FINAL SCIENTIFIC REPORT – PROJECT PN-III-P1-1.1-PD-2016-0172,

Exploring permafrost occurrence and evolution in the Rila and Pirin Mountains (Bulgaria) using a combined geomorphological, geophysical and dendrochronological approach

(02.05.2018 – 30.09.2020)

Overview

This study aims to investigate permafrost occurrence in the highest mountains of Bulgaria. Rila and Pirin Mountains are the highest mountains in Bulgaria, reaching 2900 m in elevation. Rock glaciers are widespread in both mountain units above the tree line, indicating permafrost creeping during their activity. The presence/absence of permafrost associated with rock glaciers was not investigated so far. This research will use miniature thermistors to assess the near-surface thermal regime of the rock glaciers and geophysical investigations to examine the internal structure of glacial and periglacial landforms. We will also examine the movement of the rock glaciers using ground-based geodetic surveys, tree-ring analysis and photogrammetry. In the end we plan to get more insights into the paleoenvironmental significance of rock glaciers, considering the deglaciation timing of these mountains.

The project scientific activities were divided in three phases: **2018, 2019, and 2020**.

Phase 1_2018

In this phase five different activities were covered, as follows:

1. Selecting the test sites for observations and measurements;
2. Installing data-loggers to monitor the temperature of the rock glaciers near-surface;
3. Geophysical investigations and processing the geophysical data;
4. Measurements of the spring temperatures in the selected sites;
5. Ground based geodetic measurements for assessing rock glaciers dynamics;

1. Selecting the test sites for observations and measurements

- The morphology of the landforms and the possibility to host permafrost;
- The continuity of observations in sites where we already started to measure ground surface temperatures;
- Accesibility.

Before selecting the test sites, we analyzed existing satellite images, topographical and geological maps and we made several field campaigns for geomorphological observations, starting with 2016. For the geomorphological observations, geophysical measurements, ground surface temperature monitoring and measurements of the dynamics of rock glaciers we selected five sites (fig. 1).

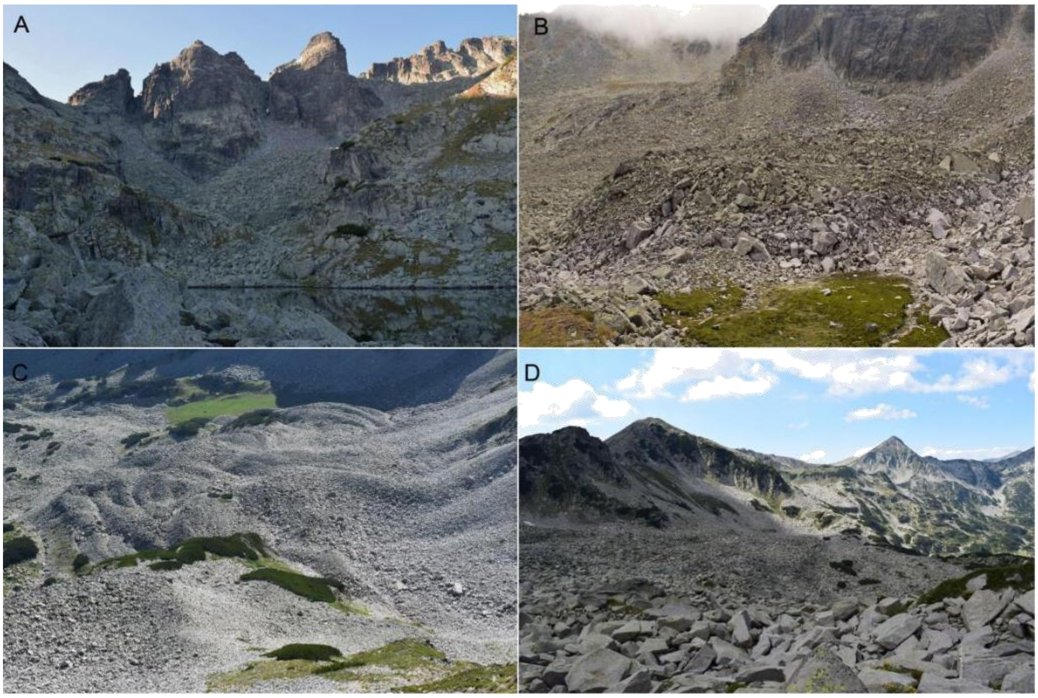

Fig. 1. Selected rock glaciers for observations and measurements within the test sites (A. Golyam Kupen; B. Musala; C. Polezhan; D. Banderishki Chukar).

Two test sites are located in the Rila Mountain and three in the Pirin Mountains. In these sites we started to monitor the ground surface temperature regime of 15 rock glaciers, the annual dynamics of 5 rock glaciers and to perform geophysical investigation on 10 rock glaciers. We will also generate high resolution digital elevation model for 10 rock glaciers. We are also interested to explore permafrost occurrence in the vicinity of the two small glaciers (Snezhnika and Banski Suhodol) and in several rock walls.

2. Installing data-loggers to monitor the temperature of the rock glaciers near-surface

We started in 2016 to monitor rock glaciers near-surface thermal regime and now we extended the measurements. In total we installed 100 thermistors within 15 rock glaciers and in other different periglacial landforms. We placed between 4 and 8 thermistors in each rock glacier and we also placed thermistors to measure air temperature, snow cover timing and temperature of the rockwalls.
To measure the near-surface temperature regime of rock glaciers we used miniature dataloggers (iButton Digital Thermometers DS 1922L). The thermistors were used to register the ground surface temperature every 2 hours. Readings were recorded with a resolution of 0.065^{o}C and less than ± 0.5^{o}C error. The thermistors are designed to measure temperatures between -40 and +85^{o}C. We placed the miniature dataloggers at 5-10 cm beneath the surface of the rock glaciers and we covered the thermistors with pebbles to avoid direct exposure to solar radiation.
In the field we used a portable computer to set the thermistors through a special reader and the 1-Wire Viewer software (fig. 2). The coordinates of the sites where we installed thermistors were saved by a GPS device.

Based on the `rule of thumb`, permafrost is probable where values lower than -3^{o}C occur in the late winter when the snow depth is thick enough to insulate the ground. Temperature values between -2^{o}C and -3^{o}C suggest the possible presence of permafrost, whereas values above -2^{o}C indicate the absence of permafrost (Hoelzle, 1992).

Fig. 2. Installing the dataloggers in the selected test sites.

3. Geophysical investigations

In alpine environments, geophysical measurements have been widely used to get information on permafrost distribution and characteristics. In Bulgaria this is the first time when electrical resistivity tomography (ERT) and ground penetrating radar (GPR) are conducted on periglacial/glacial landforms (fig. 3).

ERT is probably the most applicable geophysical method for permafrost detection, because of high resistivity contrast between frozen and unfrozen materials. The resistivity of permafrost may vary between 10 kΩm and 1000 kΩm depending on ice content, temperature and quantity of impurities (Kneisel and Hauck, 2008). The geoelectrical soundings were performed using a GeoTom MK8E 1000 resistivity meter in the vicinity of Banski Suhodol glacier. For the inversion of measured resistivities we used Res2DINV software.

Fig. 3. Geophysical measurements near Banski Suhodol glacier.

GPR measurements were used to map the internal structure of glaciers and rock glaciers in the selected sites. This technique is based on transmitting high frequency electromagnetic pulses into the ground and measuring the pulse signal travel time form the transmitter to the object that reflect the pulse and back to the receiver. The investigations were conducted using a Mala ProEx system and a 100 Mhz unshielded rough terrain antenna. By now we performed investigations on five rock glaciers and on two glaciers in the Pirin and Rila Mountains. For processing the data, we used Reflexw 6.0 software and we followed the protocol for the processing based on the existing literature (Degenhardt, 2009). The results revealed the thickness of the glaciers, the distribution of permafrost in different rock glaciers and near the glaciers and different types of structures in the substrate.

4. Measurements of the spring temperatures in the selected sites

The measurement of spring water temperature during August-September period is an easy and rapid way to get indirect information on permafrost probability in rock glaciers. Generally, if the temperature of the water is close to the freezing point (below 2ºC) the source of the water might be thawing permafrost (Warhafting and Cox, 1959). In the present study we measured the temperatures of 6 springs in the Rila and Pirin Mountains seeping from the fronts of rock glaciers, using a digital thermometer with ± 0.1ºC accuracy (fig. 4).

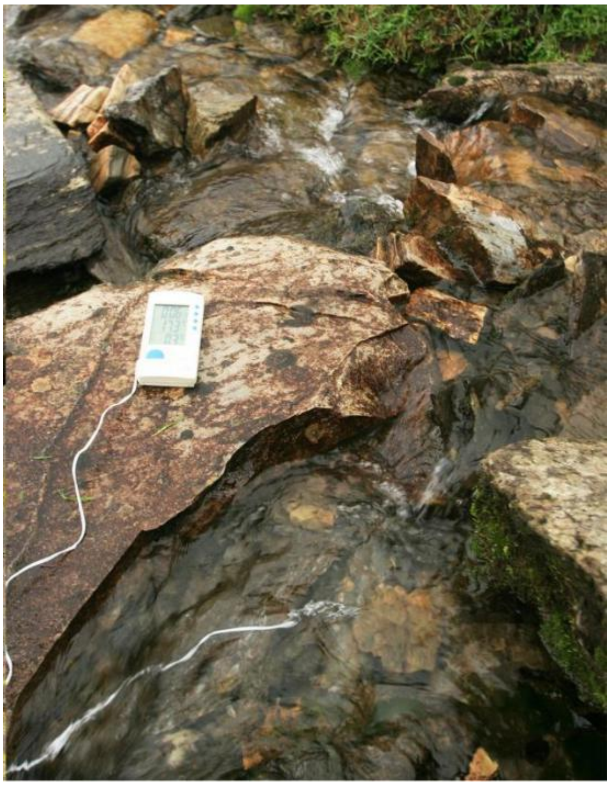

Fig. 4. Measurements of the spring temperatures using a digital thermometer.

The measured temperature values range from 1.7 to 6.7ºC, but only in two cases a temperature below 2ºC was recorded. In one case the temperature of the spring was measured at 150 m distance from the rock glacier front and is possible that the source of the water to be from the ground too. One spring revealed a low temperature (below 2ºC) in 2017 too confirming the probability of permafrost occurrence in that rock glacier. Ground based geodetic measurements for assessing rock glaciers dynamics. We initiated measurements of movement on five rock glaciers in the Rila and Pirin Mountains using a high-precision differential GPS TopCon Hiper V (fig. 5). The accuracy of the measurements is below 2 centimeters for each point we measured. We set up the base antenna in a stable location and we used a rover to receive corrections via radio from the base antenna and to record coordinates for different points within the investigated rock glaciers. We collected between 10 and 28 points on each rock glacier and we marked these points in the field.

Fig. 5. Ground based geodetic measurements using a differential GPS.

One of the main objectives of this project was to realize a database with all the thermal data concerning rock glaciers collected in Rila and Pirin Mountains during the current project and before. We established such a database where encountering three different types of thermal measurements:

a. Thermal regime monitoring at the near-surface of rock glaciers;
b. BTS measurements;
c. Spring temperatures measurements.

We standardized the recording of data and established the attributes for each measurement. We used ArcGIS to create layers with the location of each measurement point. For each point we stored an ID, geographic coordinates, elevation, type of landform, name of the mountain unit, geology and detailed description of the place where the measurements were taken. For the thermistors we also created an .xls file where we stored information on data and time of each measurement, temperature value, daily mean/minimum/maximum, measuring interval, winter equilibrium temperature, mean annual temperature, „zero curtain" interval, freezing and thawing indexes.

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Phase 2_2019

In this phase we continued the thermal (bottom temperature of the snow cover - BTS, ground surface temperature monitoring - GST and spring water termperature), geophysical and topographical measurements started in the previous year. In addition, we enriched the database containing temperature data and horizontal displacements of selected blocks within rock glaciers. A statistical approach was also applied to examine the linkages between thermal regime and local topo-climatic factors. Tree-ring analysis of Pinus Mugo installed on two different rock glaciers was also performed within this phase.

In this phase we have planned nine different activities, as follows:

1. BTS measurements and spatial analysis of achieved values.
2. Geophysical measurements and processing geophysical data.
3. Processing all the thermal data achieved.
4. Calculating specific thermal indices (mean annual grouns surface temperature – MAGST; winter equilibrium temperature – WeqT, GST evolution, freezing and thaving indices and `zero curtain` period).
5. Assessing the cooling effect of the coarse deposits (e.g., thermal convection, chimney effect, low thermal conductivity).
6. Statistical analysis of the relationships between GST and local topo-climatic factors.
7. Assessing the dynamics of rock glaciers by ground-based topographic measurements.
8. Tree-ring analysis of Pinus Mugo growing on rock glaciers.
9. UAV photogrammetry and Structure from Motion for high resolution digital elevation model production and monitoring long term horizontal displacement of blocks.

