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Journal of Alpine Research | Revue de géographie alpine
Varia

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Édition électronique
URL : https://journals.openedition.org/rga/8780
ISSN : 1760-7426

Éditeur :
Association pour la diffusion de la recherche alpine, UGA Éditions/Université Grenoble Alpes

Référence électronique
Pierre Pech, Mahé Ajinca, Sylvain Abdulhak, Eric Hustache, Laurent Simon et Brigitte Talon, « The Geoecological Evaluation of the Heritage Interest of Polygonal Soils Inherited in Alpine Mountains. The Example of the Col du Noyer (Massif du Dévoluy, Hautes Alpes, France) », *Journal of Alpine Research | Revue de géographie alpine* [En ligne], Varia, mis en ligne le 18 juin 2021, consulté le 18 juin 2021. URL : http://journals.openedition.org/rga/8780

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Acknowledgements

The authors would like to thank Marie Chenet who supervised the granulometric analyses at the Laboratoire de Géographie Physique, UMR 8591, as well as Brigitte Van Vliet-Lanoë and a second anonymous reviewer for their valuable advice but also Constance Schéré, King's College of London, who corrected the English version of the article.

Introduction

1 In the mountains - and particularly in the Alps - as in other regions, the patrimonialisation of nature is based on the qualification of the stakes of conservation management (Reynard *et al.*, 2011; Senzaki *et al.*, 2017; Garcia-Lamas *et al.*, 2018). For biodiversity, this considers both the taxa to be protected (flora and fauna), and the habitats containing these taxa (Mathevet & Godet, 2015; Johnson *et al.*, 2017). The need for regulation, which is involved in development projects, has made it necessary to address these species and their habitats. This is not only the basis of numerous international conventions, such as the Ramsar Convention, but also of the entire European strategy for nature conservation, with the Directives that have given rise to national law in all European states and to the definition of the conditions for the protection of species and habitats on the sites of the European Natura 2000 network (Biondi *et al.*, 2012). Among other things, the implementation of natural environment

management measures or impact studies prior to any temporary (e.g. a sporting event) or permanent (e.g. the development of an infrastructure or a building) intervention is largely based on inventories and fauna-flora monitoring in the sectors concerned. Systematic inventories make it possible to establish the importance of considering species listed in the regulatory lists, such as species classified on the Red Lists: these are remarkable or rare species and therefore must be protected. However, ordinary biodiversity is also considered. In particular, the taxonomic richness and diversity of a habitat constitutes an aspect of biodiversity as well as the rarity of a species according to the area considered: for example, the eightpetal mountain-aven (*Dryas octopetala* L.), an abundant plant in the middle of polar tundra or in very high mountains, is considered for conservation if it is present at low altitudes as a testimony to a relict habitat, as is the case on certain cold scree slopes (Debay & Huc, 2015). In this case, we combine the interest of making ecosystems and geomorphological supports a part of heritage.

2 The mountains, particularly the Alps, constitute an interesting environment for considering sites of geological and geomorphological interest (Feuillet, 2010; Feuillet & Sourp, 2011; Reynard *et al.*, 2011). This concerns the diversity of minerals, fossils, rock deformations and landscapes due to structural forms. The alpine domain also contains witnesses to the action of morphodynamic processes inherited from the ice ages, cirques, glacial locks, morainic vallums etc. Some sites are marked and valorised by appropriate signalisation and some are protected because of their heritage value, such as in the National Geological Nature Reserve of Haute Provence. However, it is also about protecting and monitoring active forms that bear witness to changing environmental conditions. This is the case for many alpine glaciers (Zekollari *et al.*, 2019). The ROCVEG programme, led by the Alpine National Botanical Conservatory (CBNA), concerns the adaptation of Alpine periglacial rocky habitats in the context of climate change. This programme targets three types of habitats: cold scree slopes, rocky glaciers, and the proglacial margins of retreating glaciers in the Alps. With their evolution, these environments are sentinels of ongoing environmental change (Reed *et al.*, 2016). Bodin *et al.* (2015) estimate that mountain permafrost represents between 700 and 1500 km^2, "or 10 to 20% of the land above 2000 m altitude" in the Alps (Bodin *et al.*, 2015). Its degradation has important consequences on the stability of the slopes progressively affected by the melting of this permafrost, which constitutes a marker of climate change.

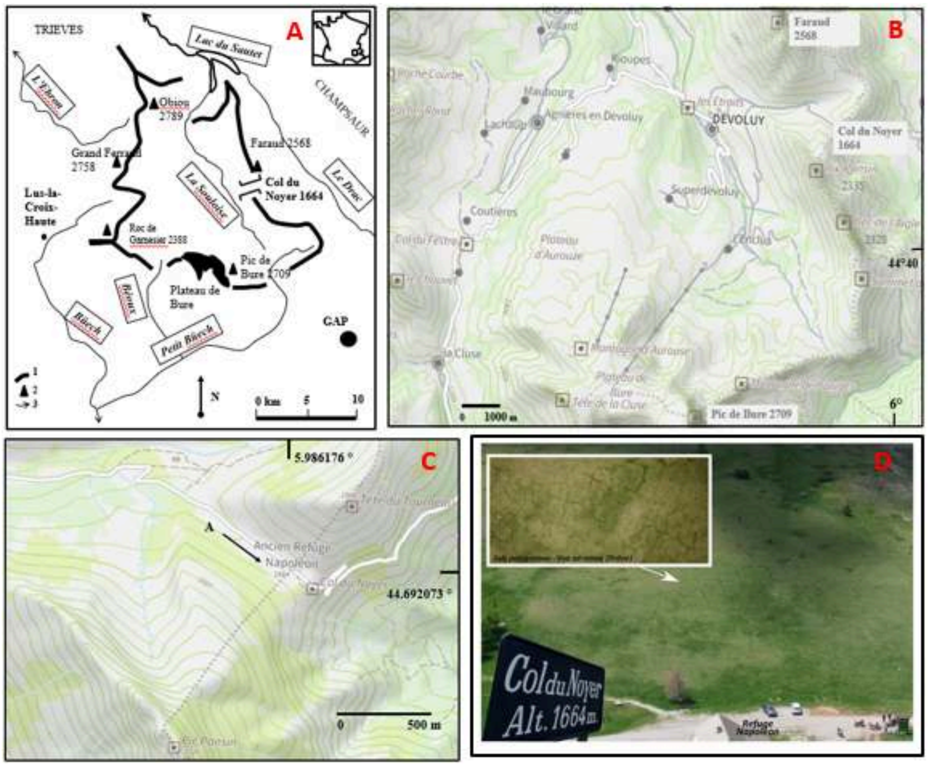
3 The paradox is that polygonal grounds, spectacular periglacial formations, are not considered as markers for climatic change. Indeed, active polygonal grounds are found at altitudes above 2500 m, at least in several sites in the Hautes-Alpes, for example on the Plateau de Bure, in the Dévoluy, on the Mortice ridge, east of Vars, or at the foot of the Tête de Vautisse in the south of the Écrins, but other polygons have been recorded in other sectors of the Alps (CNRS Caen, 1980). In addition, D'Amico *et al.* (2019) consider that for the Alps, traces of permafrost activity and in particular polygonal grounds dating from the Pleistocene, (i.e., during the great glaciations) are rare and need to be protected. This two-pronged question on the recognition of these original periglacial landforms, polygonal grounds, and their interest in being protected, is addressed in this paper on the Col du Noyer site, at 1664m, on the edge of the Dévoluy massif.

