landforms occurs (rock glaciers, talus cones and scree slopes, block fields and block streams, patterned ground, solifluctions etc.). The study areas include four different periglacial sites (Fig. 1). The sites were chosen to represent different periglacial environments (rock glaciers, patterned ground, solifluctions and scree slopes).

### 2.1. The Roșiile rock glacier site (Parâng Mountains)

Roșiile rock glacier (45° 20′ 34.50″ N, 23° 33′ 17.16″ E) belong to the talus foot lobate type, and it is located in Roșiile north-facing glacial cirque of the central part of Parâng Mountains on the southern side of Roșiile glacial lake. The rock glacier is dominated by 200-250 m high granite rock walls situated below Gruiu (2345 m a.s.l.) – Pâcleșa (2335 m a.s.l.). The surface morphology of the rock glacier shows well developed transversal furrows and ridges as far as large thermokarstic depressions. The debris layer is extremely coarse near the surface where large boulders up to several metres in diameter occur. Fine materials and vegetation are entirely missing suggesting that the rock glacier is active in the present. The rock glacier extends from an altitude of 2165 m a.s.l. down to 2072 m a.s.l. and it is 310 m wide in its lower part and 220 m long with an area of 0.45 km$^2$. The lithology consists of gneissic granites.

### 2.2. The frost-crack polygons site (Țarcu Mountains)

Two different types of patterned ground were investigated in this paper. In the first case, a gentle slope (2-6°) with fossil ice-wedge polygons located on the south-eastern side of Căleanu Peak (2190 m a.s.l.) (45° 18′ 10.02″ N, 22° 33′ 25.49″ E) was studied. Described by Niculescu & Nedelcu (1961) the frost-crack polygons are covered with soil and vegetation in the present ranging in size from 0.5 to 5 m. The angular blocks representing the borders between the frost-crack polygons have decimetric sizes. Different types of rocks (low metamorphosed conglomerates, microconglomerates, green sandstones and siltstones interbedded with black mudstones, slates, shales and ultramafic rocks of the Brustur Formation, part of the Danubian basement (Iancu et al., 1990) prevail in the studied area. The vertical position of few angular clasts suggests the frost heaving influence.

### 2.3. The earth hummocks site (Muntele Mic massif)

The second location from Ţarcu Mountains is in Muntele Mic massif at 1750-1780 m a.s.l. (45° 22' 40" N, 22° 28' 48.53" E). This site situated on the north-eastern slope of the Muntele Mic plateau is characterised by well developed closely spaced earth hummocks in nearly flat terrain (below 5° inclination).

Their height varies from 8 to 62 cm and averages around 31 cm while their basal diameter is between 40 and 260 cm, with most of the mounds close to 110 cm. The mounds are covered with subalpine vegetation (*Polytrichum commune, P. formosum, Pogonatum aloides, Cetraria islandica, C. tilesii,* *Cladonia uncialis, C. portentosa, Poa alpina vivipara, Nardus stricta, Vaccinium myrtillus, V. vitis-idaea*) and fine-grained soils prevail in the area. Recent studies have shown that the frost heave is more efficient in the earth hummocks than on the flat terrain (Urdea et al., 2003).

### 2.4. The solifluction phenomena and scree slope site (Făgăraș Mountains)

Since solifluction is probably the most widespread periglacial phenomena from the alpine area of Southern Carpathians, it was necessary to investigate the subsurface of these landforms to improve our knowledge about their formation and evolution. A slope affected by small solifluction terraces found on the southern side of Laița Peak (2397 m a.s.l.) (45° 35' 39.08" N, 24° 35' 49.18" E) and a south facing solifluction lobe close to Paltina Peak (2398 m a.s.l.) (45° 35' 52.79" N, 24° 36' 25.81" E) were selected for geophysical surveys. In both cases, the slopes were moderate inclined (10-15°, respectively 15-25°) and covered by small alpine vegetation.

In addition, a scree slope located in Văiuga glacial cirque and covered by angular clasts at the surface was investigated in order to capture the thickness of the unconsolidated sediments. The slope is between 35° and 45° and it is heavily affected by wet snow avalanches and debris-flows. Situated below the rock walls of Văiuga (2443 m a.s.l.) and Vânătoarea lui Buteanu (2507 m a.s.l.), scree slopes are very common for this narrow cirque (Urdea, 1995).