1. BTS measurements and spatial analysis of achieved values

The BTS method is one of the most efficient for permafrost mapping and has been widely used in different alpine environments. Classical BTS measurements using two lightweight BTS probes equipped with digital thermometers were carried out at the end of 2018-2019 winter season. Two long probes (2.5 m in length) equipped with digital thermometers (0.1ºC precision) were used to measure the temperature at the bottom of the snow cover. According to „rules of thumb” values lower than -3°C indicate that permafrost occurrence is probable, values of -2 to -3°C suggest the possible presence of permafrost while values higher than -2°C indicate the absence of permafrost (Hoelzle et al., 1999).

We planned our BTS investigations on four different rock glaciers (M3 and M4 in Rila Mountains and P8 and P9 in Pirin Mountains). We made similar investigations at these sites in the previous two years. The BTS points were collected in March 2019, when the ground was covered by a thick snow cover (fig. 1)

Fig. 1. BTS investigations in March 2019.

In total we collected 83 BTS points (table 1).

Tabelul 1. Characteristics of BTS values measured in March 2019.

Site code	No. of measurements	Mean BTS (°C)	Minimum BTS (°C)	Maximum BTS (°C)	Mean thickness of snow (cm)
M4	31	-3.4	-5.4	-1.5	142
M3	21	-2	-5.5	0.3	128
P9	21	-4.1	-5.7	-1.9	172
P8	10	-2.5	-3.6	-2.4	162

At site M4 we measured 31 points, from which 28 were made within the outline of the rock glacier, two on a protalus rampart and one outside the rock glacier (fig. 2). Only one BTS value indicated the absence of permafrost, whereas 10 BTS values suggested the possible presence of permafrost and 19 the probable occurrence of permafrost at this site. The mean BTS value for this rock glacier was -3.4°C and it was lower than the corresponding value measured in the previous two years (Onaca et al., 2020).

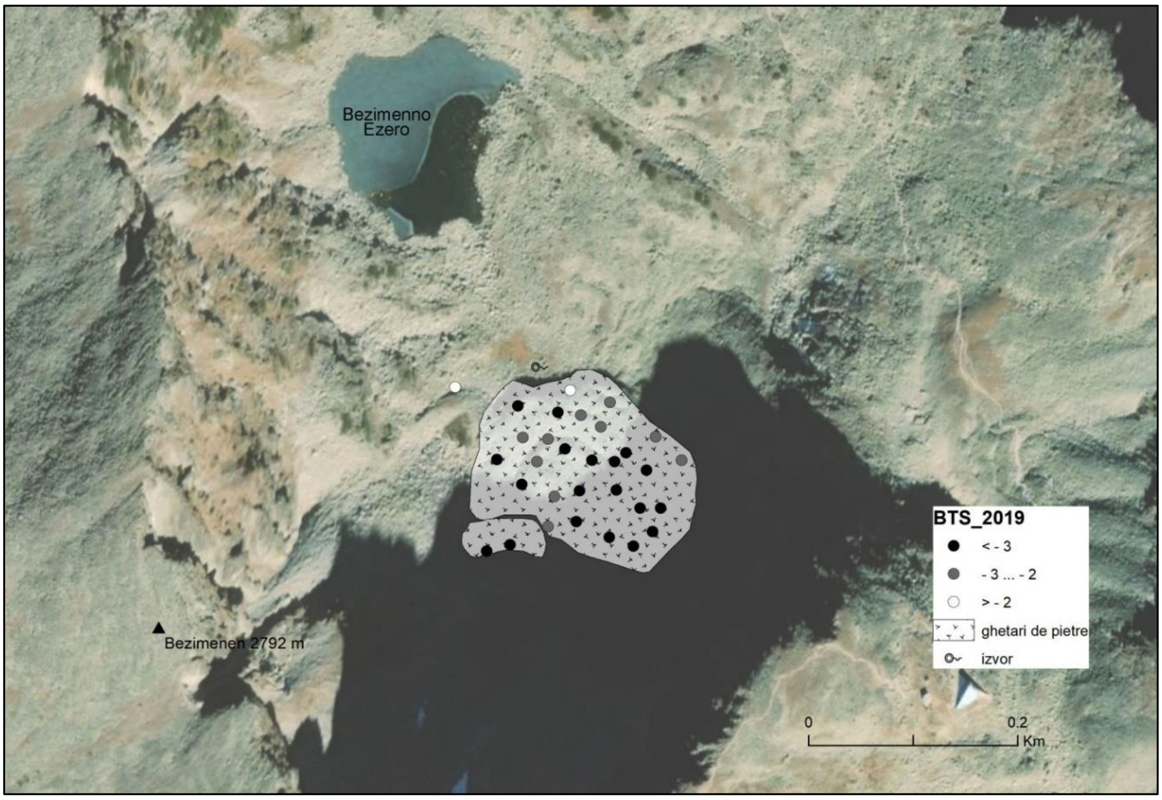

Fig. 2. BTS value measured on M4 rock glacier.

In case of M3 rock glacier, only five BTS values indicated the probable presence of permafrost, but three of these were located on a debris cone feeding the rock glacier. Within the rock glacier outline, four BTS values indicated the absence of permafrost, four suggested the possible presence and two the likely occurrence. The mean BTS value for this rock glacier was -2.2°C, with 1,2°C lower than in March 2018 (Onaca et al., in press).

In the Pirin Mountains, from 31 BTS points, two were measured outside the rock glaciers outlines for comparisons. Both values were greater than -2°C, confirming the absence of permafrost at those locations.

In case of P9, 18 BTS values were lower than -3°C confirming that like in previous years the permafrost is probable to occur at this site. Only two values were between -2°C and -3°C suggesting the possible presence of permafrost, whereas near the front of the rock glacier one BTS point has a -1.9°C value. At P8 site only at three locations the BTS point indicated the probable presence of permafrost, whereas in five locations the permafrost is possible. The lowest BTS value recorded was on the P9 rock glacier (-5.7°C). At this site was also calculated the lowest mean BTS (-4.1°C), with 0.6°C lower than in the 2016-2017 cold season (Onaca et al., 2020).

The thickness of snow cover was above 100 cm at all the locations where we made BTS measurements. In the Pirin Mountains the snow cover thickness was greater than in Rila Mountains. In M4 site the snow cover had a similar thickness with the one measured in 2017, but greater than in 2018. In the Pirin Mountains the snow cover was greater than in 2017, but thinner than in 2018. At M3 we observed also several funnels in the snow.

2. Geophysical measurements and processing geophysical data (second part)

In this phase we have continued to investigate the internal structure of rock glaciers using geophysical methods. Two different campaigns were organized, one during the time of BTS measurements (March) and one in September (fig. 3). We used a MALA ProEx GPR equiped with unshielded *Rough Terrain* antensas of 50 and100 Mhz. This method is suitable to investigate low electrical conductivity materials (e.g. ice, sand, bedrock etc.).

Fig. 3. GPR investigations performed in September (a) and March (b) 2019.

As Common Midpoint (CMP) or Wide Angle Reflection and Refraction (WARR) measurements are impossible using RTA antennas an overall wave velocity of 0.15 m/ns was used for the depth conversion of the radar signal (Onaca et al., 2015). GPR data processing and interpretation was performed using Reflexw 4.5, applying a sequence exemplified in similar studies (Ardelean et al., 2017). Background noise was eliminated by applying a *running average* filter, whereas for signal saturation a *dewow* filter was used. In order to compensate for the attenuation factor of radar signal with depth *energy decay* filter was applied. The last stages of processing included the application of *zero time corrections*, *background removal* and *bandpassfrequency*, as well as *topographic correction* to render the local topography of the investigated rock glaciers

We performed 26 GPR profiles with lengths between 70 and 330 m. The maximum depth of penetration was between 16 and 34 m. We identified three types of situations, regarding the occurrence of permafrost:

- The presence of permafrost was identified on the entire length of the profile or at least on a considerable part of the radargram. This situation was identified in case of M4, P9, B14 and K2 rock glaciers. In these cases, we were able to identify four types of reflections, which were interpreted as (1) the base of the snow cover; (2) the base of the active layer; (3) the floor of the rock glaciers; (4) stacked reflections. Our findings showed that the active layer was very thick (between 4 and 12 meters). Within this layer there are many reflections, suggesting the presence of a coarse layer with voids and/or seasonal ice lenses (Otto et al., 2012). Below the active layer we identified another layer characterized by high amplitudes of the electromagnetic waves and 7 to 14 meters thick which was interpreted as permanently frozen (Angelopoulos et al., 2013). The bedrock was intercepted between 15 and 33 m.
- The presence of permafrost is patchy along the profile line and it seems that permanently frozen ground occurs only in specific areas, such as: G1, P10, P7, P8, P10, B11, B12, B15. In these cases, the thickness of the active layer is great as well (between 6 and 13 m). The main characteristic of

this typology is that permafrost occurs only on small areas. The thickness of most of these rock glaciers is around 15 m.

- The presence of permafrost was not detected. It is the case of K1, M3, G2, P5, P6 and B13 rock glaciers. In these situations, we were unable to identify any sharp reflection characterized by high velocities of the electromangnetic waves, specific for permafrost. The mean thickness of these rock glaciers is between 13 and 22 m.

3. Processing all the thermal data achieved

Within this project we performed three types of thermal measurements: i) BTS measurements at the end of the cold season; ii) continuous GST monitoring and iii) spring water temperature at the end of warm season.

In case of BTS values the processing consisted in calculating the mean/minimum/maximum values of BTS for each rock glacier, the mean thickness of snow as wel as the number of points indicating probable/possible or improbable occurrence of permafrost. All these calculations were done in Microsoft Excel and after that transferred in ArcGIS where the maps with the distribution of BTS values were realized.

For the monitoring of the GST we used iButtons DS1922L thermistors installed in 2018 and 2016. In September 2019 we downloaded all the recorded data in a portable computer. Initially the data were in .txt format, but we changed it to .xls. The processing process consisted in the evaluation of all the values and making necessary corrections (e.g., deleting the values recorded before setting the thermistors in the field; adjusting the values using the `zero curtain` interval values). After all these corrections we calculated several specific indices (ex: mean annual ground surface temperature – MAGST; winter equilibrium temperature – WeqT, freezing and thawing indices and the date of snow dissapearence).

In September 2019 we also measured the temperature of several springs seeping from the base of the rock glaciers using a handheld thermometer with ± 0.5°C accuracy. For each measurement location we recorded information about the geographical coordinates, measurement date, site code and air temperature. The values recorded in September 2019 were: K1 – 2,2°C; K2 – 3,2°C; P6 – 6,3°C; B12 – 6,5°C; B14 – 0,9°C; B15 – 2,4°C.

4. Calculating specific thermal indices (mean annual grouns surface temperature – MAGST; winter equilibrium temperature – WeqT, GST evolution, freezing and thaving indices and `zero curtain` period)

Table 2 reveals the results of the thermal indices extracted from the GST values recorded at K1 and K2 site. Permafrost is probable to occur at all the location in K2, but only in one location in K1 is possible. The MAGST values are very low in all the cases, whereas the mean freezing index is considerably lower at K2 compared with K1. At K1.1 the snow disappeared completely in 13 August, resulting in a prolonged zero curtain interval. At all the sites in K2 the MAGST values are negative and the freezing index is below -800°C days. In site B we monitored GST values of two rock glaciers, one talus cone, one protalus rampart and two rock walls. Excepting the rock walls, in most of the sites the MAGST was negative. WeqT ssuggested probable permafrost conditions in M4, whereas in M3 only one location showed possible permafrost conditions. Permafrost presence in the investigated rock walls is unlikely, but is probable to occur in the talus cone and protalus rampart.

Table 2. Thermal indices at site A.

Code site	Code location	Morphology	MAGST	WeqT	GFi	GTi	0 curtain
A	**K1.1**	GP	0.0	0	-192.63	189.38	161
	K1.2	GP	0.7	-0.8	-324.71	782.19	76
	K1.3	GP	0.5	-1.7	-363.80	742.19	64
	K1.4	GP	0.2	-2.1	-474.53	686.16	58
	K2.1	GP	-0.3	-3.6	-864.56	730.36	23
	K2.2	GP	-0.8	-4	-1004.68	713	33
	K2.3	GP	-0.6	-3.7	-894.32	694.14	36
	K2.4	GP	-0.2	-3.2	-821.45	786.25	44

GP – rock glacier.

Table 3. Thermal indices at site B.