Surveyed site: patterned soils of the Col du Noyer, Dévoluy (Hautes-Alpes)

4 The Dévoluy (Figure 1) is the highest of the French pre-Alpine massifs. A large part of its crests and slopes are in a high-mountain range, especially on its southern flank, with the Bure plateau at an altitude of more than 2550 m and a total surface area of 4 km². Between the Northern Alps and the Southern Alps, this massif is located between the Vercors - to the west -, and the Écrins, - to the east. It borders the Hautes-Alpes, Isère, and Drôme departments. It is bordered to the east and north by the Drac valley and its tributaries, including the Ébron, to the south by the Petit Buëch and to the west by the Buëch valley and the Col de la Croix Hautean extension of the Trièves. The massif is organised along a long valley, drained by the Souloise, oriented N-S, and bordered by two high crests: to the west the Grand Ferrand (2 761 m) and the Obiou (2 789 m); to the east the ridge dominated by the Faraut mountain (2 568 m) and bordered to the south by the Bure plateau culminating at more than 2700m. This massif corresponds to a synclinal structure in sedimentary series culminating with the Senonian Cretaceous (Mesozoic era).

5 This massif is exposed to several climatic influences, from the north, and west, and from the upwelling of Mediterranean air. Its climate is theoretically linked to the transition between the northern and southern Alps, but the isolation and the N-S valley effect blocked to the south by the Bure plateau creates an atmosphere marked by heavy snowfall and cold conditions. This topographical arrangement creates a variety of bioclimatic conditions and makes the Dévoluy a territory rich in habitats and associated species. The Dévoluy is known for its remarkable flora with one third of the species of higher plants native to metropolitan France (Pteridophytes, Gymnosperms, Chlamydosperms and Angiosperms) including many endemics (*Carduus aurosicus* Chaix 1785, *Iberis aurosica* Chaix 1785). These exceptional characteristics contribute to various designations including Natura 2000.

Figure 1: Location of the Col du Noyer, Dévoluy, France



Map of the Dévoluy and its regional context (1. ridge line, limestone crests; 2- summits; 3. rivers); B- The south-east of the Dévoluy; C- The Col du Noyer (arrow and point A: location of the polygonal grounds); D- The polygonal grounds on the south side of the Col du Noyer.

Credits : (A) P. Pech ; (B) © IGN-Géoportail ; (C) © IGN-Géoportail (D) Photo E. Hustache.

6 The massif thus has an original configuration which has a certain isolation because it is only open to the north by the Souloise pass, to the south-west by the narrow valley of the Béoux and to the east at the level of a single pass equipped with a road, the Col du Noyer. The Col du Noyer, 1,664 m in altitude, corresponds to the lowering of the axis of the eastern ridge and forms the junction between the heart of the Dévoluy and the Drac, to the east. This pass, between Champsaur and Dévoluy, is dominated by rocky walls still affected by scree slopes but having produced slope deposits that have been altered by solifluction and avalanches. These inherited slope forms are dominated by vegetation. The lower slopes are therefore made up of gently sloping landforms often occupied by pastoral routes like most of the slopes of the Dévoluy, one of the agricultural specialties of which is sheep breeding. However, this pass, which is considered one of the great Alpine passes, is very popular, not only with hikers during the summer period, but also with motor vehicles, quads, motorcycles or cars, which use the gentle slopes of the pass. In addition, there is the increase in traffic and trampling and even the occupation by cars during large media events such as the Tour de France or other cycling races and the Monte Carlo Rally. It is at the level of this pass, opposite the restaurant and Napoleon refuge that the fossil polygonal grounds were identified in 2016, by the Natura 2000 animator, Eric Hustache, attached to the SMIGIBA, *Syndicat Mixte de Gestion Intercommunautaire du Buëch et de ses Affluents* (Joint Syndicate of Intercommunity Management of the Buëch and its Tributaries). He proceeded to contact and gather the researchers, - geographers and ecologists - who worked

together to produce this paper, the purpose of which is to highlight the scientific interest of the site.

Study methods

7 Our objective was to determine whether these are indeed inherited polygonal grounds, because the altitude does not allow the expression of currently active periglacial processes. However, the objective is also to explore whether or not these polygonal grounds are interesting habitats for their floristic biodiversity. This global approach to the natural environment, or geoecological approach (Stallins, 2006; Pech et al., 2007; Huc, 2008; Pech, 2013) involves two types of methods: morphopedological, morphometric and anthracological methods, and plant ecology methods. The approach consisted in analysing the entire slope on which the polygonal grounds were inventoried, and focusing in on three polygonal grounds in order to study the geoecological parameters selected.

Morphopedological, morphometric and anthracological analysis

8 The approach consisted in listing and mapping polygonal ground forms and then focusing on three morphopedological units. A polygonal grounds map at the Col du Noyer was produced by photo-interpretation from high-precision ortophotography from IGN using QGIS 2.18 LTR - Las Palmas (2018) software. These data made it possible to create an exhaustive census of the polygons and to produce a descriptive statistical analysis. Morphometric parameters and topographic profiles (Fig. 2 and Fig. 3) were taken on three polygons chosen for their significance in the population surveyed. Precise topographic sections were made on the three polygonal grounds selected in order to specify the surface morphology and compare it with the data from the floristic surveys.

9 In order to take samples for the production of a thin blade as well as samples for anthracological analysis, a limited soil pit was dug at the junction of two polygonal grounds, approximately 80 cm deep and 2 m long by 50 cm wide (Fig. 4). The aim was to remove portions of soil from this pit for granulometric analysis, thin blades for micromorphological analysis and an exploratory anthracological analysis to document the site's past forest history (Fig. 4). The samples were taken without disturbing the soil topography, which was reconstructed after a cross-sectional study: in two years, the site's physiognomy had been reconstructed.