The bedrock in the area consist of schists (micashists, sericitous schist, amphibolitic schists), and paragneisses, but strips of crystalline limestones occur in few areas (e.g. Paltina).

## 3. METHODOLOGY

DC resistivity tomography or electrical resistivity tomography (ERT) method is based on the varying electrical conductivity of subsurface materials. The resistivity values specific for rocks vary in large limits and depends mainly on water content, structure of pores and chemical properties (Kneisel, 2006). For permafrost the resistivity values range from 10 to 1000 kΩm or even more, depending on the ice content, the quantity of impurities and the temperature (Kneisel & Hauck, 2008).

Two-dimensional (2D) resistivity imaging is probable the most applicable geophysical method for permafrost detection due to a high resistivity contrast between permafrost and unfrozen sediments.

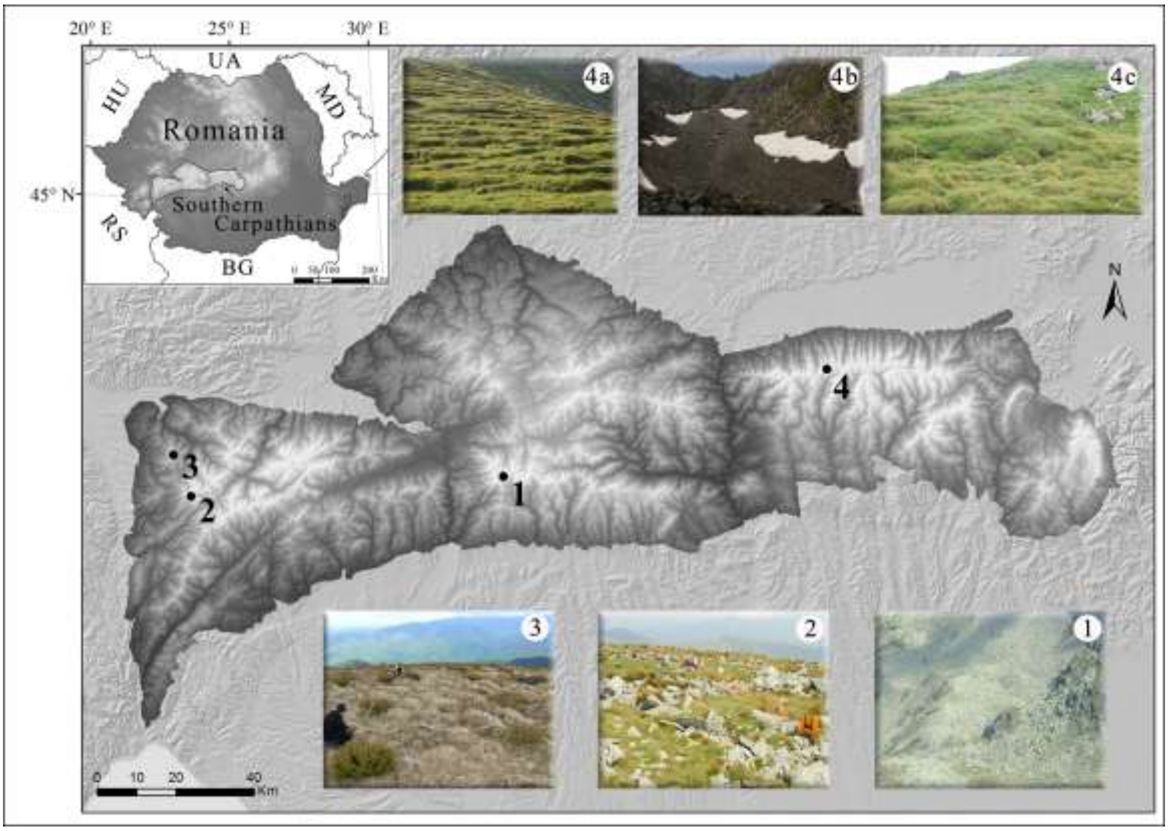

Figure 1. Location of the study areas in Southern Carpathians: 1.the Roșiile rock glacier site; 2. the frost-crack polygons site; 3. the earth hummocks site; 4. the solifluction phenomena and scree slope site (4a solifluction terraces, 4b scree slope, 4c solifluction lobe).