Code site	Code location	Morphology	MAGST	WeqT	GFi	GTi	0 curtain
B	**M3.1**	GP	-1.36	-	-1047.30	550.47	47
	M3.2	GP	-0.37	-	-682.15	546.82	50
	M3.3	GP	-0.12	-2.12	-632.81	568.45	39
	M3.4	GP	0.41	-1.45	-581.93	670.13	42
	M4.1	GP	-2.19	-4.97	-1102.43	302.34	55
	M4.2	GP	-1.85	-4.06	-793.88	117.97	68
	M4.3	GP	-1.12	-3.21	-577.98	169.77	86
	M4.4	GP	-0.54	-3.68	-761.10	570.3	36
	M4.5	GP	-1.41	-4.13	-779.03	265.19	48
	M4.6	GP	-0.73	-3.86	-812.07	584.25	37
	M4.7	GP	-0.47	-3.25	-694.11	543.14	43
	M4.8	GP	-1.64	-3.53	-674.16	490.15	67
	M4.9	CG	0.18	-3.69	-786.11	852.51	25
	M4.10	PR	-1.83	-5.43	-1126.31	459.86	36
	M4.11	P	1.00	-	-785.32	1151.99	-
	M4.12	P	2.28	-	-816.48	1647.72	-

GP – rock glacier; PR – protalus rampart; CG – talus cone; P – rock wall.

The thermal measurements performed in site C are highlighted in table 4. Accoring to measurements permafrost is possible at G1.1 and G1.2 locations.

Table 4. Thermal indices at site C.

Code site	Code location	Morphology	MAGST	WeqT	GFi	GTi	0 curtain
C	**G1.1**	M	0.13	-2.30	-438.76	487.77	66
	G1.2	VG	-0.91	-2.27	-347.79	15.87	87
	G1.3	VG	0.42	-0.57	-491.23	502.58	72
	G1.4	VG	0.35	-1.54	-407.53	554.31	70
	G2.1	M	2.23	-0.24	-392.41	709.34	54
	G2.2	VG	-0.03	-0.34	-48.56	34.29	107
	G2.3	CG	0.56	-1.47	-457.35	603.25	63
	G2.4	PR	0.21	-1.89	-537.23	485.32	71

M – moraine; PR – protalus rampart; CG – talus cone; VG – scree slope.

In site D we analysed six rock glaciers, one talus cone, one protalus rampart, two rock walls, one block stream and one soliflcution lobe. In addition, one thermistor measured air temperature variation (table 5). Accroding to the WeqT values permafrost is probable in P9 and P10 and may occur only in some locations in P5, P6, P7 and P8. During field work in September we noticed that snow was still present in some shaded places. MAGST values are also, very low, indicating that the thermal conditions are favorable for permafrost maintanence. Permafrost is unlikely to occur in rock walls, block stream or solifluction lobe, but is possible to occur in talus cone and protalus rampart.

Table 5. Thermal indices at site D.

Code site	Code location	Morphology	MAGST	WeqT	GFi	GTi	0 curtain
D	**P5.1**	GP	-0.42	-3.31	-737.07	583.1	79
	P5.2	GP	1.53	-1.74	-319.22	680.24	58
	P5.3	GP	0.91	-0.72	-359.14	753.12	52
	P5.4	GP	1.22	-2.02	-672.14	613.13	65
	P5.5	RP	3.11	-0.33	-98.03	1234.57	44
	P6.1	GP	0.83	-2.20	-463.13	765.58	53
	P6.2	GP	1.39	-1.36	-268.26	775.87	46
	P6.3	GP	1.14	-1.79	-398.12	691.32	57
	P6.4	GP	1.65	-1.12	-366.34	748.52	48
	P7.1	GP	1.87	-3.19	-533.11	1216.54	31
	P7.2	GP	1.08	-2.04	-475.26	870.95	41
	P7.3	GP	1.53	-1.97	-434.75	983.21	35
	P7.4	GP	2.08	-0.94	-254.14	1121.24	42
	P7.5	GP	1.91	-1.35	-309.13	863.15	46
	P7.6	GP	2.32	-0.83	-254.44	1015.24	48
	P7.7	CG	1.20	-2.38	-501.44	939.37	52
	P7.8	P	2.69	-	-579.96	1562.05	-
	P7.9	LS	2.58	-	-325.29	1267.29	26
	P8.1	GP	-0.20	-2.29	-455.93	382.17	56
	P8.2	GP	1.13	-1.63	-331.34	744.20	48
	P8.3	GP	0.85	-3.56	-504.02	815.13	58
	P8.4	GP	0.52	-2.74	-494.27	775.37	43
	P8.5	GP	0.02	-3.16	-524.11	694.20	55
	P8.6	GP	0.94	-2.23	-473.28	682.19	44
	P8.7	GP	1.32	-1.84	-486.21	734.76	47
	P8.8	GP	1.09	-1.74	-394.35	805.54	42
	P8.9	PR	0.82	-2.91	-471.51	771.11	50
	P9.1	GP	0.39	-3.63	-650.66	792.05	35
	P9.2	GP	0.15	-2.40	-460.36	519.94	54
	P9.3	GP	-1.06	-3.50	-609.75	221.96	73
	P9.4	GP	-1.18	-3.62	-564.40	132.28	100
	P9.5	GP	-0.54	-3.32	-522.38	323.88	58
	P9.6	GP	-0.42	-3.15	-603.17	448.61	67
	P9.7	GP	-1.24	-3.65	-709.23	257.89	93
	P9.8	GP	-1.11	-3.57	-680.06	274.25	76
	P10.1	GP	0.35	-3.51	-614.45	741.90	47
	P10.2	GP	0.36	-3.11	-576.91	707.36	55
	P10.3	GP	0.43	-2.97	-583.13	712.34	49
	P10.4	GP	0.52	-2.68	-577.43	744.30	46
	P10.5	P	1.52	-	-798.66	1353.2	-
	P10.6	A	-0.75		-1207.48	931.11	-

GP – gheţar de pietre; PR – protalus rampart; CG – con de grohotiș; P – perete; LS – lob de solifluxiune, RP – râu de pietre; A – aer.

In site E we analysed the GST of five rock glaciers (tabel 6). In B14 permafrost is probable at all the locations, the MAGST are negative and GFi values are also very high. Permafrost is also possible/probable in the other rock glaciers too.

Table 6. Thermal indices at site E.

Code site	Code location	Morphology	MAGST	WeqT	GFi	GTi	0 curtain
E	**B11.1**	GP	0.56	-2.23	-578.13	714.21	45
	B11.2	GP	0.82	-2.77	-537.44	721.09	48
	B11.3	GP	1.13	-	-471.21	809.41	41
	B11.4	GP	1.52	-1.43	-455.09	873.54	39
	B12.1	GP	0.37	-3.02	-682.74	817.69	53
	B12.2	GP	0.51	-2.96	-659.03	822.45	51
	B12.3	GP	0.63	-2.68	-612.77	851.23	53
	B12.4	GP	0.92	-2.28	-585.39	884.09	47
	B13.1	GP	0.53	-5.17	-869.78	1062.85	34
	B13.2	GP	0.91	-	-812.49	1124.51	31
	B13.3	GP	1.14	-2.52	-642.12	1037.81	41
	B13.4	GP	1.17	-2.30	-594.15	1147.15	37
	B14.1	GP	-1.85	-4.42	-889.95	213.81	74
	B14.2	GP	-1.52	-4.82	-983.88	430.59	36
	B14.3	GP	-0.81	-4.51	-737.71	440.81	60
	B14.4	GP	-1.52	-4.66	-1017.57	461.92	34
	B14.5	GP	-2.69	-6.79	-1273.43	289.93	67
	B14.6	GP	0.92	-4.83	-810.91	1145.03	33
	B14.7	GP	-0.47	-4.03	-814.33	509.22	59
	B14.8	GP	0.53	-3.87	-783.12	493.22	67
	B15.1	GP	-0.94	-4.87	-948.75	604.98	57
	B15.2	GP	-0.31	-3.95	-803.16	672.14	53
	B15.3	GP	0.76	-3.21	-709.12	804.22	45
	B15.4	GP	0.43	-2.87	-691.32	903.24	39
	B15.5	GP	-0.13	-4.51	-862.12	689.15	59
	B15.6	GP	0.91	-3.12	-781.21	813.41	46

GP – rock glacier;

Analyzing the thermal regime of GST during 2018-2019 season we identified four different types, according to the temperature characteristics during the winter.

a. GST evolution reveals below -3°C values in the `BTS window`. In autumn and early winter under thins snow cober the substrate is cooled intensively, as a result of air exchange with the atmosphere (fig. 4). After the onset of the insulating layer, the temperature values remain very low and constant. This type of regime is typical for sites with permafrost (Hoelzle et al., 1999). In our case this regime was observed in case of K2, M4, P7, P8, P9, P10, B12, B13, B14 and B15 rock glaciers.
b. GST values are between -2 and -3°C at the end of cold season below a thick insulating layer (fig. 5). This type of thermal regime is typical foar sites where the occurrence of permafrost is possible. In the se locations more investigations are required to elucidate if permafrost occur. In some of these locations in the previous seasons the values were below -3°C. This type of regime was observed at K1, M3, G1, P5, P6, P7, P8, P9, P10, B11, B12, B13 and B15 locations.

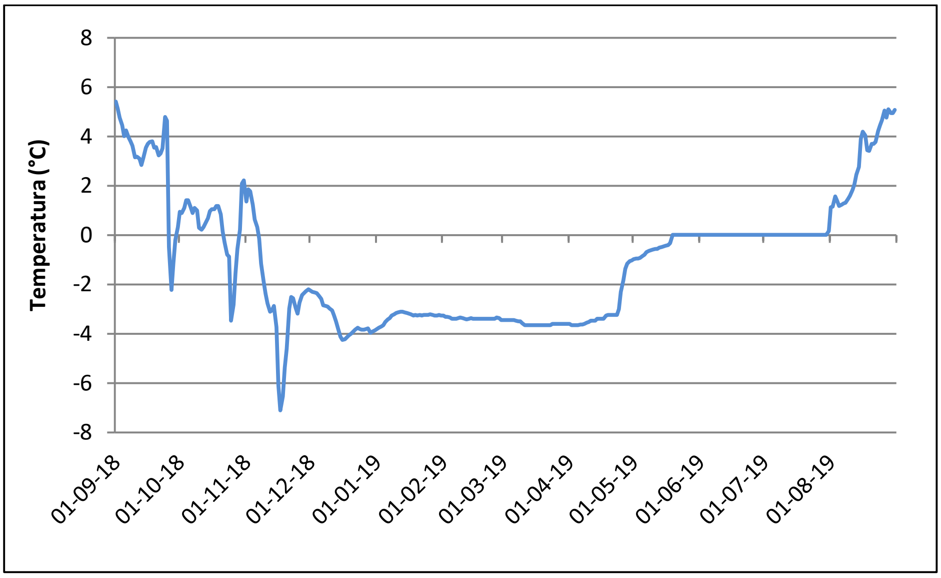

Fig. 4. Mean daily ground surface temperature at P9.3.

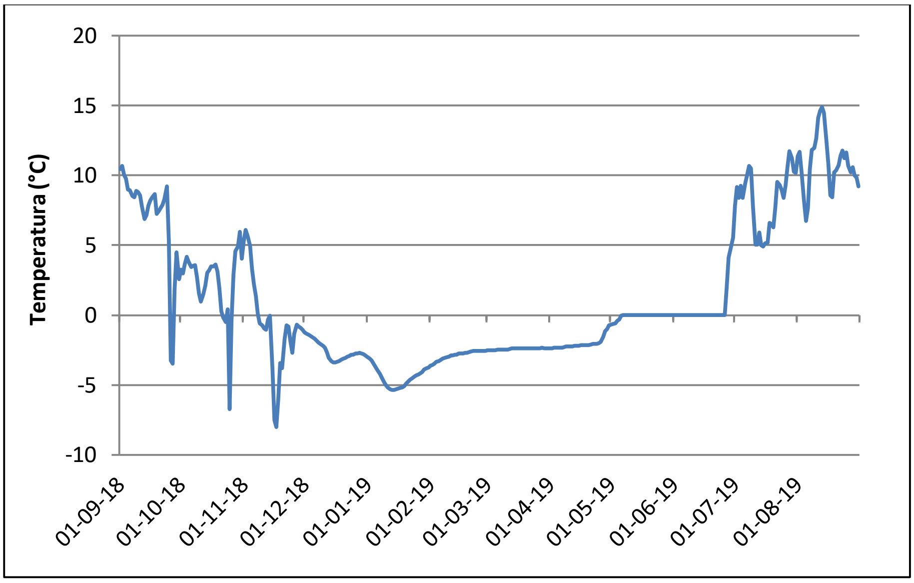

Fig. 5. Mean daily ground surface temperature at P9.2.

c. This regime is characterised by relatively high values of WeqT at the end of the winter (between 0 and -2°C). The temperature evolution is constant and does not show temperature fluctuations, indicating that permafrost in unlikely (fig. 6). This regime was observed at K1, M3, P5, P6, P7, P8 și B11, but also in G1 and G2.

d. The evolution of the temperature during the winter is characterized by significant temperature fluctuations. This regime coincides with the sites where during the winter the snow cover was either to thin, or there were funnels in the snow cover allowing air exchange with the atmosphere. At these sites permafrost occurrence should be investigated with other methods, too (Ishikawa, 2003). An example of this type of regime is illustrated in fig. 7. This type of regime is characteristics for M3, B11 and B13.