Figure 2: Location of the three polygonal grounds selected for the analysis of morphopedological and floristic parameters, Dévoluy, Col du Noyer

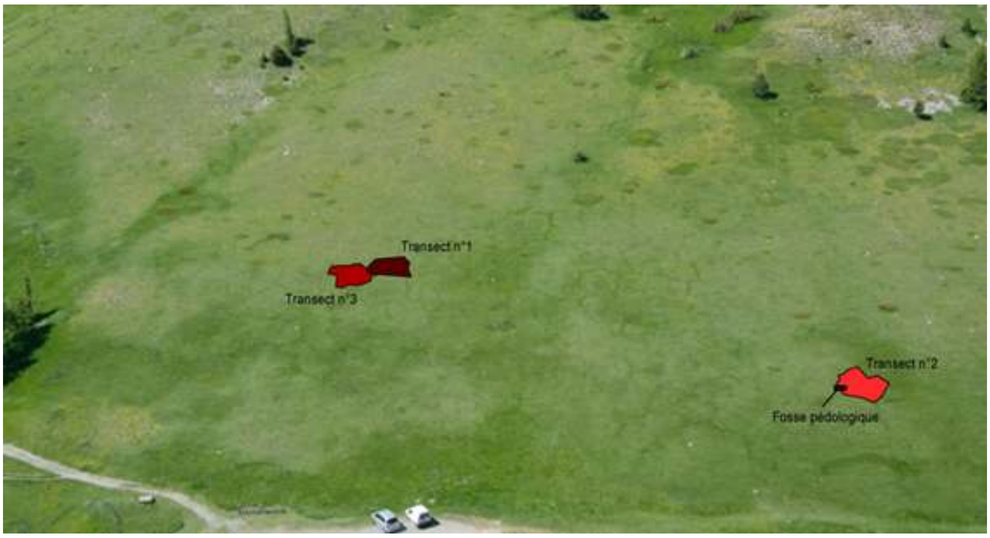


Photo M. Ajinca.

Figure 3: Morphotopographic parameters recorded on the three polygonal grounds, Dévoluy, Col du Noyer

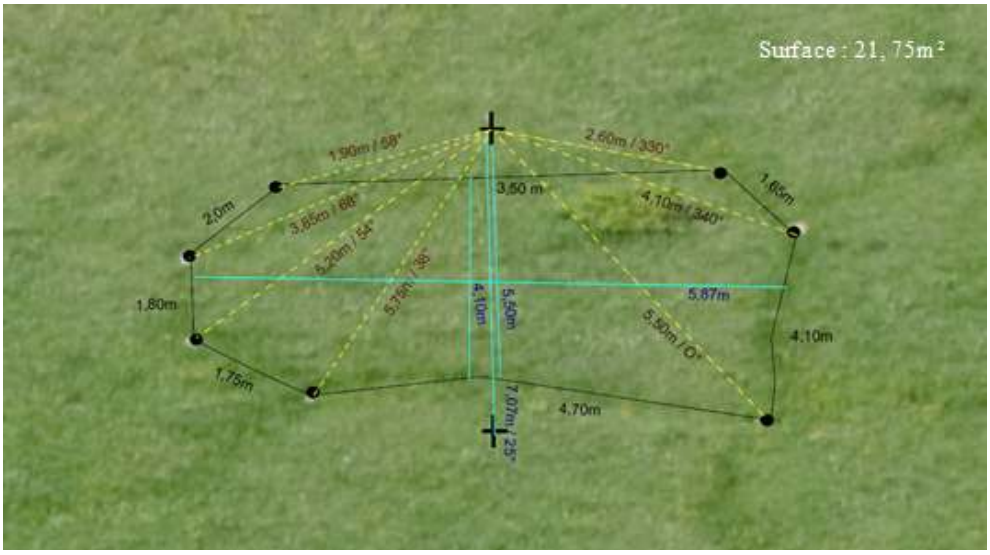
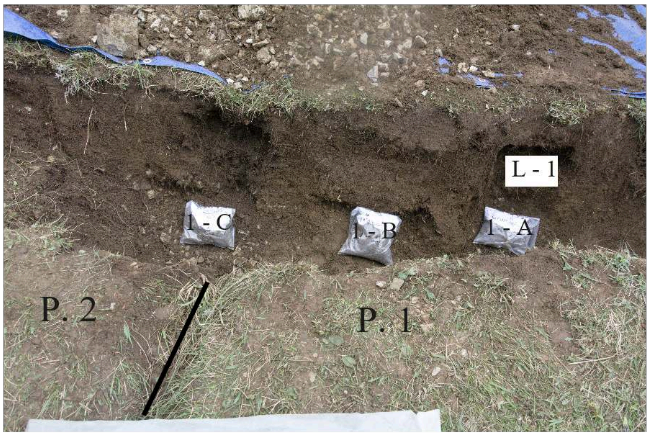


Photo M. Ajinca.

Figure 4: Soil pit at the junction of two polygons, with a view of the samples for granulometric analysis, Col du Noyer



L1. Samples for thin blades; 1-A, 1-B; 1-C. Samples for granulometric study; P1 and P2 and black line: limit between two polygons, samples for anthracological analysis.

Photo: M. Ajinca, 23/05/2018.

10 For the micromorphological analysis, we collected a soil sample at a depth of 50 cm in an airtight plastic box (Fig. 4). The protocol consisted of dehydrating the sample in an oven at 100°C and then impregnating it in a resin according to the protocols recommended by soil scientists (cf. *L'analyse du sol, échantillonnage, instrumentation et contrôle*, 1998, Pansu M., Gautheron J., Loyer J-Y., Paris, Masson, 513p.). After impregnation, the resin blocks were sawn and polished and then observed with a binocular magnifying glass. The photos were taken at 40x magnification. Particle size analysis, carried out within UMR LGP 8591, made it possible to determine the size of the elements making up three samples taken from the pit (Fig. 4).

11 The anthracological analysis was carried out at the UMR IMBE in Aix-Marseille (UMR CNRS 7263-IRD 237) by Brigitte Talon, who took two separate samples from the pit: the first in the centre of the polygon (sample P 1 at three different depths: 10-20, 20-30 and 30-40 cm) and the second (corresponding to 1-C in the photograph in Fig. 4) at the edges (sample P 2 at 0-10 cm and 10-20 cm depth). These samples were sieved with water on a column of 3 sieves (2 mm, 800 µm and 400 µm) and the coals extracted by flotation and dried (Talon, 2010). About a hundred fragments were collected and half of them identified by episcopic microscopy.

Analysis of the flora on polygonal grounds

12 The analysis of the flora on polygonal grounds aims to determine the role of these soils as habitats. It includes an analysis of the floristic diversity of polygonal grounds and a physiognomic analysis of the plants. The analysis of the floristic data was carried out using two indices, the Shannon index and the Sörensen index.

