Periglacial environments and frozen ground in the Central Pyrenean high mountain area. Ground thermal regime and distribution of landforms and processes

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Abstract. The periglacial belt is located in the highest parts of temperate mountains. The balance between mean air and ground temperatures and the presence of water determine the effectiveness of periglacial processes related to permafrost, the active layer or seasonally frozen ground (SFG). This work puts together the thermal and geomorphological data obtained in four Pyrenean massifs, Infierno-Argualas, Posets, Maladeta and Monte Perdido, to improve knowledge on the occurrence and distribution of frozen ground. The methodology used is based on the study of landforms as frozen ground indicators, mapping processes, ground temperature analysis, basal temperature of snow, thermal mapping and geomatic surveys on rock glaciers and protalus lobes. In the Pyrenean high mountain areas the lower limit of frozen ground is at ~2,650 m a.s.l., possible permafrost appears above 2,650 m a.s.l. in N and S orientations and probable permafrost is dominant above 2,900 m a.s.l.. Unfrozen ground with cold-associated geomorphological processes reach 2,900 m a.s.l. and unfrozen and frozen ground distribution points to a patchy pattern throughout the periglacial belt. The most widespread frozen grounds are SFG. The thermal data -MAGT, cold season temperatures, BTS measurements, freeze/thaw cycles and distribution of landforms permit the establishment of a periglacial land system divided into three main belts: infraperiglacial, middle and supraperiglacial. The large number of processes and landforms that are involved and their altitudinal and spatial organization make up a complex environment that determines the geoecological dynamic of the high mountain areas.

Key words: periglacial belts, altitudinal distribution, high mountain, mountain permafrost, Pyrenees.

1. Introduction

The periglacial belt of the temperate mountains is located in the highest part of the mountain and the present-day landscape dynamics are dominated by glacial retreat, paraglacial activity and the gradual atmospheric cooling with altitude. The topoclimatic factors results in high-relief slope processes, with characteristic cascade systems that define alpine environments. Snow, water, ice and thermal changes determine surface processes, among which frozen grounds are one of the primordial elements of the periglacial belt of temperate mountains. Mountain permafrost is a complex cryogenic phenomenon defined by instability, high sensitivity to environmental changes and a highly heterogeneous spatial distribution pattern, topography, vertical and lateral variability in the local climate, snow cover distribution and surface and subsurface temperatures[1,2,3]. There is no full agreement on the main factors determining the distribution of frozen ground, seasonally frozen ground (SFG) or permafrost, in the mountains. These maybe either the solar radiation related to snow cover or the temperatures decline with altitude, but the relation between the mountain permafrost degradation and the increased air temperature and therefore its vulnerability to climate change has been observed[4], which raises the importance of knowledge of permafrost distribution.

Permafrost mapping is an important tool for gaining knowledge of the state and extent of mountain permafrost and has been applied in many mountain ranges. Permafrost distribution maps have been drawn up based on the combination of field observations and semi-empirical models[6,7,8,9,10,11,12] and are based on different classifications of permafrost (Table 1). Maps based on spatial classifications are useful for knowing the potential area the mountain permafrost extends to on a regional scale, whereas maps on a local scale are not common since they require evidence of permafrost, geoelectrical and thermal field data and the relationships among factors, applied by modelling[20].

Table 1

Frozen ground is highly sensitive to global warming and in this respect there are processes related to the active layer that increase natural hazards in the high mountain areas[14,2,5]. Mountain permafrost gives rise to singular thermal and hydrological conditions that create unique ecosystems. Detailed knowledge of which, in the case of the Pyrenees, would facilitate the incorporation of frozen grounds in the estimate of geodiversity, geoconservation management and resources for geotourism in protected areas and the high mountain.