That is why the geophysical investigations have focused on the permafrost distribution and stratigraphy within rock glaciers, talus slopes or moraines (Kneisel et al., 2008, Scapozza et al., 2011).

ERT measurements are conducted by injecting current into the ground using two electrodes and measuring the resulting voltage difference of potential at two other electrodes. Calculating the ratio between the difference of potential (ΔV) and the current (I) multiplied by a geometric factor (K), which depends on the arrangement of the four electrodes, the apparent resistivity is calculated (Kneisel & Hauck, 2008). Since this specific resistivity is not the real resistivity of the subsurface a conversion from apparent resistivity to true resistivity is required. Finally, an image with the resistivity variation in the subsurface is achieved.

The two-dimensional surveys were made using a complex geophysical system PASI 16GS24N with 32 electrodes. In this paper, Wenner and Dipole-Dipole electrode configurations types were used. The Wenner array is recommended for subsurface structures with vertical changes of resistivity, providing an acceptable horizontal resolution and a moderate investigation depth (Kneisel, 2006). Dipole-Dipole configuration offers a better horizontal resolution and the greatest number of readings but a shallower depth and a weaker vertical resolution (Loke & Barker, 1995).

Setting the unit electrode spacing and electrode configuration influence the maximum depth penetration and the horizontal and vertical resolution. Reducing the inter-electrode spacing will decrease the depth of penetration, but will increase the horizontal and vertical resolution. Depending on the goal of the survey the appropriate unit electrode spacing and the array will be selected. If the aim is to delineate the permafrost extent and ice content or to capture the thickness of the unconsolidated materials respectively the depth of the bedrock, than a unit electrode spacing of 5 m is suitable (e.g. rock glaciers, scree slopes). When a superior lateral resolution is required than the unit electrode spacing should decrease (below 1 m) and Dipole-Dipole configurations should be selected (e.g. earth hummocks, periglacial polygons, solifluction landforms).

The conversion from apparent resistivity to true resistivity was done by applying the least-squares inversion technique offered by Res2DINV ver. 3.55.18 Software produced by M. H. Loke (Loke & Barker, 1996).

All the resistivity tomographies were performed in the warm season when the surface was free of snow.

## 4. RESULTS AND INTERPRETATION

### 4.1. Roșiile rock glacier

In the summer, of 2012 one ERT profile was carried out on Roșiile rock glacier. Sponges soaked with salt water were used to improve the poor electrical contact between electrodes and the bouldery surface of the rock glacier. Figure 2 shows the results of a 160 m long ERT cross-section profile, with electrode spacing of 5 m and a maximum penetration depth of 30 m. The survey results reveal resistivity values of 0.5 to 10 kΩm in the near-surface part, between 1 to 10 meters. These resistivity values are characteristic for the unconsolidated dry materials with medium and large size boulders (Ikeda, 2006). The near-surface high resistivities between 30 and 35 m and 110 and 120 m along the line are probably due to poor electrode coupling. At a horizontal distance of 50 to 120 m at 10 m depth, a high resistivity anomaly was found. Here, high resistivity values, exceeding 25 kΩm indicate the presence of two ellipsoidal permafrost bodies in the subsurface (Farbrot et al., 2005). The main body represents probably massive ice (resistivity values above 100 kΩm), while the second one is composed mainly by ice cemented sediments with a low content of ice. Below the permafrost layer, a 1-3 m thickness layer (with resistivities between 10 to 20 kΩm) would probably corespond to the transition to unfrozen sediments. A sharp differentiation between the unfrozen sediments and the bedrock is made difficult because dry materials shows simillar resistivities as the bedrock (between 6-10 kΩm) (Scapozza et al., 2011).

Since the resistivities of the permafrost range from 25 to 175 kΩm it is possible to conclude that the ice content is low to medium (Kääb & Kneisel, 2006). Most of these resistivity values are below 100 kΩm denoting the presence of sediments cemented by interstitial ice (Leopold et al., 2011). The decreasing of resistivity values downslope suggests that the permafrost is not in equilibrium with the present climate. Thus, the frozen materials originate probably from former cold periods as the results of groundwater freezing as well as burial of snowdrifts.

### 4.2. The frost-crack polygons

These periglacial landforms have a notable environmental and paleoclimatic significance since their morphology and substrate structure reveal the role of frost related processes in their formation.