13 The Shannon index expresses the diversity of species that make up the flora in an environment (Konopinski, 2020). Its formula is:

14 $H' = -\Sigma [(ni/N) \times \log_2 (ni/N)]$

15 where H' represents the specific diversity, Σ is the sum of the results obtained for each of the species present, *ni* is the number of species i in the environment studied, N is the total number of individuals considering all the species, and $\log_2$ is the logarithm in base 2. This index makes it possible to quantify the heterogeneity of a site and its species richness. On 11 July 2020, Pierre Pech carried out 24 surveys on 1m x 1m quadrats, 12 on the three polygons studied and 12 on three sites located on the lawns above the polygons (Fig. 2). The quadrats on the polygons were deliberately placed by integrating one of the borders of each polygon.

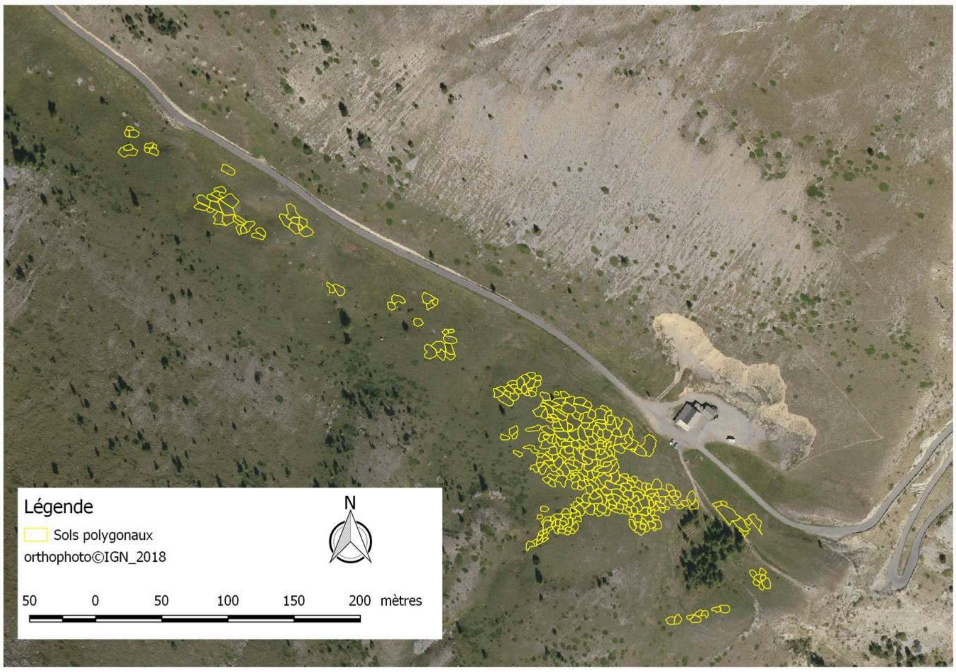
16 The Sörensen similarity index is = 2c/ (S1+S2), where 2c is the number of species common between the two samples, S1 is the total number of species present in the first sample, S2 is the total number of species present in the second sample. The Sorensen index is a simple measure of biodiversity. This coefficient varies from 0 to 1 and has a value of 0 when there are no common species between the two samples and a value of 1 when the two samples have exactly the same species. A weak similarity results from a difference in the composition and physiognomy of the vegetation, and vice versa for a strong similarity. This similarity coefficient makes it possible to quantify the degree of association of two entities. Contrary to other similarity indices, this one weights the term co-occurrence by 2. It is also an asymmetrical similarity index. In other words, it does not consider the double absence of the same species in two distinct samples to be a resemblance, unlike symmetrical similarity indices (Chao *et al.*, 2006).

17 Three transects divided into 5 quadrats of 50 cm by 50 cm were carried out on 3 polygons of the Col du Noyer (Fig. 2) by Sylvain Abdulhak, botanist (CBNA) in June 2018. For each polygon a quadrat was placed in the middle, two quadrats at the edges and the other two in an intermediate position between the middle and the edges. These transects were coupled with surveys of average vegetation height. The aim was to determine the coefficient of abundance of each plant at different positions in a polygon in order to know whether its microtopography determines the physiognomy and composition of the floristic procession. To verify this hypothesis a statistical treatment is carried out. Our hypothesis is that the microtopography of polygonal grounds has an influence on the heterogeneity of the floristic procession. The border quadrats (Q1 and Q5) should be the most similar to each other and the peripheral quadrats (Q2 and Q4) as well. The Sörensen index was used to test this hypothesis.

Results

Morphopedological and anthracological analysis of polygonal grounds

Figure 5: Location by photo-interpretation of the polygonal grounds of the Col du Noyer (Dévoluy, Hautes-Alpes)



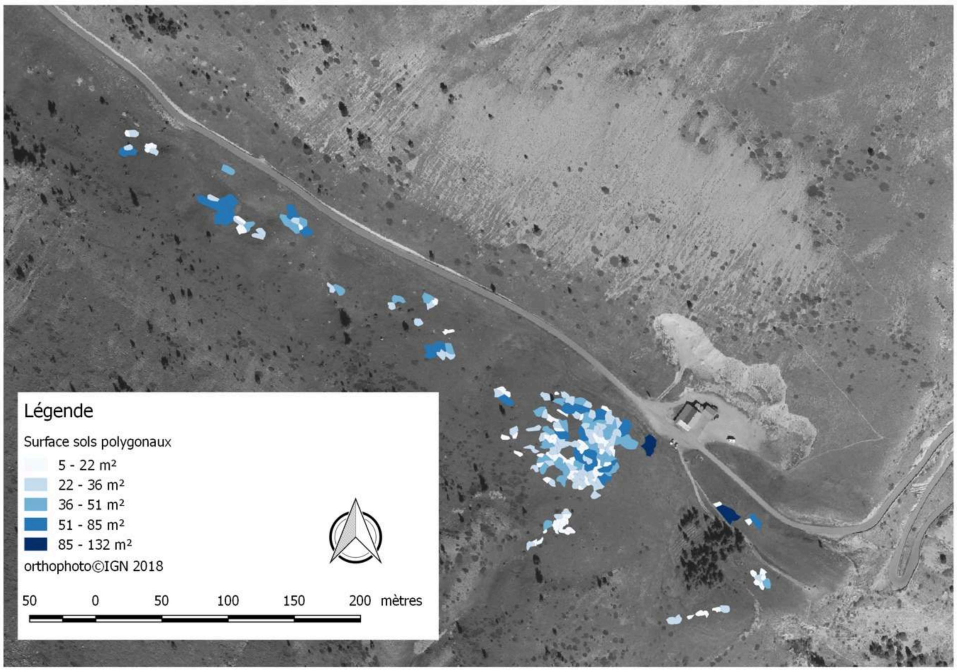
Geographical coordinates of the pass with the Napoleon refuge: Lat. 44,692073°; Long. 5,986176°.
Credit : Photo © IGN-2018.