The first contributions on the presence of periglacial landforms and processes in the Pyrenees come from geomorphological studies defining landforms, such as debris talus, nivo-karst, patterned grounds, solifluction lobes and rock glaciers[14,15,16,17,18,19]. Also, the presence of permafrost was confirmed by observation in the field[26]. In the 1980s significant progress was made in the study of the active periglacial processes through the analysis of rock glaciers[32,21,22,23,24], but it was not until the 1990s that studies began to deal with frozen grounds, mainly on mountain permafrost. Their study increased with the application of analysis and mapping of geomorphological indicators, ground thermal records, geophysical surveys, permafrost distribution mapping and the creation of empirical models[24,25,26,27,28,29] as well as ongoing observation of active periglacial processes[29,30,31,32,26,27,29,33,21]. Pyrenean permafrost was included in the permafrost map of the northern hemisphere[49]. In the 21st century periglacial processes are still monitored using geomatic techniques and detailed analysis of the activity and distribution of active rock glaciers and permafrost[34,36,37,38,39,40,41,13,41,42,43,44]. Synthetic mapping on a regional scale (1:300.000[37]) uses permafrost indicators (rock glaciers, gelifluction, ice caves, frost mounds, vertical electric soundings and thermal ground recordings), digital terrain models and modelling of basic parameters (Mean Annual Air Temperature -MAAT-, aspect, slope) that determine permafrost using the classification of possible or probable permafrost. These studies established the distribution of permafrost as being possible above 2,400 m a.s.l. in northern orientations and from 2,650 m in southern ones, though it may be present as low as 2,000 m a.s.l. under favourable topoclimatic conditions; probable permafrost above 2,700 m a.s.l. in northern orientations, whereas on south-facing slopes the lower limit is 2,800 m a.s.l.[37, 42]. Similar distributions have also been put forward, with possible permafrost from 2,800 m a.s.l. and probable from 2,900 m a.s.l.[13], or discontinuous permafrost over 2,600 m a.s.l. on north-facing slopes and 2,850 m a.s.l. on south-facing slopes[45].

The aim of this work is to put together the thermal and geomorphological data obtained from four Pyrenean massifs to improve the knowledge on the occurrence and distribution of frozen grounds and the altitudinal and morphodynamic definition of the

Pyrenean periglacial belts. In so doing, this research seeks the answers to three basic questions:

- How are frozen grounds distributed in the Pyrenees and what importance do they have as elements of the cryosphere?

- How important are frozen grounds in the periglacial landsystem of the Pyrenees and what are their key elements, thermal regime, landforms and processes associated?

- How do frozen grounds contribute to the morphogenic altitudinal zoning of the Pyrenees and provide a model for the temperate mountain of moderate altitude?

3. Study site: The Pyrenees.

The Pyrenees is a mountain range located in the north of the Iberian Peninsula (between 42° and 43° North latitude) which extends over 435 km (Figure 1). The study was applied in high glacial cirques of four Pyrenean massifs, Infierno (3,175 m a.s.l.), Posets (3,375 m a.s.l.), Monte Perdido (3,355 m a.s.l.) and Maladeta (Aneto peak, 3,404 m a.s.l.) located in the southern side of the central Pyrenees (Figure 2).

Figure 1.

The collision of the European and Afro-Iberian plates raised the Pyrenees, forming a central core, the axial zone, where the highest altitudes are located, formed by Paleozoic rocks (slates, schist, granites, marble, gneiss, hornfels, skarns and limestones). Two thrust systems were developed to the north and south of the axial zone, the southern one involving cover rock (sedimentary rocks, limestone, marls, sandstones)[46,47]. The Infierno is located in the axial zone, a folded massif of schists, marbles and slates; Posets, at the boundary between the granitic batholith and the contact metamorphism aureole; and Maladeta massif, situated in a wide granitic batholith. The Monte Perdido massif is a part of the Monte Perdido thrust sheet formed by a calcareous fold cascade reaching 3,335 m a.s.l. All massifs are on the southern slope in the Ebro river basin.

The central portion of the Pyrenees is in a Atlantic-Mediterranean transitional climate defined by the eastward transition from Atlantic to Mediterranean conditions, whose topographic heterogeneity explains the large spatial variability in annual precipitation and temperature distributions. The sites studied are located in the high mountain, where precipitations are >2,000 mm a^{-1} above 2,000 m a.s.l. and around 2,500 mm a^{-1} at the highest points[48]. Summer and winter are relatively dry, with snowfalls alternating with long anticyclonic periods[48]. Temperatures indicate a clear altitudinal gradient. Above 1,000 m a.s.l. the average annual temperature is less than 10ºC but at 2,000 m a.s.l. it is around 5ºC. The 0ºC isotherm varies among the massifs, and has been placed at different altitudes: 2,750 m a.s.l.[48], 2,780-3,000 m a.s.l.[13] and 2,950 m a.s.l.[49].

The Pyrenean high mountain occupies around 365 km^2, and makes up just 0.83% of the total surface, which ranges from 2,400 m a.s.l to 3,404 m[50,13]. It is a rocky high mountain environment dominated by the periglacial belt and just 19 small glaciers and ice patches[51], all of which are located in glacial cirques, all beneath summits of over 3,000 m a.s.l. The four studied massifs still contain active glaciers, four in Maladeta, two in Posets, one in Infierno and one in Monte Perdido[49,51,52].