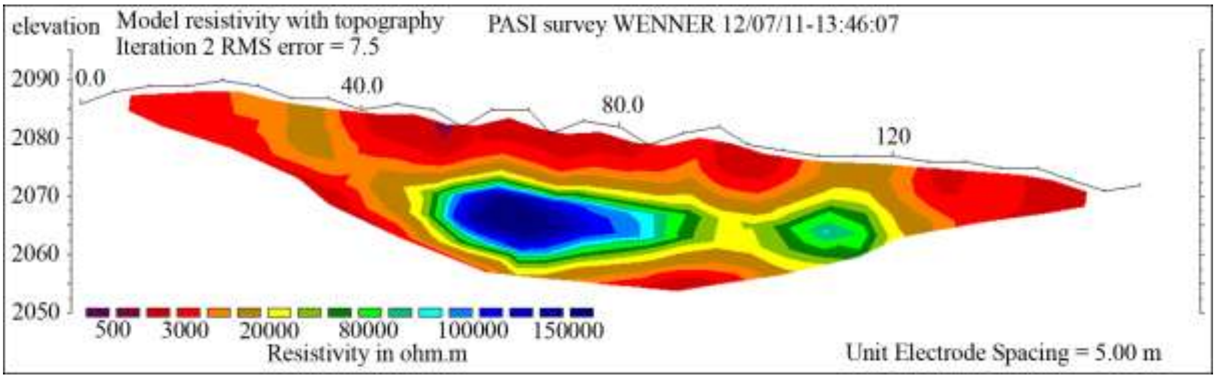

Figure 2. Transversal ERT profile on Roșiile rock glacier.

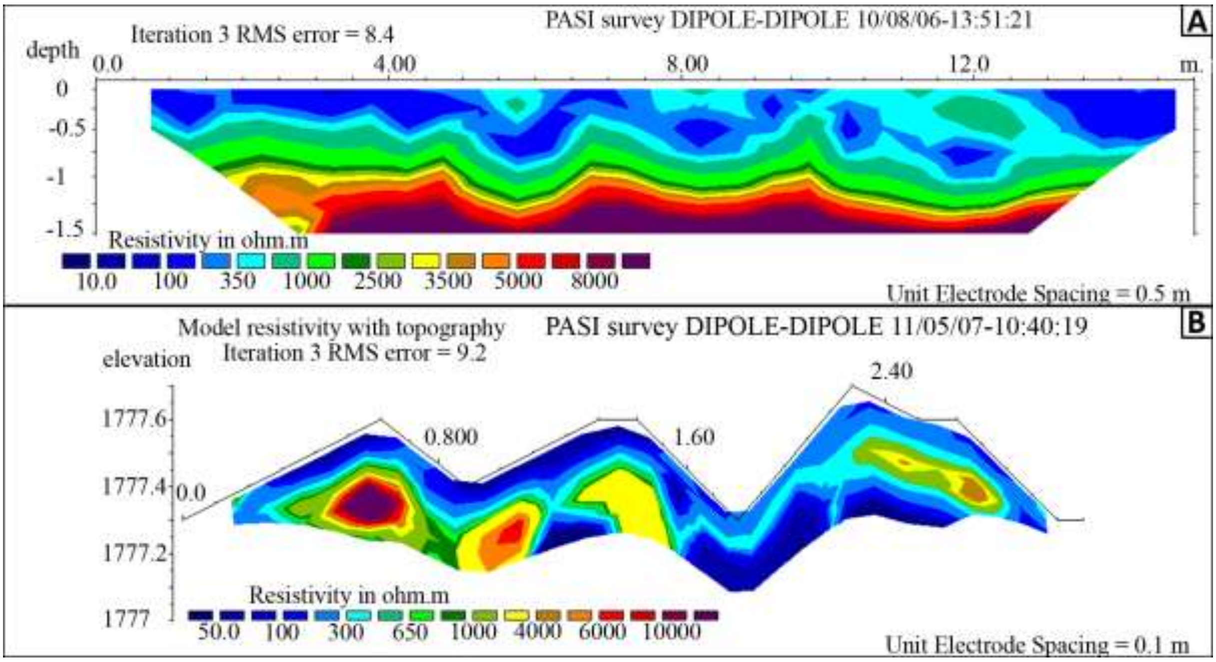

Figure 3. ERT profile across two different types of patterned ground: A Frost crack polygons on Căleanu peak; B earth hummocks on Muntele Mic massif.