18 The photo-interpretation analysis results in an inventory of 342 polygons mapped using QGIS software (Figs. 5 and 6). This software allows for the calculation of the areas and perimeters of the polygons whose data were collected in Table 1. We have added the diameter of the polygons. Some polygons are very large, (e.g. exceeding 80 m² and more than 5 m in diameter) but on the whole the data show the homogeneity of these polygonal soils, which are larger than the polygons currently active in the Alps: for example, the diameters of the polygonal grounds in the Upper Ubaye and Mortice valleys measure between 0.8 and 1.5 m in diameter (CNRS Caen, 1980).

Table 1: Average and median of the areas (S²), perimeters (P) and diameters (D) of the 342 polygons of the Col du Noyer (Hautes-France), calculated with QGIS software

	S²	P	D
Moyenne	28.8	22.7	3.6
Médiane	24.75	21.44	3.4
Ecart-type	17	7.3	1.2

Figure 6: Distribution of polygonal grounds with area categories (mapping carried out with QGIS)



Credit : photo ©IGN-2018.

19 Micromorphological analysis of thin-sheet (Fig. 7) soil samples reveals a compact silty aggregate structure of granular type related to cryoturbation (Pissart, 1969 ; Van-Vliet, 1982, 1995; Frenot *et al*., 1995).

Figure 7: Thin vertically oriented blade of a soil sample from a polygon at the Col du Noyer, Dévoluy, Hautes-Alpes

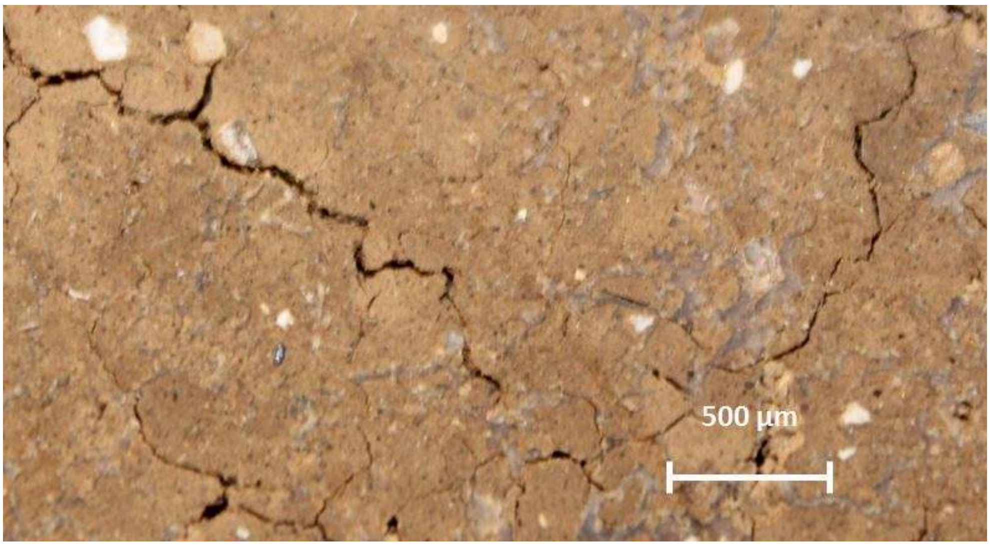


Photo P. Pech.

20 The particle size analysis is presented in Table 2. It is clear that there is a sorting of the sediments. Coarser rocks such as pebbles are concentrated in the edges (63%) and are less present in the central part (23%). Conversely, there is an increasing gradient of fine

elements (silts and clays) from the edges (11.5%) to the centre (33.5%) where they are more abundant. In the central part, the conditions are therefore more favourable for the formation of ice lenses, which is logical as according to Van Vliet-Lanoë (1982 and 1995), silts have a maximum capacity for ice segregation. These soils are thus able to swell because they retain water better, which increases their susceptibility to frost. On the other hand, sands and gravels have a minimal potential for ice segregation. From these results it can be concluded that in this polygon there is a sedimentary sorting from the centre to the edges (D'Amico *et al.*, 2019).

Table 2: Granulometric analysis of 3 soil samples taken from the Col du Noyer in a polygonal ground, from the centre (G1 A) to the periphery, at the level of the cracks (G1 C) and in between (G2 B)

Samples	**Total weight (g)**	**Fraction weight > 20 mm (g)**	**Weight fraction between 20 mm and 2 mm (g)**	**Weight fraction between 2mm and 50 µm**	**Weight fraction < 50 µm (g) deducted**	**Fraction weight < 50 µm (g) weighed**	**Recovered weight**
G1A centre of polygon	685.43	158.94	21.49	23.81	287.19	230.23	628.47
G1B	1,204.03	332.99	277.72	38.05	555.27	292.3	941.06
GIC edge of polygon	1,098.23	695.94	274.48	6.93	121.18	126.68	1103.73

21 Anthracological analysis of samples P1 and P2 enabled the analysis of about a hundred small charcoals, ranging in size from 2 mm to 400 µm. 54 were precisely identified, the others being indeterminable, either because of their size or because of their state of conservation. These charcoals mainly come from coniferous species: fir (*Abies alba* Mill.), pine, *Pinus* "*sylvestris/uncinata* type" (to date, it is not anatomically possible to distinguish Scots pine from mountain pine) and juniper (*Juniperus* sp.). One notes also the presence of an identified maple charcoal (*Acer* sp.) in the upper level P1.

Table 3: Anthracological analysis of the 5 soil samples taken at the Col du Noyer, in polygonal ground, in the centre (P1) and at the level of the cracks (P2)

		Abies	*Pinus t. sylv/ unc.*	*Juniperus*	*Acer*	Softwood	Hardwood	Not identifiable	*Total*
P1	10-20 cm	9			**1**		2	3	*15*
	20-30 cm	10					3	3	*16*

	30-40 cm	4	4			3	2	21	*34*
P2	0-10 cm	8	5	6		1	1	2	*23*
	10-20 cm	3	3	1			1	4	*12*
	TOTAL	*34*	*12*	*7*	*1*	*4*	*9*	*33*	***100***

22 These results reveal the past presence on the site of several tree species, such as *Abies*, which was well represented in both samples, and *Pinus* t. *sylvestris/unicinata* and *Juniperus*, which are slightly more frequent in P2. Is it by chance that fragments of *Juniperus* were only found at the edges of the polygon (sample P2) and *Acer* in the centre (sample P1)? It is unfortunately not possible with so little anthracological material and only one sampled pit to attempt a more robust interpretation of these initial results. However, this exploratory analysis confirms the potential of the discipline implemented and the paleoecological interest of the site in terms of reconstructing the consequences of human activities on past vegetation.