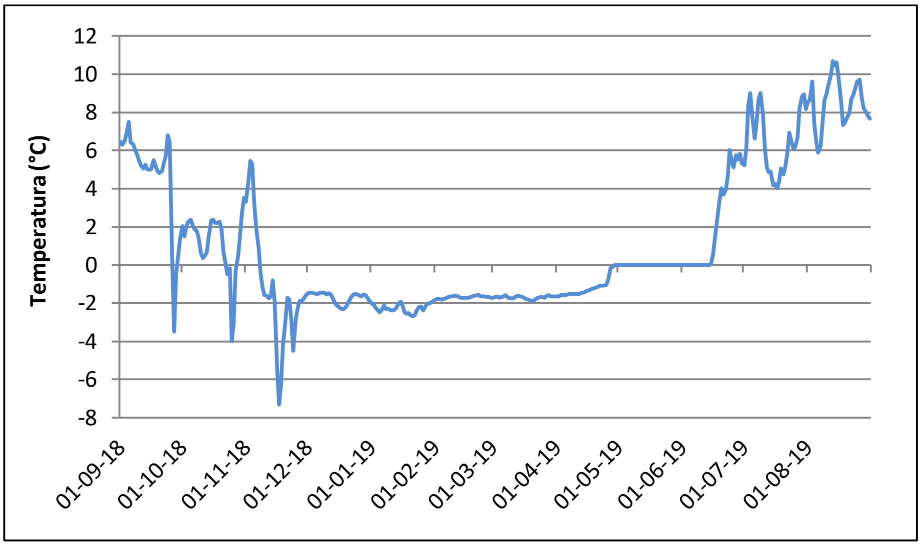

Fig. 6. Mean daily ground surface temperature at P8.2.

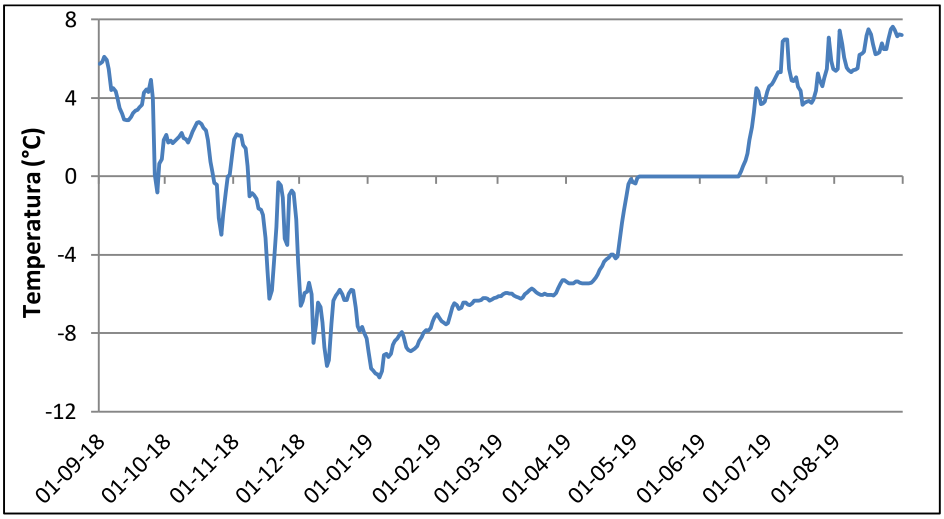

Fig. 7. Mean daily ground surface temperature at M3.1.

5. *Assessing the cooling effect of the coarse deposits (e.g., thermal convection, chimney effect, low thermal conductivity).*

Snow cover plays a decisive role on GST regime small-scale variability. After the onset of the insulating snow cover isothermal conditions characterize the surface of the ground. In several cases (G1.2 or G2.2) the ground was covered by snow for more than 350 days in the 2018-2019 season. At these sites the maximum temperatures recorded at the end of August 2019 was below 5°C.

Between October and December, until the onset of the insulating snow cover, the continuous air exchange with the atmosphere favored the cooling of the active layer. This mechanism was extremely efficient during cold episodes, when because of free convection cold air replace warm air within the coarse deposits. Now, the minimum values of temperatures are recorded at all the sites (between -5 and -15°C) (fig. 8).

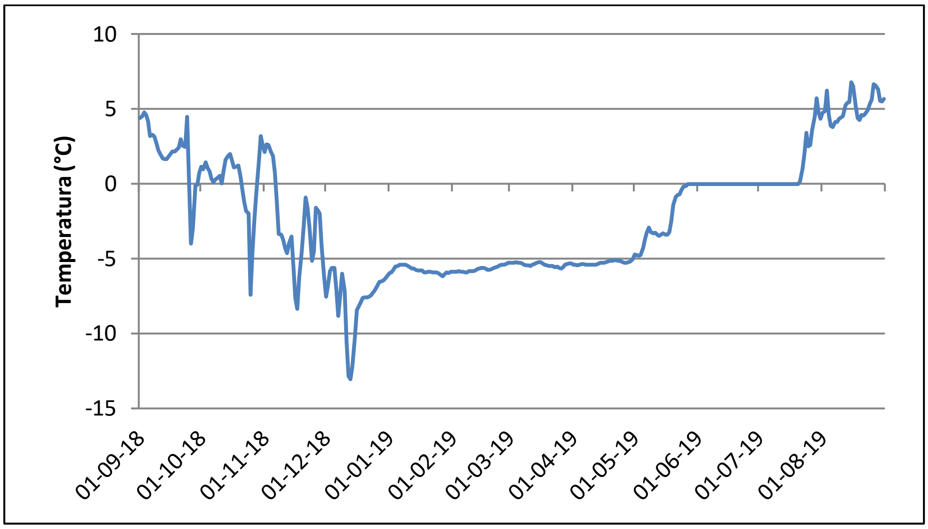

Fig. 8. Mean daily ground surface temperature at M4.1.

In some cases, at the beginning of winter and during the cold seasons, chimney mechanisms operated at different sites (fig. 9). As a result of the air advection warm air was expelled at the upper part of some rock glaciers. In most of the cases the temperature at the surface of of the coarse deposits are mainly controlled by conductive mechanisms (Gruber, Hoelzle, 2008) (fig. 10). This additional mechanism for cooling the ground operates exclusively during the winter, when a sufficiently thick snow covers the ground. In coarse deposits, with high porosity, this mechanism is able to decrease the thermal conductivity of the ground. Because of this mechanism the warming of the ground which normally occur below the snow cover is absent, resulting instead the cooling of the debris surface.

This mechanism is strongly controlled by snow cover, but slope or surface exposure plays an important role too.

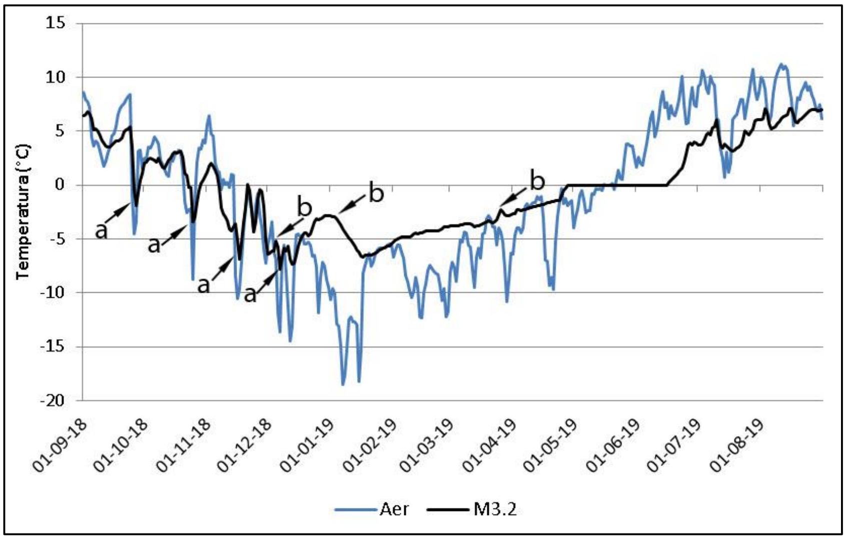

Fig. 9. Mean daily air and ground surface temperature. Arrows indicate intense cooling of the ground by efficient winter convection (a), inverse behavior due to air ventilation (b).

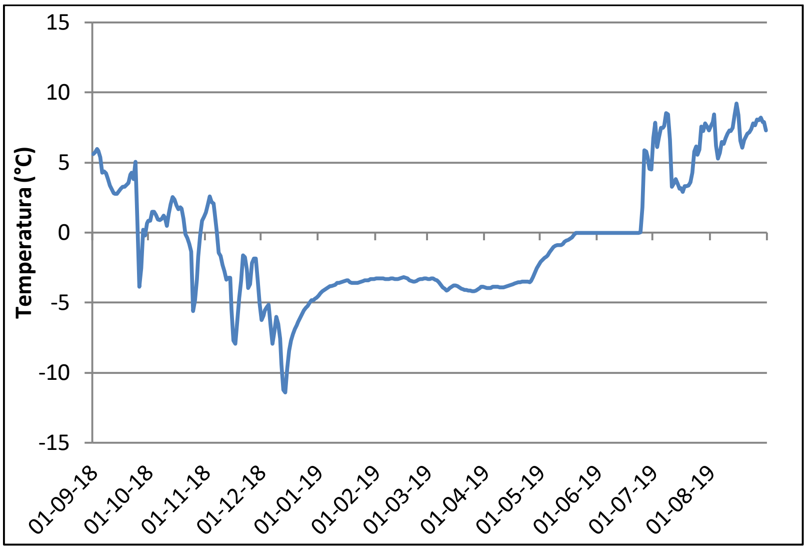

Fig. 10. Mean daily ground surface temperature at M4.4.

6. Statistical analysis of the relationships between GST and local topo-climatic factors.

Air temperature has the greatest influence on the GST regime. At most of the sites there is a strong dependence between air temperature and GST value (the correlation factor is above 0.6). The lowest influence of air temperature corresponds with the locations where snow persisted until August and where the correlation factor is below 0,6.

The results of linear regressions revealed weak dependencies of GST with slope, curvature or solar radiation. The strongest statistical relationships are with snow cover and elevation, but are considerable weaker then the correlation with air temperature.

Table 7. Results of linear regression between GST and local topo-climatic factors.

Elevation vs	r	p-value	Slope vs	r	p-value	Cuvature vs	r	p-value
WeqT	**0.09***	0.010	WeqT	0.00	0.944	WeqT	0.01	0.336
MAGST	**0.14***	0.000	MAGST	0.00	0.877	MAGST	0.00	0.666
GFi	0.03	0.081	GFi	0.00	0.588	GFi	0.00	0.708
GTi	0.09	0.004	GTi	0.00	0.966	GTi	0.00	0.851
0 curtain	0.00	0.560	0 curtain	0.00	0.797	0 curtain	0.00	0.954
Potential radiation vs	**r**	**p-value**	**Snow cover duration vs**	**r**	**p-value**			
WeqT	0.02	0.153	WeqT	0.00	0.466			
MAGST	0.00	0.644	MAGST	**0.47***	0.000			
GFi	0.00	0.374	GFi	0.01	0.310			
GTi	0.03	0.073	GTi	**0.54***	0.000			
0 curtain	0.02	0.193	0 curtain	**0.56***	0.000			

r – Correlation coefficent; p-value – Pearson value; * significant correlation (significance level p=0.01).

7. Assessing the dynamics of rock glaciers by ground-based topographic measurements.

Measurements of movement of five rock glaciers in the Rila and Pirin Mountains were initiated in 2018 using high precision DGPS system from Topcon. In August-September 2019 we measured the first annual horizontal rates of displacements for several points marked in 2018. The magnitude of the horizontal movement, as well as the direction of movement was determined for P8, P9, P10 and M3 and M4. On each rock glacier we monitored between 10 and 28 blocks.

Despite the high accuracy of the GPS systems we estimated that only the values representing movement greater than 2 cm can be attributed to rock glacier movement, whereas values smaller than 2 cm might be in the range of the errors.

At M3 rock glacier we measured 15 points, and as we expected all the measured values are below 2 cm/year. It is likely that this rock glacier is iactive/relict, considering that is covered by vegetation on a high degree.

At M4 only four points from a total of 18 revealed horizontal movement below 2 cm/year. 77% of the total points showed horizontal movement higher than 2 cm/year, indicating that probably this rock glacier is an active one. The highest number of monitored blocks recorded a velocity between 2 and 5 cm/year, whereas two points showed movement rates between 5 and 10 cm/year. Other two points revealed movement rates higher than 10 cm/year (in one case we measured 29 cm/year in the southern part of the rock glacier).