Results of two ERT measurements across patterned ground with frost-crack polygons and earth hummocks are displayed in figure 3A. Since a significant heterogeneity was expected to be found in the subsurface of the investigated patterned ground, the Dipole-Dipole array was applied at both survey sites. In the first case, a 16 meters long profile was laid out with electrode spacing of 0.5 m. The profile was made across three polygons at 2181 m on Căleanu summit plateau, showing resistivity values ranging from 0.1 to 12 kΩm. The general aspect of the subsurface resistivity image displays sharply the individualization of the sorted polygons by frost cracks. These frost splits were filled by large blocks and slabs produced by congelifractation. The specific resistivities can be grouped into three layers. The upper heterogeneous layer corresponds mainly to a region with fine materials and resistivity values below 1 kΩm. The uppermost layer contains also small and medium sized angular boulders and has 0.6 m depth. The cobbles prevail mainly between 5-6 m, 8-9 and 10-12 m along the line in the top layer. Below this layer, the resistivities increase to 1-5 kΩm because coarser-grained fragments occur here. Decimetric sized boulders and a pebble matrix are expected to be found between 0.6 and 1.2 m just above the bedrock. The resistivity values corresponding to the bedrock (>6 kΩm) is to be found below 1.2 m.

The near-surface materials representing a chaotic structural pattern of unconsolidated fine and medium grained materials with different moisture contents indicate that the materials appear to be strongly disturbed by frost heaving (French, 1996). In fact, the undulating aspect of the upper part of the tomography suggests the existence of disturbed unconsolidated deposits, caused by persistent freeze-thaw cycles, specific for the active layer of permafrost. On the other hand, three visible „cvasicircular bodies” suggests the genesis of these sorted patterned ground according to buoyancy-driven convection cells theory (Krantz, 1990).

### 4.3. The earth hummocks site

Investigations at Muntele Mic site include monitoring of freezing regime in the substrate using ERT. In order to capture the near-surface ice structures the profile was laid out with a spacing of 10 cm between the electrodes, resulting in a profile length of 3,2 m. Due to a reduced distance total spread the penetration depth was superficial (0.4 m). Figure 3B shows the survey profile across three earth hummocks at the beginning of May, at two weeks after snow melting.

From the range of resistivity values, it can be assumed that the top layer consists of unfrozen fine grained soils (clay and silt size particles), angular clasts and porous organic structures (Schunke & Zoltai, 1988). Below 15 cm four small patches of high resistivity values (>1000 Ωm) are visible. The asymmetric bodies of high resistivities represent the frozen core of the earth hummocks at the end of the cold season. Excepting the frozen area between 0.3 and 0.8 m along the line the other ellipsoidal bodies contain a lower content of ice and a higher content of unfrozen materials. However, the depth of the frozen bodies is extremely shallow (maximum 30 cm). In the case of the middle mound, it can be seen that the initial frozen core was split in two smaller frozen bodies, indicating a fast melting of the ice. The large trench between the second and the third mound (where the snow layer was thicker and more persistent) show small resistivity values (below 100 Ωm) because of the high content of moisture.

The measurement highlights the effects of the frost in earth hummocks at the end of the cold season as far as the configuration and the dimensions of the frozen core.

### 4.4. Solifluction lobe and terraces from Făgăraș Mountains

The solifluction landforms are widespread in the landscape of the alpine domain of the Southern Carpathians. Figure 4 displays two upslope-downslope profiles, 32 m length each, across few solifluction terraces (Fig. 4A) below Laița Peak and a solifluction lobe (Fig. 4B) on the southern side of Paltina Peak. In the first case, the tomogram (Fig. 4A) reveals a heterogeneous 1 m thickness layer at the surface. The shallow top layer shows a range of resistivity values from 0.2 kΩm to 5 kΩm due to high differences in the size of the existing materials. Most of the terraces are upholstered with frost-sorted centimetric to decimetric size clasts, and in this case the resistivity values are slightly higher (3-5 kΩm). On the upper part of the terraces where the resisitivities are lower, finer sediments (clay and sand size particles) as far as isolated small angular clasts could be found. According to the resistivities the fine grained matrix described above is rather dry, excepting the materials between 26 and 30 m along the profile line where a higher content of moisture is suspected to occur. Further down in the subsurface the ERT image indicate resistivity values for the bedrock (> 6 kΩm).