Floristic analysis

23 This analysis aims to determine whether polygonal ground has an impact on the flora. All the environments around the ground consist of grasslands (Fig. 2). The floristic surveys were established in two stages, one to determine the alpha biodiversity calculated using the Shannon index and the other for the beta biodiversity using the Sörensen index. The analyses are supplemented by heights of the herbaceous stratum.

24 For the data and calculations used to calculate the Shannon indices, according to Table 4 (Tab. 4), it is easy to see that the values are higher on polygonal grounds than on grassland outside the polygon areas (Fig. 2).

Table 4: Shannon index values for the three polygons studied (P1, P2, P3) and for three sampled sites in the grassland (Fig.2)

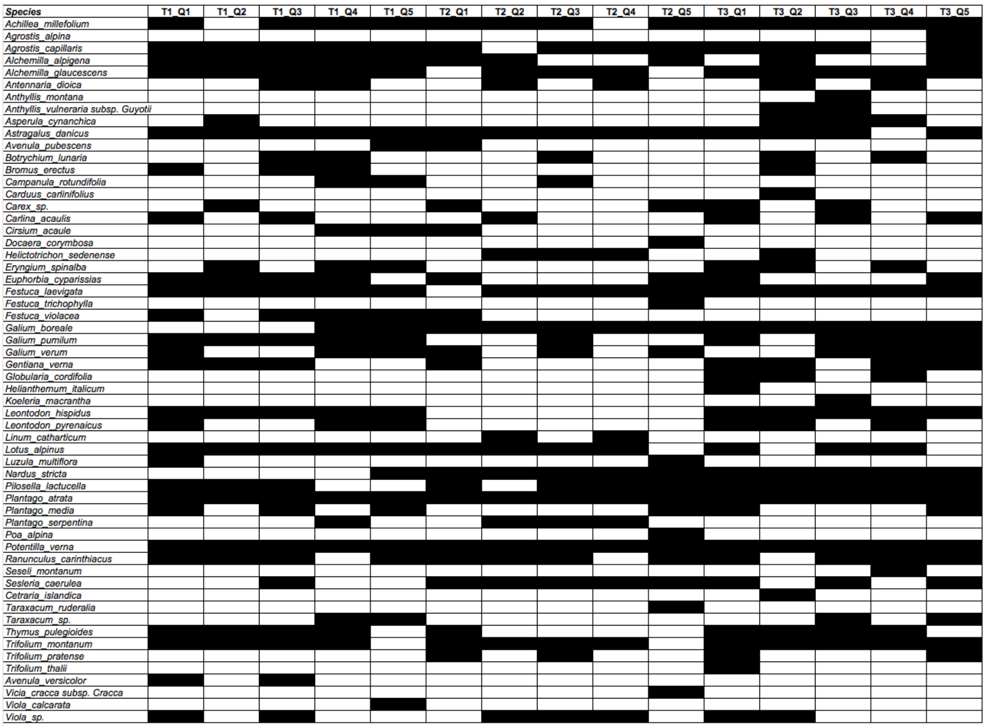
P1		A	B	C	D	Total
	N	21	23	26	22	92
	ni / N	0.22826087	0.25	0.2826087	0.23913043	
	$\log_2$ (*ni* / N)	-2.13124453	-2	-1.82312224	-2.06413034	
	H'=shannon	-0.48647973	-0.5	-0.5152302	-0.49359639	1.99530631
P2		A	B	C	D	Total
	N	23	25	26	22	96
	ni / N	0.23958333	0.26041667	0.27083333	0.22916667	

	$\log_2$ (*ni* / N)	-2.06140054	-1.94110631	-1.88452278	-2.12553088	
	H'=shannon	-0.49387721	-0.50549644	-0.51039159	-0.48710083	1,99686606
P3		A	B	C	D	Total
	N	26	21	22	25	94
	ni / N	0.27659574	0.22340426	0.23404255	0.26595745	
	$\log_2$ (*ni* / N)	-1.85414913	-2.16227143	-2.09515723	-1.91073266	
	H'=shannon	-0.51284976	-0.48306064	-0.49035595	-0.50817358	1.99443993
S1		A	B	C	D	Total
	N	11	21	7	8	47
	ni / N	0.23404255	0.44680851	0.14893617	0.17021277	
	$\log_2$ (*ni* / N)	-2.09515723	-1.16227143	-2.74723393	-2.55458885	
	H'=shannon	-0.49035595	-0.51931277	-0.4091625	-0.43482363	1.85365485
S2		A	B	C	D	Total
	N	9	11	18	7	45
	ni / N	0.2	0.24444444	0.4	0.15555556	
	$\log_2$ (*ni* / N)	-2.32192809	-2.03242148	-1.32192809	-2.68449817	
	H'=shannon	-0.46438562	-0.49681414	-0.52877124	-0.4175886	1.9075596
S3		A	B	C	D	Total
	N	6	8	21	3	38
	ni / N	0.15789474	0.21052632	0.55263158	0.07894737	
	$\log_2$ (*ni* / N)	-2.66296501	-2.24792751	-0.85561009	-3.66296501	
	H'=shannon	-0.42046816	-0.4732479	-0.47283716	-0.28918145	1.65573466

Columns A, B, C, D correspond to the 4 quadrats in which the plants were sampled.

25 Figure 8 shows the presence and absence values of the plant species determined on all three transects carried out on the polygonal grounds included in our analysis. Sörensen index calculations were performed on the three quadrats studied on the three polygonal grounds selected. The aim is to cross-check the results to verify the similarity of the analysed samples in relation to the location in the polygons.

Figure 8: Distribution by presence-absence of the species recorded on the five quadrats carried out on three transects on the three polygonal grounds of the Col du Noyer (Hautes-Alpes)



Q1 and Q5 correspond to the edges of the polygonal grounds; Q3 corresponds to the centres of the polygonal grounds.

Realization : P. Pech, M. Ajinca, S. Abdulhak, E. Hustache, L. Simon, B. Talon.

26 According to Table 5, the similarities are generally strong on these polygonal grounds. However, species are most homogeneous on the central parts of the polygonal grounds. The similarities are weakest when comparing the border and centre quadrats of the polygonal grounds. There is an impact of polygonal ground morphology on plant distribution.