At P8 from 15 blocks only eight revealed horizontal movement between 2 and 5 cm/year, whereas one point showed a horizontal movement between 5 and 10 cm/year. At P9 only in five situations the movements were below 2 cm/year, in 18 cases the horizontal velocity of the blocks was between 2 and 5 cm/year and in foru cases between 5 and 10 cm/year. P10 was the smallest rock glacier we investigated. On his surface we monitored 11 points and only six of these moved with more than 2 cm, but less than 5 cm between the summer of 2018 and 2019.

8. Tree-ring analysis of Pinus Mugo growing on rock glaciers.

In this study we sampled 30 shrubs of Pinus Mugo located on two different rock glaciers (one is below Lovnitsa peak in Rila Mountains and the other is near Popovo Lake in Pirin Mountains). The sampling was performed in September 2019, using two Pressler borer (length 100 and 300 mm and diameter 5.15 mm) (fig. 11) and we extracted at least two increment cores from each shrub. Only Pinus Mugo looking old were selected for sampling. All samples were prepared following standard dendrochronological procedures (Bräker, 2002), which consisted in air-drying, mounting and sanding of increment cores (with grit from 150, 240, 400 and 800). Tree rings were then counted and tree-ring widths were measured using a LINTAB-5 positioning table, connected to a Leica stereo-microscope and TSAP-Win Professional 4.64 software. During the lab analysis several samples were not dated, due to the impossibility of counting all the tree-rings. For this, only 20 shrubs were dated and their corresponding annual growing rate was calculated.

Fig. 11. Extracting cores from Pinus Mugo in Lovnitsa (a) and Popovo (b) rock glaciers.

As revealead in fig. 12 the shrubs installed on Popovo are much older compared with those from Lovnitsa. The average age of the Lovnitsa stand was 59 years, whereas on Lovnitsa the corresponding was 97.6 years. Thus, in site K1 only one sample was older than 100 years, whereas in case of Popovo, seven from a total of eleven are older than 100 years.

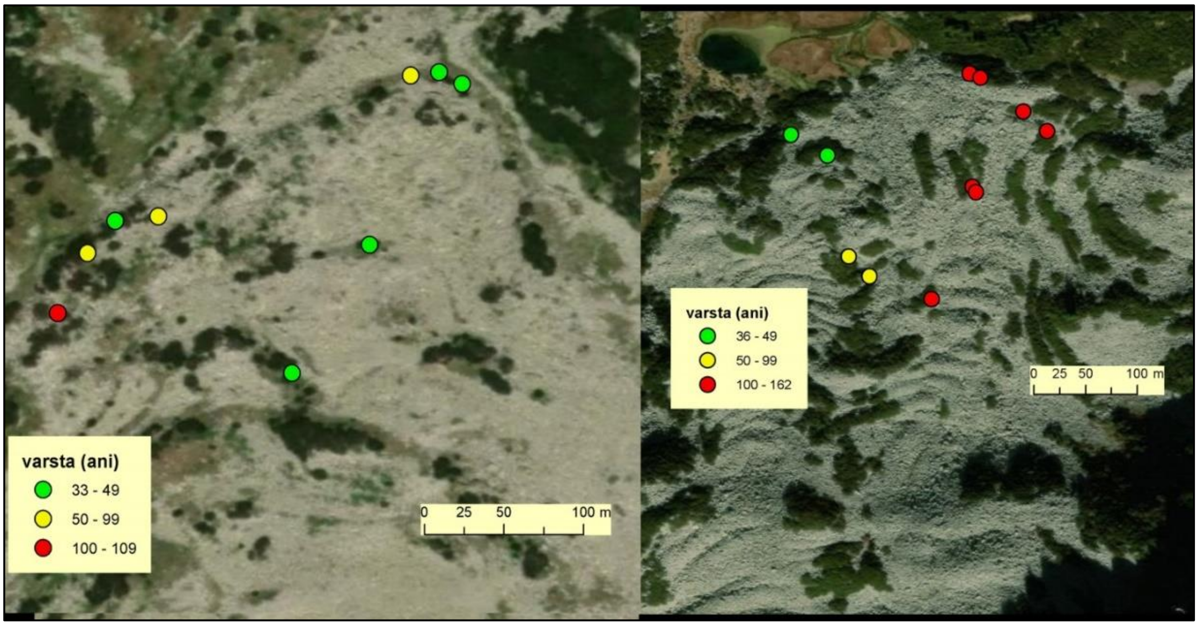

Fig. 12. Age structure of shrubs sampled on Lovnitsa (left) and Popovo (right) rock glaciers.

The mean multiannual growth rate was also considerably different between the two investigated stands (fig. 13). In case of Lovnitsa, the mean rate was 0.68 mm/year, whereas the corresponding for Popovo was only 0.39 mm/year. Only one shrub has a growth rate below 0.4 mm/year at Lovnitsa site, whereas in Popovo eight shrubs show a mean growth rate below this threshold. It is obvious that very young shrubs show growth rates considerably higher than old shrubs.

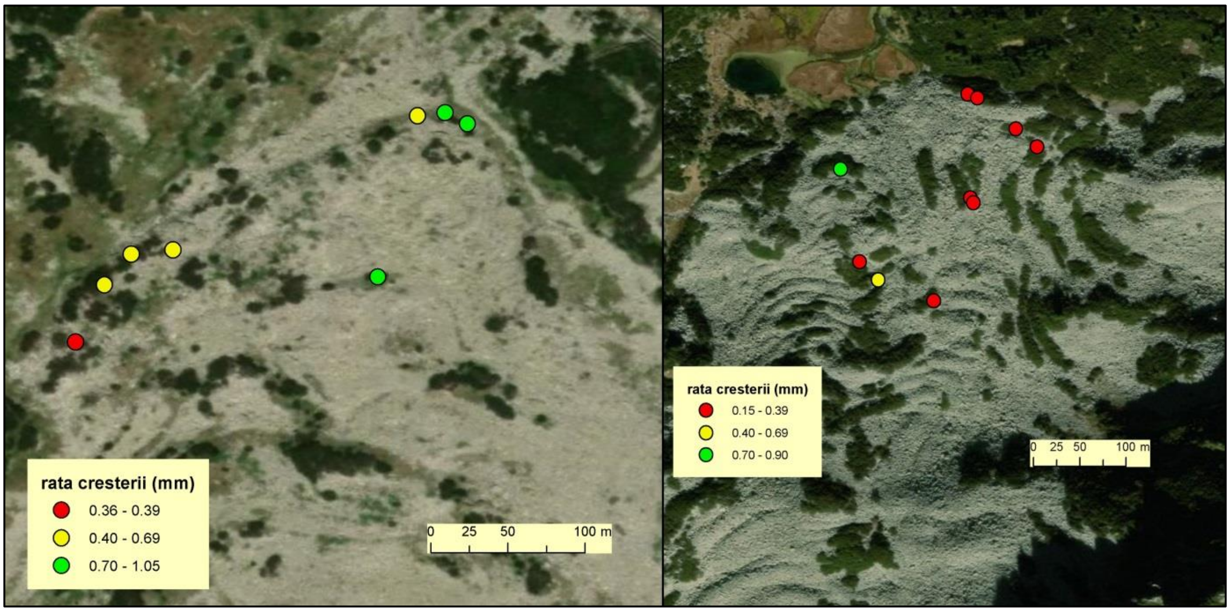

Fig. 13. Multiannual growth rates of shrubs sampled in Lovnitsa (left) and Popovo (right) rock glacier.

9. *UAV photogrammetry and Structure from Motion for high resolution digital elevation model production and monitoring long term horizontal displacement of blocks.*

The recent development of digital photogrammetry and computer vision algorithms (e.g. Structure from Motion), enabled the construction of high-resolution and high-accuracy digital elevation models at an affordable price compared to airborne LiDAR (light detection and ranging) technique (Cook, 2017). Using a cost-effective UAV Phantom 4 Pro equipped with a commercial digital camera we were capable to acquire high-density and high-accuracy 3D terrain point data for 15 sites.

The construction of high-resolution digital elevation models (DEM) (10-20 cm/pixel) will allow us to evaluate more carefully the differences in the surface elevation, and the role of topo-cimatic factors on GST regime. To geometrically correct the image locations during processing we used field ground control points with very accurate GPS systems (DGPS). The camera was setted to take pictrues every 3 seconds. All the acquired images were processed using Agisoft Photoscan Professional software, which uses photogrammetric algorithms to generate digital elevation models of the rock glaciers. The cloud points consisted on an initial cloud points counting tens of thousands of points. In addition, the drone aerial photographs allowed a more accurate delineation of the rock glaciers and of course served to better geomorphological mapping of the selected investigation sites. In the end we were able to produce an orthophoto for each investigated rock glacier. All the achieved digital elevation models had spatial resolution below 0.5 m/pixel, whereas the orthophotos had a resolution below 0.2 m/pixel. The orthophotos and the digital elevation models of the rock glaciersare presented in figs. 14-26.

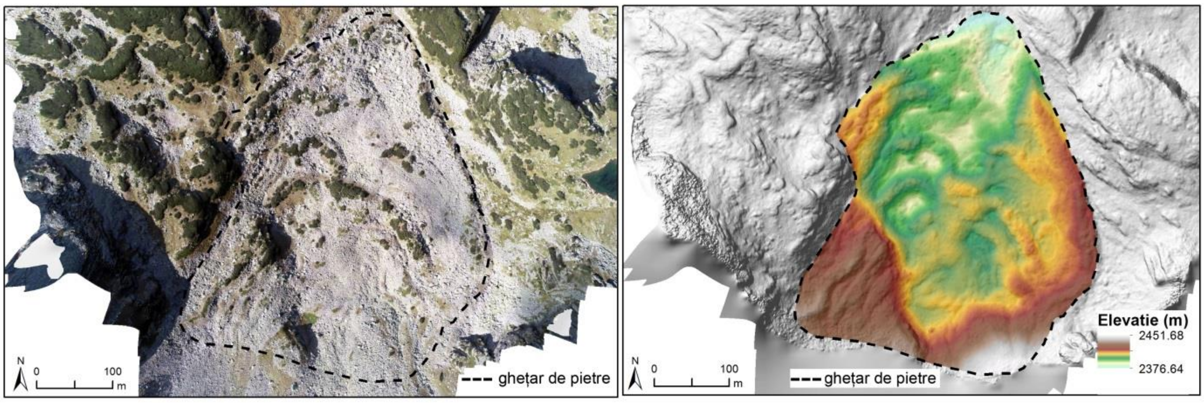

Fig. 14. Ortophoto and digital elevation model of the surface of K1.

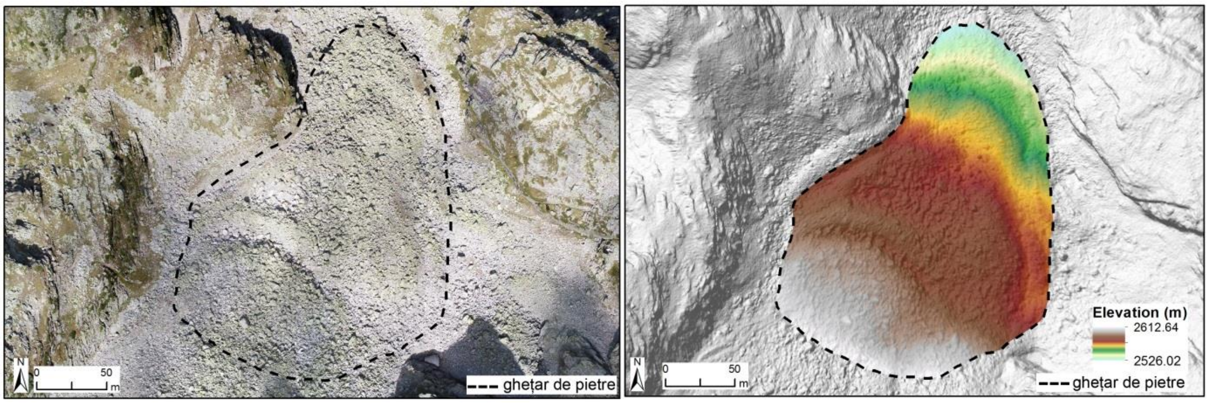

Fig. 15. Ortophoto and digital elevation model of the surface of K2.