The subsurface lithology revealed by ERT profile (Fig. 4A) and the arrangement of the clasts on the terraces floor confirm that frost heaving plays a decisive role in the present dynamic of the slope despite the lack of frozen materials during the summer (Ballantyne & Harris, 1994).

The ERT profile in figure 4B was performed on a south-exposed slope of Paltina Peak where well developed solifluction lobes occur (Urdea et al., 2008a). The resistivity values obtained for the upper heterogeneous layer are lower than in the previous case due to prevalence of finer sediments. The top layer appears to be thicker and not as heterogeneous, probably because the fine grained matrix contains less coarser fragments. Therefore, low resistivity values (below 2 kΩm) specific for unfrozen fine grained sediments are to be found at the surface, on 1,5 m depth. At the foot of the slope between 23 and 30 m along the line, this fine grained layer seems to be thicker indicating the accumulation of the solifluction deposits where the slope angle is decreasing.

The results of these two surveys lead to the interpretation that the morphodynamics is not related with the presence of permafrost. In both cases, the chaotic structural pattern of the materials in the upper layer supports the idea that seasonal frost (involving frost heaving, frost sorting and creep) is responsible for the actual gelifluction and formation of solifluction terraces and lobes (French, 1996). On the other hand, the downslope movement of the superficial deposits is strongly conditioned by the moisture content within the soil and the high pore pressure generated during spring thaw consolidation of ice-rich frozen soil (Harris, 2007).

### 4.5. Văiuga scree slope

Scree slope deposits are very common elements in the landscape dominated by glacial cirques and valleys, associated with their steep rock walls. Their importance derives from the fact that they are a key proxy for the understanding of the impact of external and internal control parameters on rockfall deposition (Krautblatter & Moser, 2009).