Table 5: Sörensen similarity indices calculated on polygonal grounds of the col du Noyer (Hautes-Alpes)

	T1Q1	T1Q2	T1Q3	T1Q4	T1Q5
T1Q1	1	0.696	0,741	0,692	0,64
T1Q2	0.696	1	0,667	0,609	0,545
T1Q3	0.741	0.667	1	0,704	0,577
T1Q4	0.692	0.609	0,704	1	0,76
T1Q5	0.64	0.545	0,577	0,76	1
	T2Q1	T2Q2	T2Q3	T2Q4	T2Q5
T2Q1	1	0.537	0,636	0,513	0,636

T2Q2	0.537	1	0,732	0,833	0,488
T2Q3	0.636	0.732	1	0,769	0,545
T2Q4	0.513	0.833	0,769	1	0,462
T2Q5	0.636	0.488	0,545	0,462	1
	T3Q1	T3Q2	T3Q3	T3Q4	T3Q5
T3Q1	1	0.643	0,704	0,692	0,755
T3Q2	0.643	1	0,577	0,72	0,549
T3Q3	0.704	0.577	1	0,667	0,735
T3Q4	0.692	0.72	0,667	1	0,596
T3Q5	0.755	0.549	0,735	0,596	1
average	Average Q1	Average Q2	Average Q3	Average Q4	Average Q5
Average Q1	1	0.625333333	0,693666667	0,632333333	0,677
Average Q2	0.625333333	1	0,658666667	**0,720666667**	***0,527333333***
Average Q3	0.693666667	0.658666667	1	**0,713333333**	***0,619***
Average Q4	0.632333333	**0.720666667**	**0,713333333**	1	***0,606***
Average Q5	0.677	***0.527333333***	***0,619***	***0,606***	1

Quadrats Q1 and Q5 correspond to the edges of the grounds and Q2, Q3 and Q4 correspond to the centres. Values in regular bold are the highest and values in bold italics correspond to the lowest.

Discussion

27 The interpretation of the data prompts considerations of the morphodynamic context. The flatlands concerned by these polygons are located in a context of classic flat slope deposits under rocky ledges largely dominated by Tithonian limestones producing, above all, scree slopes made up, sectionally, of congelifracts organised in alternately thin lenses, of coarse and greasy structure, containing a fine matrix with a more abundant silty-sandy texture. In their distal part, these scree cones are relayed by formations with gentler slopes (less than 10-15°) where polygons are developed. In cross-section and in micromorphological analysis, the concentration of silts shows an action of the segregation ice (Washburn, 1979; Van Vliet, 1982 and 1995; Frenot *et al.*, 1995). This segregation ice also acts in the transfer of coarse elements to the superficial part of the formation (Pissart, 1969; Van Vliet, 1982 and 1995; Frenot *et al.*, 1995). Organisational elements are here recognised as characteristic of periglacial conditions (Pissart, 1969; Washburn, 1979; Van Vliet-Lanoë, 1982 and 1995; O'Neil and Burn, 2012).

These follow reworking of the fines in the distal parts of the scree slopes, but they bear witness to the action of active periglacial conditions over a sufficiently long period of time to have allowed the migration of the coarse elements on the surface of the polygons under the effect of cryoexpulsion (Van Vliet-Lanoë, 1982 and 1995; Frenot *et al.*, 1995). In the genesis of polygonal grounds, the processes are dominated by the action of frozen water in the porosities (Washburn, 1979). This segregating ice also acts by reorganising the soil, which undergoes a granulometric sorting that concentrates a high proportion of fine elements (sands, silts, clays), in the upper part. On the surface, the blocks are lifted by ice needles which encourage migration towards the edges of the polygons made up of frost-related cryodrying slits (Van Vliet, 1995). Cryogenic bulging is preferentially done in the central part of the soils where the fine elements are located. Conversely, on the edges, cryodessiccation slits are found where coarse elements, especially blocks, accumulate (Pissart, 1969; Van Vliet, 1982 and 1995; Frenot *et al.*, 1995).

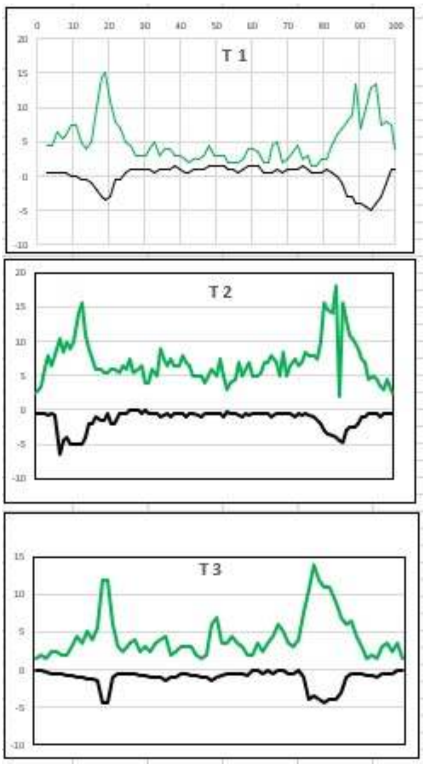
28 The topography of the soils of the Col du Noyer and the results of the granulometric analyses confirm that these are polygonal grounds. But they are inherited polygonal grounds. Polygonal grounds result from a complex of frost actions in the soil (D'Amico *et al.*, 2019) under periglacial conditions that do not exist to this extent in the Alps at present. By comparison, the polygons currently recorded in the Alps are smaller, of the order of a few m^2 (CNRS Caen, 1980; D'Amico *et al.*, 2019). The establishment of polygonal multi-metre soils corresponds to cold climatic conditions with the formation of deep permafrost (D'Amico *et al.*, 2019), which prevailed during the last Pleistocene glaciation, known as the Würm in the Alps (Montjuvent, 1973). While it is certain that the Alps, in the sector studied, were very largely glaciated during these phases, the Durance glacier passed to the south-east of the Devoluy (Jorda *et al.*, 2000) sending a transfluence into the Isère basin via the Bayard pass, the Drac passed to the east, below the Col du Noyer and apart from an ice cover limited to the Bure plateau and the valleys descending from it, the reliefs of the Dévoluy, including the Col du Noyer, were not glaciated but were strongly subjected to periglacial conditions (Montjuvent, 1973). Studies carried out at Séchilienne, south-east of Grenoble, in the Belledonne massif located a few kilometres from the Dévoluy, have suggested that 21,000 years ago the average air temperature ranged -8° C to -10° C (Lebrouc *et al.*, 2013), thus associated with deep, continuous permafrost (Lebrouc *et al.*, 2013). In some places, not glaciated, there were open landscapes, marked by intense periglacial activity. The slopes of the Col du Noyer could therefore have been subject to a periglacial context with thick permafrost at the height of the glaciation. The polygons are therefore no longer functional, inherited from the last coldest phase of the ice age, around 20,000 years ago (Jorda *et al.*, 2000; Lebrouc *et al.*, 2013). They are witnesses to this.