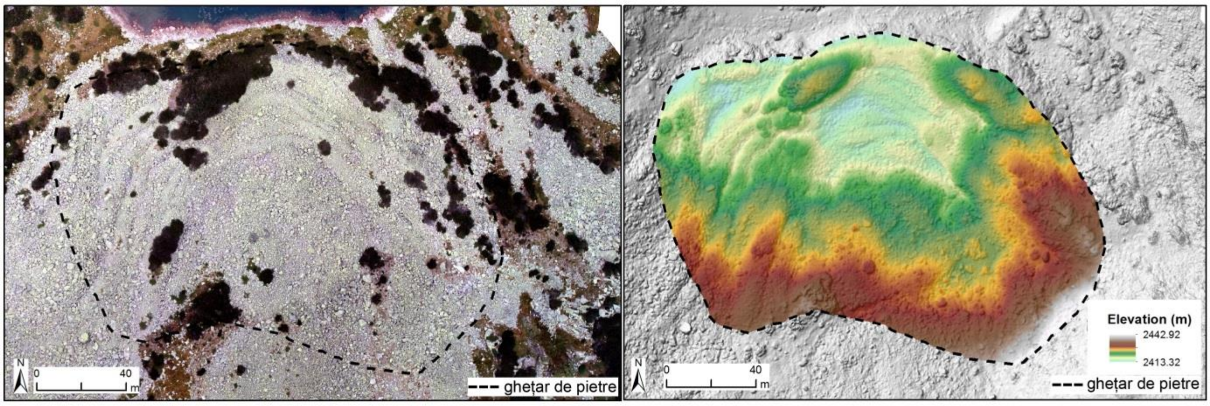

Fig. 16. Ortophoto and digital elevation model of the surface of M3.

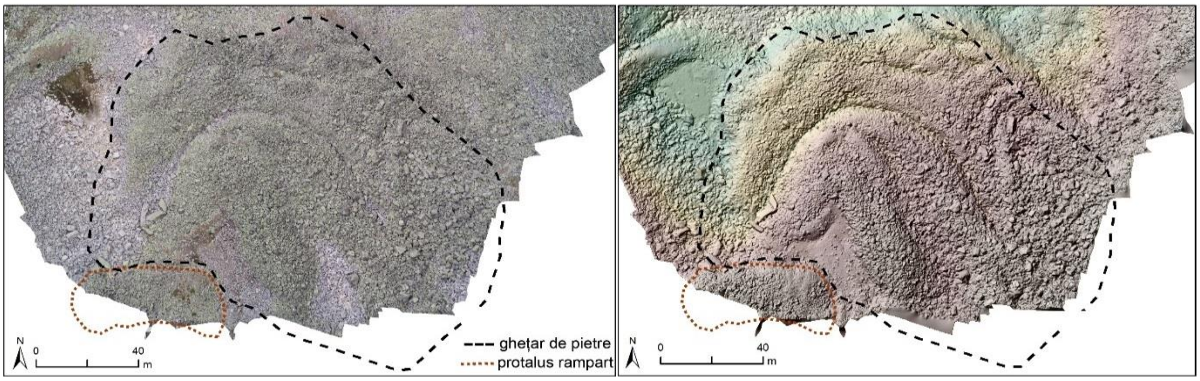

Fig. 17. Ortophoto and digital elevation model of the surface of M4.

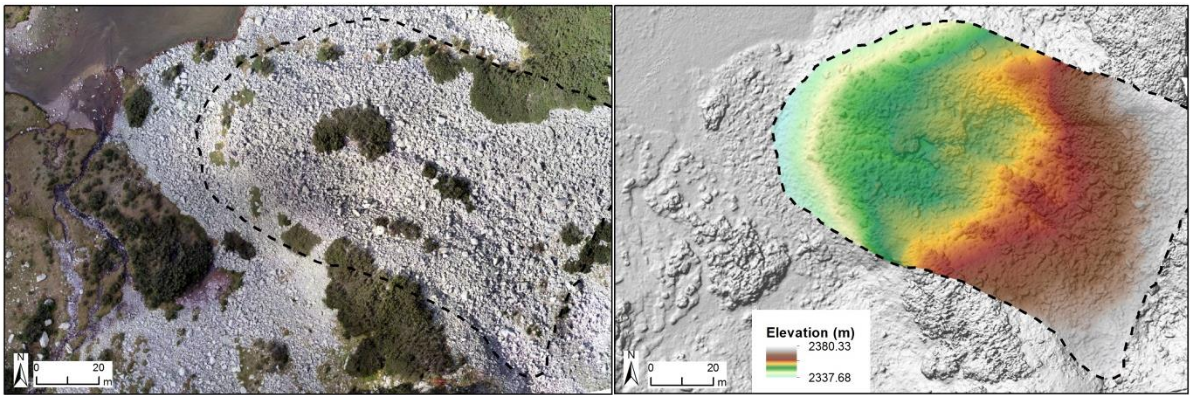

Fig. 18. Ortophoto and digital elevation model of the surface of P6.

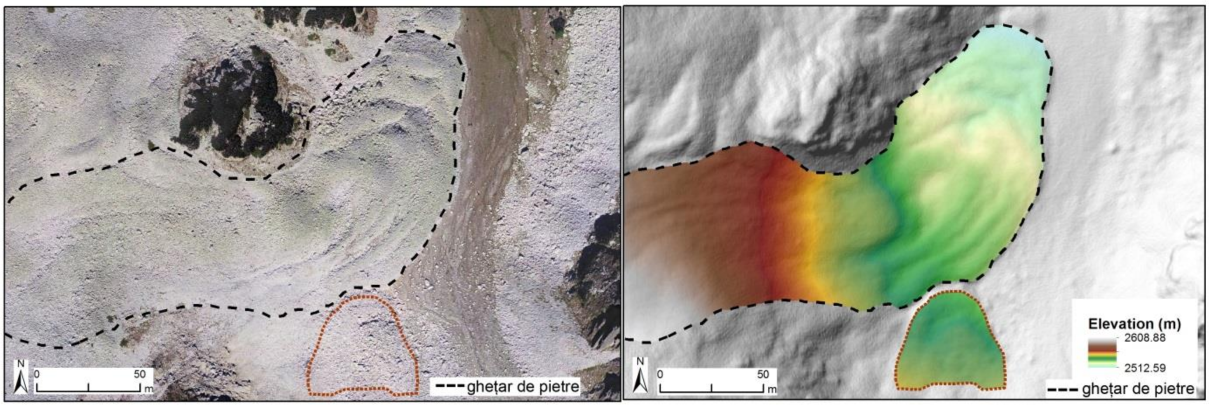

Fig. 19. Ortophoto and digital elevation model of the surface of P8.

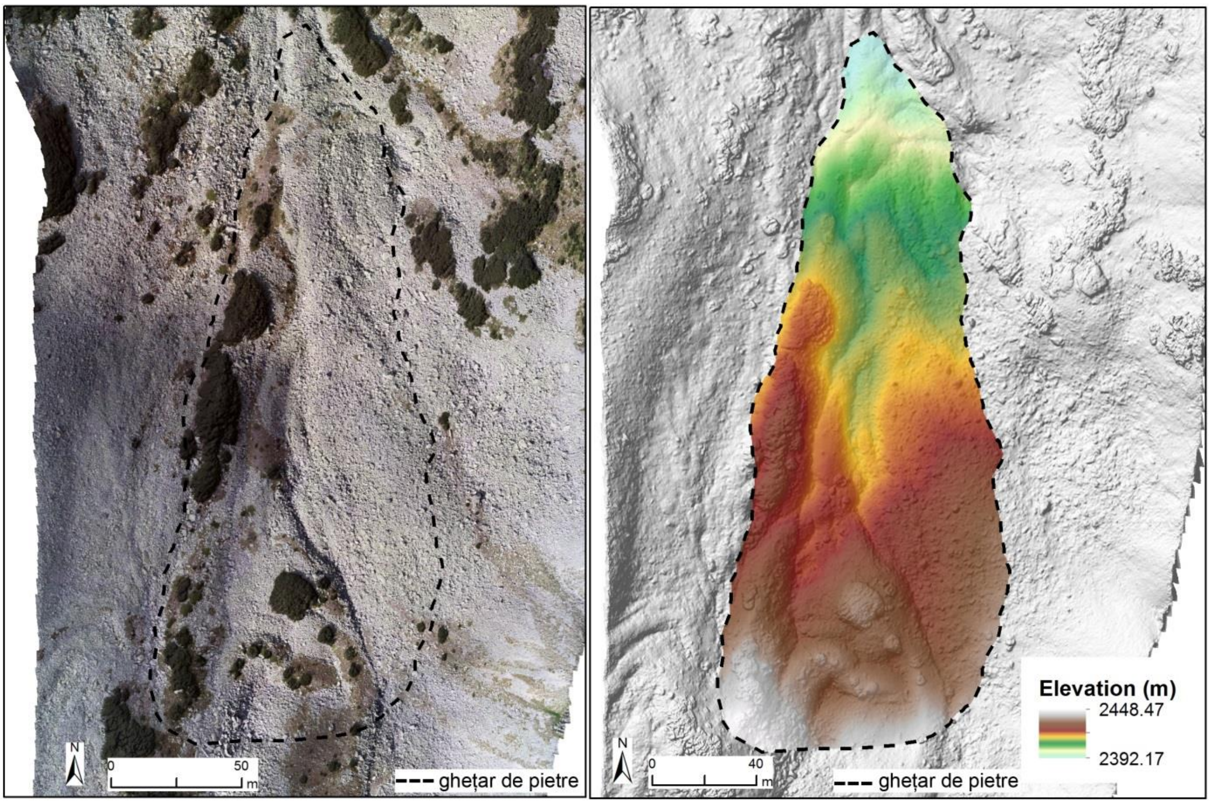

Fig. 20. Ortophoto and digital elevation model of the surface of P7.

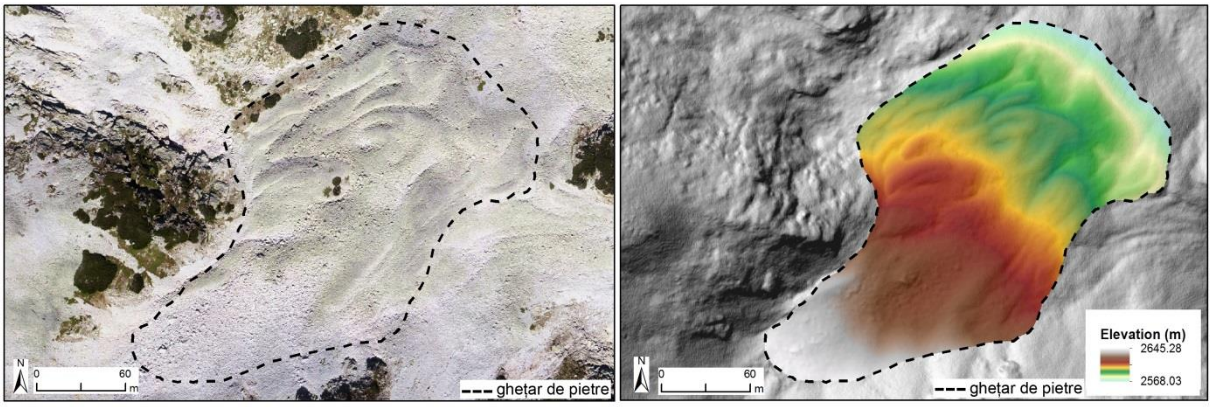

Fig. 21. Ortophoto and digital elevation model of the surface of P9.

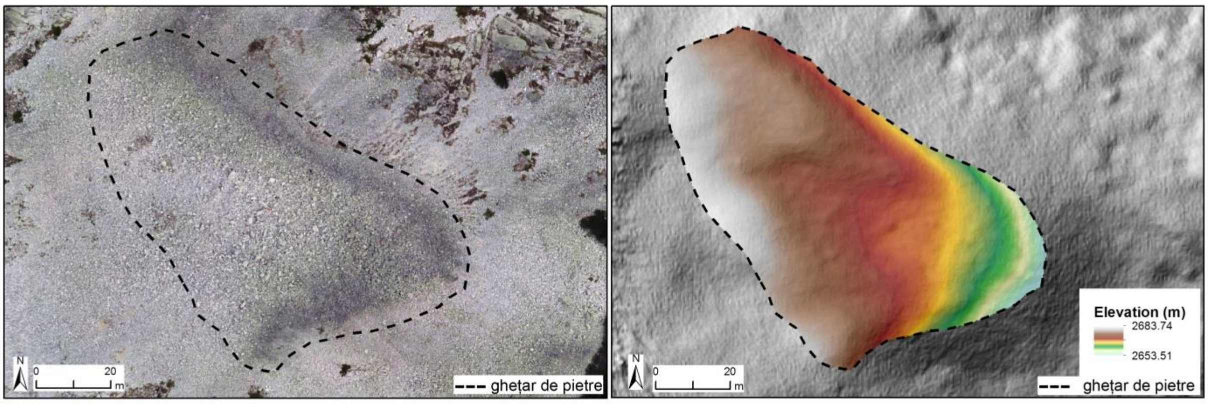

Fig. 22. Ortophoto and digital elevation model of the surface of P10.