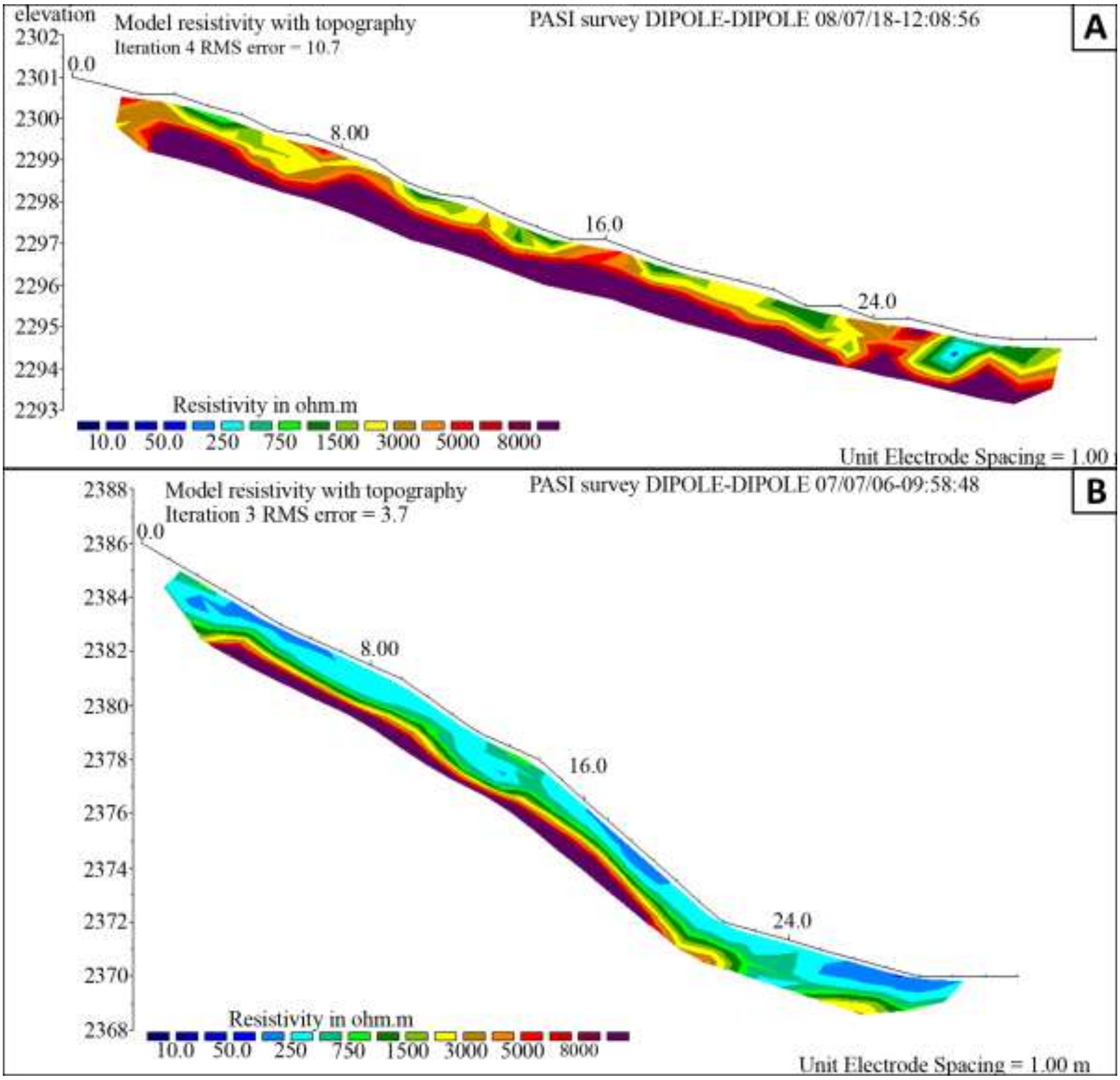

Figure 4. ERT profile across two different types of solifluction landforms: A Solifluction terraces below Laița peak; B solifluction lobe below Paltina peak.

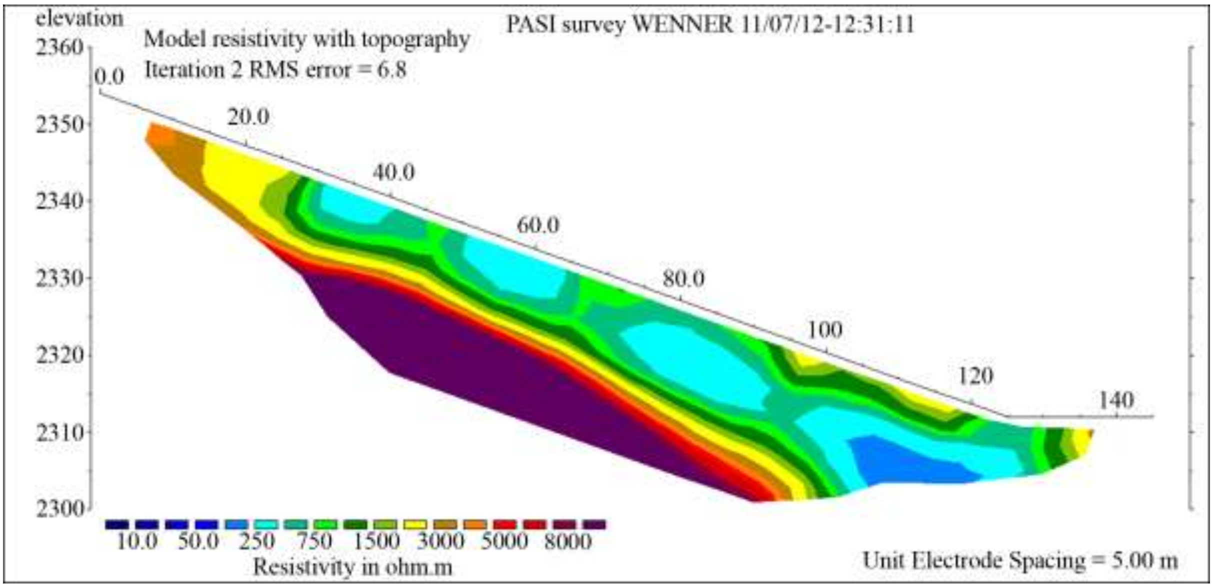

Figure 5. Longitudinal ERT profile on Văiuga scree slopes.