29 In the post-glacial period, warming is fairly rapid, especially after -10,000 years (Jorda *et al.*, 2000) and results in the development of an open forest initially consisting of pines and shrubs, before giving way to firs from -9,000 years onwards (Muller *et al.*, 2007). The fir forest, rapidly enriched with hardwoods, including maple, covers the slopes and polygons. Anthracological analyses confirm the presence of these different species, whereas the current landscape is made up of man-made lawns linked to the development of pastoralism attested at Lus-la-Croix-Haute 5000 years ago by traces of burning and the increase in pollen markers of anthropisation (Argant, 2004). Absolute dating of a few charcoals is envisaged to enable the reconstruction of the chronology of

forest recolonisation before the clearings and to establish links with the data observed at the Lus-la-Croix-Haute pass. Indeed, it was the clearings linked to the development of pastoral activity (Jorda *et al.*, 2000; Argant, 2004) that revealed these landscapes of inherited polygonal grounds that have persisted despite the successive development of forest cover and then clearings. However, do these polygonal grounds, which are very present, have an impact on the vegetation landscapes?

30 Floristic analysis shows that, at polygonal ground level, the heterogeneity of the microtopographies and their granulometric compositions favour a diversity of species. This confirms that polygonal grounds play a favourable role for biodiversity. The microtopography of polygonal grounds does indeed have an influence on the floristic procession. According to Figure 9, the average height of vegetation is greater at the edges of polygonal grounds. At the edges of the polygons, there is a predominance of Poaceae, and more perennial plant species in the centre of the polygons. Moreover, according to the results of the Shannon biodiversity index analysis (Table 4), the number of species is generally lower on the lawn surrounding polygonal soils. This proves that polygonal grounds play a favourable role in hosting a more diverse flora. The polygon cores, made of silt, and the slits filled with blocks and gravel, constitute micro-habitats that host a variety of species, much more varied than on the lawn on the rest of the slope. The biodiversity index is higher on polygonal grounds.

Figure 9: Topographic profiles and plant heights along transects carried out on the three polygonal grounds of the Col du Noyer, Dévoluy



Green curves: variations in plant height; black curves: variations in soil topography.
Realization : P. Pech.

31 For the Col du Noyer, there is therefore an original complex forming an exceptional geomorphosite allowing the observation of relict polygonal grounds. These soils are

also responsible for a biodiversity linked both to the high diversity of plant species and to the heterogeneity of their assembly in the microhabitats defined by the polygons.

Conclusion

32 Periglacial mountain landscapes, whether active or inherited, bear witness to environmental conditions, particularly climatic conditions, past or present, but also to their ongoing evolution (Feuillet, 2010; Feuillet and Sourp, 2012). The ROCVEG programme aims to identify, monitor and preserve some of these periglacial environments in the Alps (Bollati *et al.*, 2015). Polygonal grounds are rare in the Alps (D'Amico et al., 2019). Although there are still active polygons in the Alps at altitudes above 2500 m, such as in the Hautes-Alpes, at the foot of the Vautisse ridge in the Écrins or at the crest of La Mortice in the Queyras, or even on the Bure plateau in the Dévoluy, they are limited to rare sites. Their current dynamics deserve to be integrated into the network of monitored and protected periglacial forms and landscapes (Feuillet, 2010; Feuillet & Sourp, 2011).

33 Relict landscapes are rare in the Alps and original (D'Amico et al., 2019). Their preservation represents a challenge for understanding the presence of cold, periglacial environments extended during the glacial phases to altitudes with a currently more temperate climate (Bridgland, 2013; Palma *et al.*, 2017). The example of the Col du Noyer, located at an altitude of 1664 m, is a rare conservation of the past conditions for the formation of polygonal grounds. Following what various authors have shown about geological and geomorphological sites (Duval & Gauchon, 2010; Reynard *et al.*, 2011; Feuillet, 2010; Feuillet and Sourp, 2011), these polygonal grounds deserve protection and scientific and educational appreciation.

34 We have shown that these polygonal grounds are currently favourable to a greater floristic diversity than the surrounding lawn environment, which is known to be linked to land clearing and pastoral activity (Argant, 2004). It is therefore possible to develop an integrative approach in which the effects of a good state of the natural environment (Kazuhisa *et al.*, 2018) play a reciprocal role, acting, at the col du Noyer, both to preserve the inherited polygonal grounds and the rich and original forms of the floristic layout. For many authors (Bollati *et al.*, 2015; Dubois *et al.*, 2015), considering all the components, including the abiotic context, reinforces the optimisation of the conservation management of ecosystems, ecosystem functions and services. It therefore seems important to develop multi-criteria and multidisciplinary observations to highlight the value of these complex sites (Parks and Mulligan, 2010), particularly those that combine ecological and geomorphological heritage value (Brown et al., 2018). The polygonal grounds of the Col du Noyer have a heritage dimension. There is a need to work in partnerships with researchers and managers, local development operational staff and nature conservationists, around these elements - geomorphological forms and biodiversity - including ordinary ones. Promoting the heritage of polygonal grounds that are still active in the Alps seems urgent because their surface area is reduced and in this respect they are sentinels of ongoing environmental changes (Reed *et al.*, 2016). Equally important is the heritage development of these same inherited formations. They bear witness to past climate change in the Alps and provide information on the positive impacts that these

paleoforms can have on the flora and on a certain biodiversity, even ordinary biodiversity.

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RÉSUMÉS

At an altitude of 1664 m, the Col du Noyer in the French Dévoluy Mountains, which is accessible in summer by road, is one of the most popular Alpine passes. It was located in an unglaciated area during the last Quaternary ice age and suffered the effects of the severe frost. Polygonal grounds formations have recently been discovered. Our study presents the results of the identification and characterisation of these formations as well as the floristic assemblages that currently occupy them. The analyses, carried out by a multidisciplinary team, consist of photo-interpretation, geomorphological, sedimentological and pedoanthracological studies. They confirm the presence of these inherited polygonal grounds. Floristic surveys reveal that these inherited periglacial formations constitute original habitats, favouring a strong local heterogeneity. The whole constitutes a natural complex requiring protection. Enhancing the heritage value of this site would constitute a means of protecting this complex, which is a rare geomorphological landscape in the Alps: educational both in terms of its understanding and its paleoenvironmental interpretation.

INDEX

Keywords : Polygonal grounds; geoecological assessment; nature protection; heritage enhancement

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