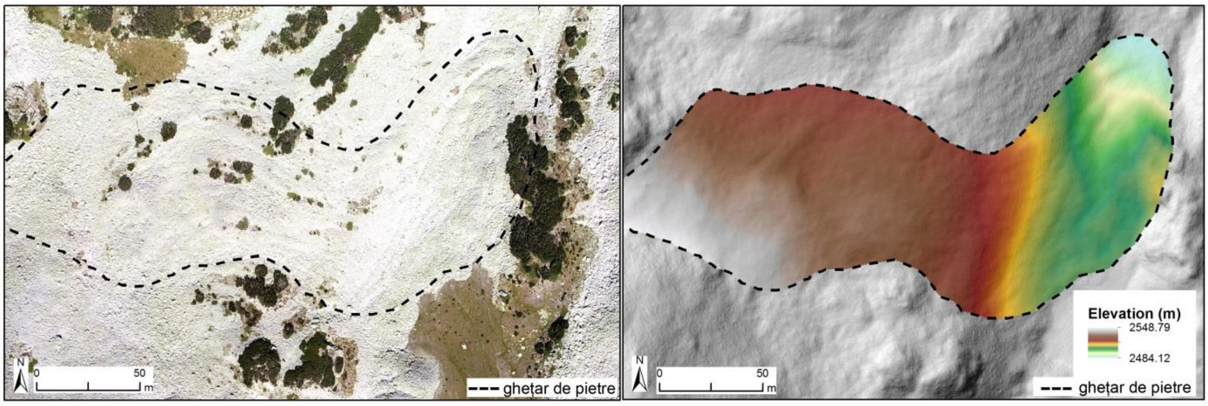

Fig. 23. Ortophoto and digital elevation model of the surface of P11.

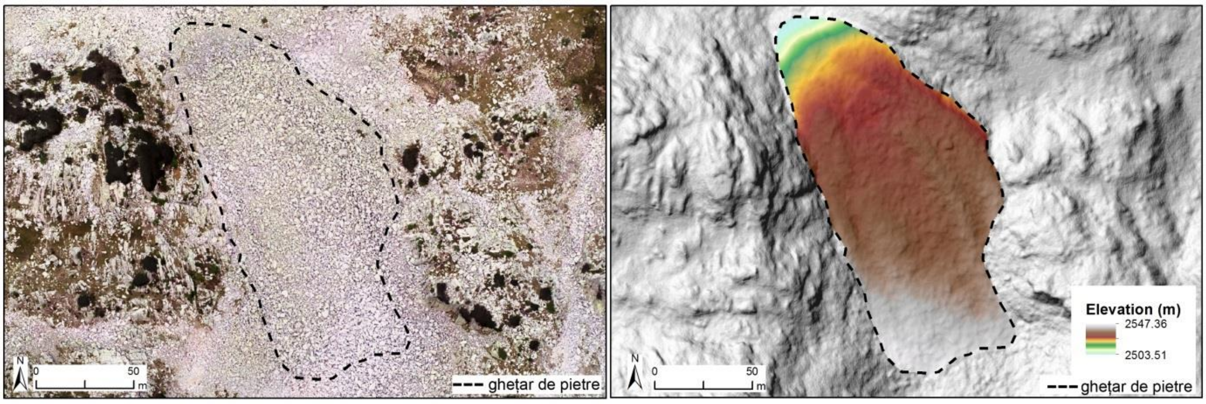

Fig. 24. Ortophoto and digital elevation model of the surface of B12.

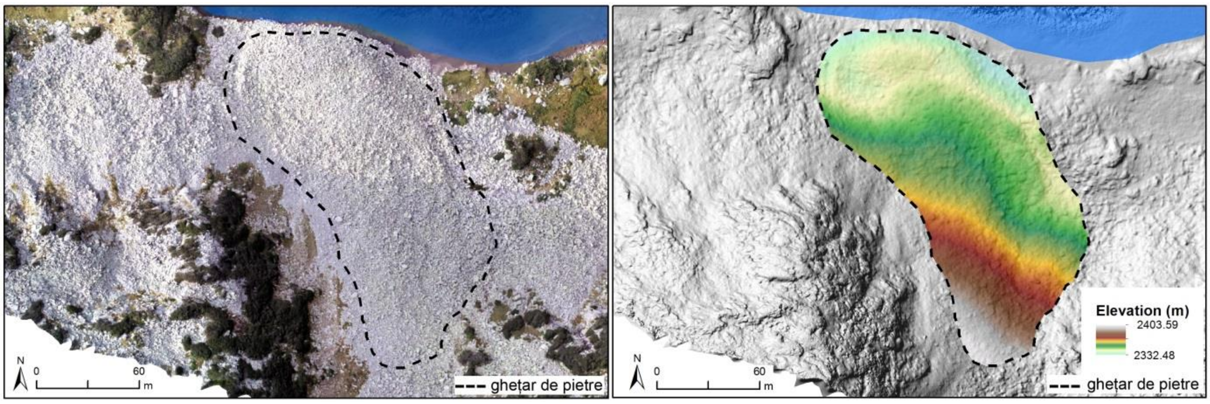

Fig. 25. Ortophoto and digital elevation model of the surface of B13.

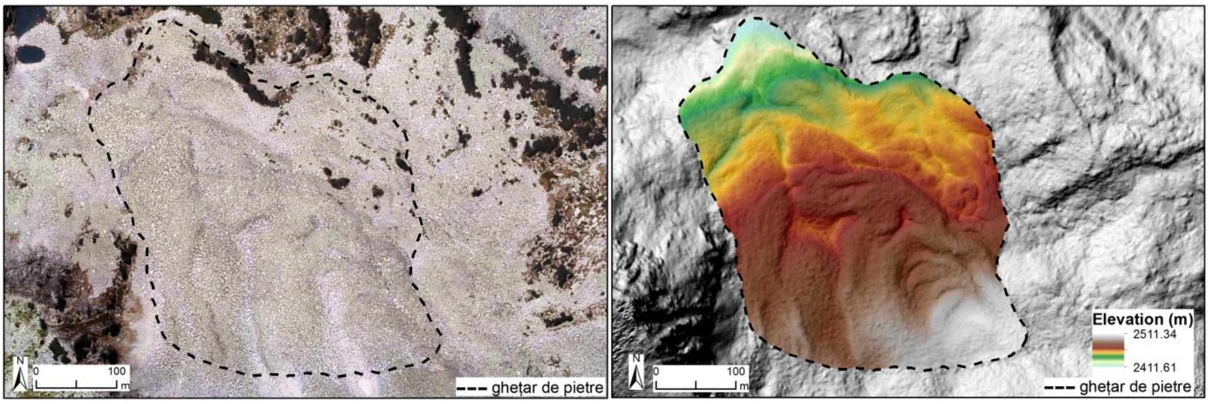

Fig. 26. Ortophoto and digital elevation model of the surface of B14.

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Phase 3_2020

In this phase, we compiled a new rock glacier inventory in the Rila and Pirin Mountains. We mapped 83 rock glaciers in the Pirin Mountains and 39 in the Rila Mountains. The analysis of the environmental controlling factors revealed that the distribution of rock glaciers is strongly constrained by elevation, aspect and terrain slope. All the rock glaciers occur between 2100 and 2650 m, indicating that probably their formation was initiated in a similar time window. To elucidate this hypothesis, we assessed the relative age of several rock glaciers using Schmidt hammer (SH) rebound values (R). The SH tests revealed reduced differences between R-values of rock glaciers lying at a different elevation, suggesting that the genesis and formation of these landforms date to the same period. We were considering the existing paleoclimatic reconstructions in the region as well as the periods of glacier advances we estimated that the age of rock glaciers goes back to Younger Dryas (YD). However, proofs of recent rockfall, feeding rock glaciers were also revealed by SH results.

In this last phase of the project, we have planned three different activities, as follows:

1. Assessing the environmental controlling factors of rock glaciers distribution and characteristics using a statistical approach.
2. Relative dating of rock glaciers using Schmidt hammer.
3. Assessing permafrost evolution in the Rila and Pirin Mountains from LGM to present.

1. *Assessing the environmental controlling factors of rock glaciers distribution and characteristics using a statistical approach.*

The first unitary rock glaciers inventory of Balkan Peninsula was accomplished within this project (Magori et al., 2020). The aim was to have a comprehensive picture of the regional characteristics of these spectacular landforms indicating permafrost occurrence. Regarding the features of rock glaciers in the Rila and Pirin Mountains, the paper by Magori et al. (2020) revealed several interesting findings, such as:

- In the Pirin Mountains rock glaciers have the largest density in the entire Balkan Peninsula (0.42 / km^2). 54% of their total occur in Rila and Pirin Mountains.
- Rock glaciers in the Rila and Pirin Mountains are the smallest in the entire Balkan Peninsula (their mean size is 433 m);
- Rock glaciers in the Rila and Pirin Mountains occur at the highest elevation in the entire Balkan Peninsula, despite their northern latitude within this region.
- All the rock glaciers in the Rila and Pirin Mountains are concentrated between 2100 and 2650 m. In all the other mountainous regions in the Balkan Peninsula, rock glaciers also occur well below 2000 m.
- In the Rila and Pirin Mountains occur the highest rock glaciers in the Balkan Peninsula (mean elevation: 2391 m).
- Rock glaciers in the Rila and Pirin Mountains occur on terrain with higher slopes than elsewhere in the Balkan Peninsula.
- Rock glaciers in the Rila and Pirin Mountains occur in locations characterized by the lowest mean annual temperatures and precipitation in the Balkan Peninsula, according to WorldClim data.
- Tongue rock glacier is more numerous than debris rock glaciers in the Rila and Pirin Mountains. They are also considerably larger with lengths which can reach 500-600 m.
- 12 rock glacier in the Rila and Pirin Mountains are at least 1000 m long.
- 35% from the total o rock glaciers in the Rila and Pirin Mountains are entirely above 2400 m.

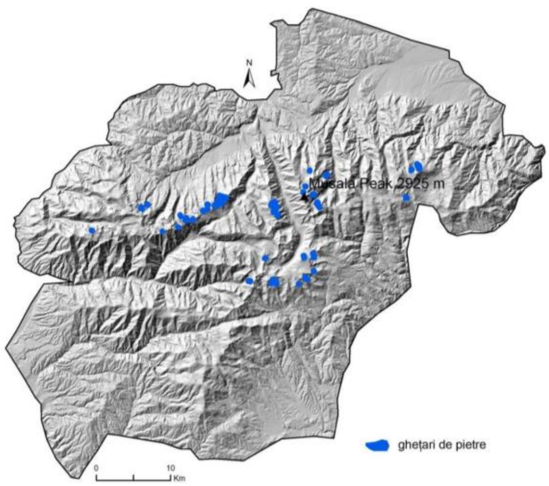

Fig. 1. Rock glaciers distribution in the Rila Mountains.

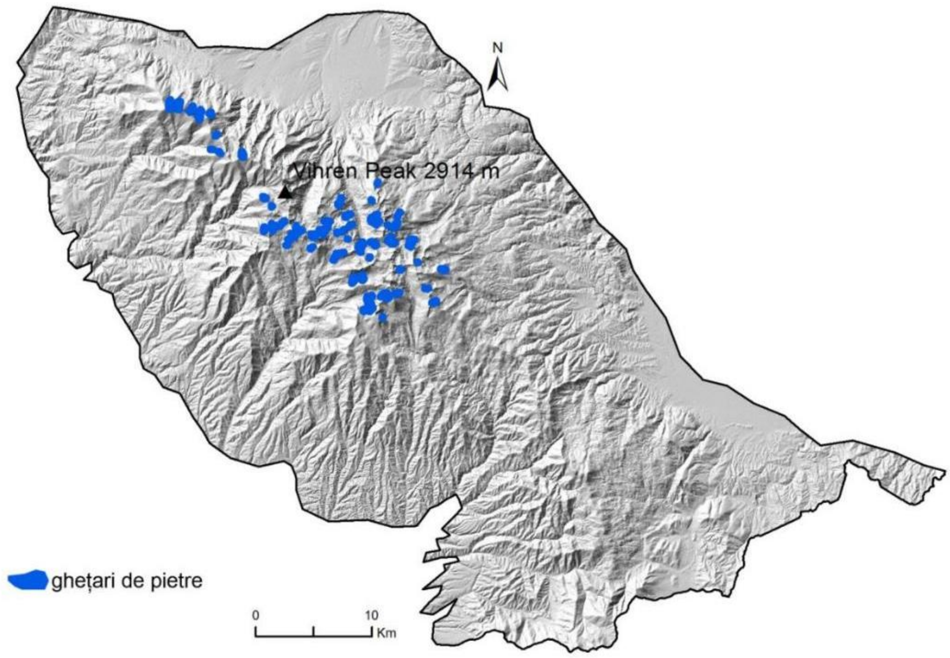

Fig. 2. Rock glacier distribution in the Pirin Mountains.

- The majority of the glaciers are north-facing features, but the mean elevation of the front does not vary significantly with different aspect of rock glaciers.
- In the Pirin Mountains, the majority of the rock glaciers are concentrated in areas with mean annual temperatures between 0 and 1° C, whereas in Rila, rock glacier between -1 and 0° C prevail.
- One rock glacier in the Rila Mountains is located between -1 and -2° C.
- 69% of the total number of rock glaciers are in locations with precipitation between 800 and 900 mm.