Results of an ERT measurement along a scree slope are displayed in figure 5 and reveal resistivity values of 0.2 to 3 kΩm in the near-surface part and above 5 kΩm in the lower part. The thickness of the upper layer containing unconsolidated fine and medium grained sized sediments increases downslope considerably (Otto & Sass 2006). In the upslope sector, the periglacial deposits have less than 1 m depth and in the lower part of the slope more than 10 m. Here, between 95 and 120 m and 130 and 140 m on horizontal distance slightly higher resistivity values occur near-surface. The angular fragments are coarser in this area and therefore the openenwork structure provides a poor electrical contact and thus higher resistivities. Smaller resistivity values corresponding to unfrozen fine-grained sediments occur below this layer suggesting that the scree slope is probably stratified, especially in the lower part. Actually, the presence of the stratified slope deposits in this area has been reported in an earlier study (Urdea, 1995).

Due to a variable content of moisture in the substrate, it is difficult to separate between different sizes of unconsolidated sediments. However, compared to the other ERT profiles the moisture content is considerably higher (especially in the lower part of the slope) because the surface becomes snow-free only recently. Despite the northern exposure of the slope, the high altitude and the greater porosity of the sediments, the permafrost is entirely missing.

## 5. CONCLUSIONS AND PERSPECTIVES

The results of the geophysical surveys performed in six periglacial sites in Southern Carpathians led to four main conclusions:

A. From a methodological point of view it is possible to conclude that DC resistivity tomography is a valuable method for the investigation of periglacial landforms. Undoubtedly it represents the best geophysical solution for mapping permafrost and to delineate layers of unconsolidated sediments with different physical characteristics. In order to validate the DC resistivity tomography data, it is recommended to be used together with GPR or refraction seismic measurements since these methods can provide complementary information on the substrate lithology. In the future, this method should be used for monitoring the freezing and thawing beahavior by evaluating the seasonal changes respectively short-term variations of the resistivity values.

B. The application of 2D resistivity imaging reveals the presence of permafrost in Roșiile rock glacier. The obtained resistivity values (25 - 170 kΩm) indicated ice-cemented and supersaturated permafrost (above 100 kΩm) originating from buried snow banks and groundwater freezing. The permafrost body is underlain by a thick active layer (10 m) suggesting that the rock glacier is probably inactive. According to similar studies performed in Southern Carpathians (Kern et al., 2004, Vespremeanu-Stroe et al., 2012) it is possible to highlight that the permafrost from Parâng Mountains is not in equilibrium with the present climate. Therefore the frozen layer is reducing because of melting. The ice lenses appeared probably in a former cold period (Little Ice Age), but nowadays exist in marginal conditions considering the actual mean annual temperature, the active layer thickness and the low ice content. The preservation of sporadic permafrost is determined by local site characteristics (altitude, slope, exposure, MAAT, incoming solar radiation, snow cover distribution and duration, substrate grain size). Since the permafrost from Southern Carpathians exists in marginal conditions, it is extremely sensitive to environmental changes; therefore its dynamic is of considerable importance.

C. The analysis of the internal structure of the investigated periglacial landforms, excepting Roșiile rock glacier, reveals that the permafrost stratigraphy is missing. Thus, the chaotic structural pattern characteristic for the near-surface layer is obviously the result of nowadays seasonal frozen. A good example in this respect was offered by the stratigraphy model displayed by the ERT performed in Muntele Mic site. Here, the insulating effect of the vegetation, the great content of moisture within the earth hummocks and the considerable porosity of the top layer allow the preservation of a frozen core within the mounds for more than 30 days after the snow is melting. The resistivity images of the investigated solifluction landforms highlighted the assumption that the instability of the alpine zone slopes does not require the presence of actual permafrost. The gelifluction occurs anywhere the percolation regime of the water within the soil is limited and the melting of the segregation ice ensures an excess of water within the soil. The stratigraphic model of the internal structure of Văiuga scree slope displays the presence of stratified deposits along the slope suggesting an alternation of different geomorphologic processes during the Holocene.

D. ERT method allows identifying the internal structure of the analyzed periglacial landforms, each with its specific design, caused by freeze regime and its connected processes (creep, frost heaving, frost sorting and solifluction). The weathering mantle, the soils and the active layer, in case of permafrost occurrence, are affected by frost in a different manner as it was shown in this study.

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