The results of the linear regression between rock glacier area and different controlling factors are displayed in Tabel 1. According to our findings, there is a strong relationship between the rock glacier area and the contributing area. Similar results were also highlighted in other studies (Onaca et al., 2017; Frauenfelder et al.

Significant statistical relationships were found between rock glaciers area and the altitudinal range of the contributing area and between rock glaciers area and minimum elevation.

The mean elevation of the rock glaciers front is controlled to a certain degree by the characteristics of the source area (area, altitudinal range, maximum altitude, mean elevation, minimum altitude), climatic characteristics (temperature, potential radiation, precipitation), but also length and width.

Table 1. Results of linear regressions (n=122)

RG Area versus	r	p-value	RG MEF versus	r	p-value
CA area	0,68	<0,000	RG Area	0,23	<0,000
CA altitudinal range	0,38	<0,000	CA area	0,22	<0,000
CA min. elevation	0,04	0,015	CA min. elevation	0,84	<0,000
CA max. elevation	0,05	0,012	CA altitudinal range	0,29	<0,000
CA mean elevation	0,00	0,942	CA mean elevation	0,64	<0,000
CA mean slope	0,00	0,712	CA max. elevation	0,33	<0,000
RG min. elevation	0,23	<0,000	CA mean slope	0,01	0,229
RG max. elevation	0,00	0,770	RG max. elevation	0,75	<0,000
RG mean elevation	0,09	0,000	RG mean elevation	0,94	<0,000
RG mean slope	0,00	0,608	RG mean slope	0,05	0,011
Longitude	0,00	0,790	Longitude	0,02	0,120
Latitude	0,00	0,730	Latitude	0,00	0,596
Mean Temperature	0,02	0,083	Mean Temperature	0,14	<0,000
Annual Precipitation	0,00	0,608	Annual Precipitation	0,31	<0,000
Potential Radiation	0,04	0,026	Potential Radiation	0,19	<0,000
RG Length	0,81	<0,000	RG Length	0,14	<0,000
RG Width	0,60	<0,000	RG Width	0,24	<0,000
Length/Width	0,12	<0,000	Length/Width	0,00	0,760

(r= correlation coefficient; p = Pearson values; CA = contributing area; RG = rock glaciers)

2. *Relative dating of rock glaciers using Schmidt hammer.*

Schmidt hammer started to be used for relative datings in geomorphology since 1980`s (Matthews and Shakesby, 1984). A number of studies used SH to date rock glaciers: Humlum (1998), Frauenfelder et al. (2004), Frauenfelder et al. (2005), Nicholas and Butler (1996), Aoyama (2005), Kellerer-Pirklbauer et al. (2008) și Klapyta (2013).

In the present project, we used a digital SH (CONTROLS 58-CO181/G) to test the degree of weathering of boulders in case of six rock glaciers. The resolution of each measurement was 0.1 R.

In the Rila Mountains, we investigated three rock glaciers (K1, M3 and M4). In all these rock glaciers, we also installed thermistors, to monitor thermal regime. In the Pirin Mountains we investigated three other rock glaciers (P8, P9 and B14).

Fig. 3. Using Schmidt hammer on M4 rock glacier in Rila Mountains.

At M4 site we also measured three boulders located outside the rock glacier extent, originating from a recent rockfall in September 2016 (fig. 4).

Fig. 4. Rock wall near Musala Peak affected by a large rockfall in September 2016.

The boulders originating from the 2016 event are fresh, and they can serve as a good proxy of current weathering conditions. All these three boulders have rebound values higher than 40. Twenty-one boulders were investigated at M4, and they all have R values between 25 and 35.

M3 rock glaciers is located with 200 m lower than M4, but revealed similar R-values. The R-values here were concentrated between 23 and 32. Only two boulders had slightly higher values, but these are located outside the borders of this landform, within a talus slope feeding the rock glacier.

Twenty-eight boulders were tested at K1 and the mean R-value was 35.2. This rock glacier is located at 2400 m, but revealed higher R-values compared with M4 which is settled at 2600 m. This notable difference might be explained by the difference of mineralogy between this site and Musala site. An erratic boulder located in Beli Iskar, at 1150 m was also tested and showed a mean R-value of 29.1. According to Kuhlemann et al. (2012) this moraine was probably initiated during LGM or OD. This means that K1 is younger than LGM.

Fig. 5. Using Schmidt hammer on an erratic block in Rila Mountains.

In the Pirin Mountains, we also investigated three rock glaciers. P8 and P9 are located close to each other below Polezhan Peak. Here the values are very heterogeneous, ranging from 27 to 52. It is difficult to interpret these heterogeneous values, but we can undoubtedly affirm that intense rock falls affect this site. On both rock glaciers, we found mean R-values higher than 50, confirming the recent detachment of these boulders from the rock walls.

B14 lies below Banderishki Chukar and is one of the largest rock glaciers in the Pirin Mountains. Here, we sampled 11 boulders and a general tendency of decreasing R-values was observed. The R-values ranged between 30 and 42 with considerably higher values concentrated in the upper part of the rock glacier. This finding suggests that the rock glacier activity lasted longer than in the other cases where a clear decreasing trend of R-values was not observed.

3.Assessing permafrost evolution in the Rila and Pirin Mountains from LGM to present.

According to Kuhlemann et al. (2012), the LGM in The Rila Mountains was synchronous with the rest of the European continent (23-34 ka BP). A second glacial major advance was dated at 18-16 ka BP (Kuhlemann et al., 2012). Glaciers in Younger Dryas were also probably present in Rila and Pirin Mountains, but there are no absolute ages to sustain this hypothesis. In the Little Ice Age several tiny glaciers occurred in the Pirin Mountains and 2 of them survived until the present.

Considering the timing of the last glacial advances in this region, it seems that the only time interval when the initiation of rock glaciers was likely in Rila and Pirin to coincide with YD. According to Kuhlemann et al. (2012), during OD the glacial descended to at least 2000 m leaving no space for rock glaciers to develop. Despite there is no information regarding a glacial advance in YD we assume that small glaciers occurred in high cirques in both Rila and Pirin Mountains. In several cases, very nice terminal moraines located above 2200 m suggest the existence of a YD glaciation. During the cold episodes of the Holocene (8.2 ka BP and Little Ice Age), small glaciers were probably sparse above 2400 m.

According to existing paleo-reconstructions in the Balkan Peninsula YD was cold and dry. The temperature of the coldest month was around 0 at sea level in the southern part of Balkan Peninsula

(Renssen and Isarin, 2001). According to Bordon et al. (2009) temperatures of the coldest month ranged from -12 to -8° C. It seems that the amplitude of temperature drop was considerably higher in this region compared with other sites in Europe (Renssen and Isarin, 2001). Based on these paleoclimatic reconstructions we can affirm that during YD the climatic conditions were suitable for rock glaciers formation.

It is well known that rock glaciers are initiated when mean annual air temperature is less than -2°C and precipitation do not exceed 2500 mm/year (Barsch, 1996). In YD these conditions characterized the alpine area of Rila and Pirin Mountains. During Holocene, only the 8.2 ka event and probably LIA were related with cooler temperatures, but insufficient to initiate rock glaciers formation at a broad scale. However, we do not exclude that several small rock glaciers to be initiated in the Holocene.

The YD age of the Bulgarian rock glaciers is also supported by several findings previously presented:

- The rock glaciers in the Rila and Pirin are concentrated in an elevation belt of only 500 m. In other mountain ranges in the Balkan Peninsula they are widespread below 2000 m as well.
- The altitude of the rock glaciers in the Rila and Pirin Mountains is very high, compared with all the other mountain ranges in the Balkan Peninsula. At a similar latitude rock glacier in the Dinaric Alps occur even below 2000 m.
- Rock glaciers in the Rila and Pirin Mountains have small sizes, suggesting that the timing of their formation was reduced. We assume that they were initiated in YD after the glacial retreat and they haven`t enough time to grow sufficiently. We speculate that some of the rock glaciers in this region have developed in less than 1000 years.
- SH results suggest that rock glaciers at 2600 m have the same age as rock glaciers situated at 2400 m. We think that the genesis of all the rock glaciers in this region started in YD. Lower rock glaciers are greater because they probably had a longer time interval. On the other hand, rock glaciers situated above 2400 m are small because their activity probably lasted few hundreds of years only.

Recent thermal and geophysical measurements revealed that permafrost is still present in several rock glaciers in the Rila and Pirin Mountains above 2400 m (Onaca et al., 2020). SH results also confirm that rockfalls are still active in this region and some sites (e.g., Polehzan) the amount of new boulders at the surface of the rock glaciers is significant. We speculate that during LIA rockfall activity was even more intense, allowing a re-activation of several rock glaciers.

Permafrost is also associated with present-day small glacierets and permanent snow patches. Below the perennial snow patches, the ground is permanently frozen, whereas near the Snezhnika and Banski Suhodol glaciers, recent geophysical and thermal measurements revealed the occurrence of permafrost.

The recent occurrence of permafrost in these mountains is also suggested in previous studies by Brown et al. (1997) and Dobiński (2005). According to the last one, permafrost is likely to occur above 2350 m in the Rila Mountains.

The existing permafrost distribution models also admit that permafrost may occur in favourable conditions in both sites. Magori et al. (2020) overlapped the rock glaciers inventory on the PZI model (Gruber, 2012) and concluded that several rock glaciers might host permafrost due to their favourable topo-climatic conditions. Similar results were presented by Obu et al. (2019), who modelled the patchy distribution of permafrost in this region.

The present-day presence of permafrost in the Rila and Pirin Mountains is also supported by the micro-morphology of several rock glaciers in this region. Rock glaciers have well-developed ridges and furrows, steep fronts and no vegetation. The preliminary results of ground-based GPS measurements revealed small horizontal displacements of several boulders in case of rock glaciers. Because we only have one year of kinematics measurements, we need to consider these initial findings with caution. However, in the last four years during our late summer field trips (late August-September), we observed each time patches of snow and ice within the boulders at the surface of several rock glaciers. This observation, together with the measurements of the springs seeping from rock glaciers fronts also indicate that the frozen core can survive at least two consecutive years above 2400 m.

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Dissemination

The results generated in the frame of this project were disseminated at 6 international **conferences**, as follows:

- Onaca, A., Ardelean, A., Ardelean, F., Gachev, E., Magori, B. Sîrbu, F., Ice thickness and internal structure of two small glaciers in the Pirin Mountains (Bulgaria) assessed by geophysical investigations, INQUA 2019, Dublin, Ireland, 25-31.07.2019 https://app.oxfordabstracts.com/events/574/program-app/submission/94392
- Onaca, A., Voiculescu, M., Ardelean, F., Gachev, E., Urdea, P., Magori, B., Sîrbu, F., Thermal and morphological characteristics of rock glaciers in the Rila and Pirin Mountains, Carpatho-Balkan-Dinaric Conference on Geomorphology, Szeged, Hungary, 24-27.06.2019 http://www.geo.u-szeged.hu/carpatho/CBDC_book_final.pdf
- Onaca, A., Voiculescu, M., Magori, B., Sîrbu, F., Ardelean, F., Permafrost investigations in the highest mountains of Bulgaria and Romanian Carpathians (Romania), Geobalcanica, Sofia, Bulgaria, 13-14.06.2019 Geobalcanica_2019
- Onaca, A., Voiculescu, M., Ardelean, F., Urdea, P., Gachev, E., Magori, B., Hegyi, A., Sîrbu, F., Băbănaș, M., 2019, Permafrost characteristics in marginal periglacial environment of Rila and Pirin Mountains, 35th Symposium on Geomorphology, Timișoara, 23-26.05.2019; SNG 2019
- Onaca, A., Ardelean, A., Magori, B., Voiculescu, M., Ardelean, F., Gachev, E., Sirbu, F., 2019, Permafrost investigations in the Rila and Pirin Mountains, Bulgaria, EGU, Viena, Austria, 7-12.04.2019 https://meetingorganizer.copernicus.org/EGU2019/EGU2019-5864.pdf
- Onaca A., Magori, B., Ardelean, F., Gachev, E., Urdea, P., Voiculescu, M., Sîrbu, F., 2018. Are there any intact rock glaciers in the Balkan Peninsula? 5th European Conference on Permafrost, Chamonix Mont Blanc, 23 June – 1 st July 2018 https://permbulg.projects.uvt.ro/wp-content/uploads/2014/07/Onaca_EUCOP2018.pdf.

Moreover, during this project, **2 ISI articles** were published in high impact journals:

• Onaca, A., Ardelean, F., Ardelean, A., Magori, B., Sîrbu, F., Voiculescu, M., Gachev, E. 2020. Assessment of permafrost conditions in the highest mountains of the Balkan Peninsula. Catena. 185:104288. https://doi.org/10.1016/j.catena.2019.104288

• Magori, B., Urdea, P., Onaca, A., Ardelean, F., 2020, Distribution and characteristics of rock glaciers in the Balkan Peninsula. Geografiska Annaler: Series A, Physical Geography. https://doi.org/10.1080/04353676.2020.1809905