Glaciers shaped the High Pyrenees during the Pleistocene glaciations, through glaciers longer than 40 km in the central portion during the Last Glacial Maximum (LGM)[25, 37, 35,52]. Features of the Dryas period are very important, and at least two stages with small glaciers shaped the highest cirques in the Late-glacial[27,53,54,55]. In the Little Ice Age (LIA) glaciers occupied cirques and fashioned moraine complexes[56,27,57,58]. Paraglacial and periglacial environments have occupied the high mountain for the last 12 ka[52], so all massifs studied have LIA moraine complexes and are in occupied areas by Dryas period moraine systems (Figure 2).

Figure 2.

3. Material and methods

The study of frozen grounds and related geomorphic processes have been made using different techniques such as geomatic surveys, continuous dataloggers, bottom temperature snow (BTS) measurements and thematic mapping (geomorphological and thermal) in the four studied Pyrenean massifs (Table 2). Previously published data are the BTS measurements of the Posets massif[59] and measures on rock glacier dynamic, displacement and thinning[30,36,60,61], where new data from years after 2011 have been incorporated.

Table 2

- Landforms and mapping processes. Four geomorphological maps of Infierno, Posets, Maladeta and Monte Perdido have been made on a 1/10,000 scale, on which all periglacial and active processes are represented. All of them are based on the Numerical Cartographic Base 1:25,000 (BCN25) of the National Topographic Map (MTN25). For the field work a digital terrain model (MDT) at 5 m resolution and aerial photography were used. The graphic representation is based on the symbols and colours assigned to each morphogenetic system[62], although only periglacial processes and landforms are used as indicators on the maps of frozen ground. The landforms used as indicators of frozen ground were rock glacier, protalus lobes, debris lobes, frost mounds and patterned ground, all of them characteristics of periglacial landsystem[63]. A periglacial landsystem can be defined as the set of processes, landforms and sediments associated with changes in water status and frozen ground in polar, upland or periglacial mountain environments[63], where the last one can divided in altitudinal belts.

- Ground temperatures (GTS): The ground thermal regime was monitored between 2010 and 2016 by means of 37 continuous dataloggers (Ibuttons DS1922L and DS1921G) distributed between 2250 and 3070 m a.s.l. and placed at depths between 2 to ~10 cm, depending of existing surface formation, in the Infierno (3 units), Posets (5 units), Maladeta (11 units) and Monte Perdido (18 units) massifs. A thermoregister recorded data at four-hour intervals within a thermal range of -40 and +85°C and with a resolution of ±0.5°C. The data obtained revealed the ground thermal regime so that the evolution and thermal periods of the ground and possible existence of frozen grounds could be established[64,65].

Several parameters were used in this work. The Mean Annual Ground Temperature (MAGT) indicative of the existence of permafrost when ground temperature is <0°C throughout the year[66]. The mean cold period ground temperature (MWGT), complementary of the basal temperature of the snow measured in March, is an indicator of the presence of frozen ground when between <-2°C and <-6ºC, seasonal frozen ground (SFG) when temperatures are between 0ºC and -2ºC, and freeze-thaw processes and unfrozen ground, when temperatures are at ~0°C or moderately negative at ~-1°C[89,90]. The freezing index (FI index) and freeze/thaw cycles facilitate the quantification of the cooling of the ground and are used to indicate the presence of SFG and the geomorphological effectiveness in the top 10 cm of the ground[69].

- Basal temperature of the snow (BTS) measurements. Over the last ten years the BTS has been measured in March in all the massifs studied, totaling 290 BTS measurements. Two steel probes (2 m length) were used together with a sensor at the tip connected to a RTD thermometer “PHD 2307.0 Delta” with a precision of ±0.2°C (-120 to 200°C) and ±1°C (exterior). Thermal profiles of the snowpack were made in all studied areas to know the thermal structure and changes in snow depth. BTS is a very common technique for the detection of permafrost conditions in the ground and it has been shown to be a useful method for the indirect detection of permafrost[6,67,70]. Some studies have demonstrated a high dependence of BTS measurements on the characteristics of the snow cover itself[71] and some dysfunctions in locating permafrost by applying geophysical techniques and BTS[72]. BTS measurements are commonly used to determine ground surface temperatures and to identify areas of homogeneous thermal behaviour[70,72]. The technique is especially useful when the measurement between snow and ground can be compared with GTS obtained by continuous dataloggers.

- Thermal mapping. Four thermal maps have been made in the studied areas[41,13] at 1/10,000 scale. Thermal maps represent the thermal conditions of the grounds according to GTS and BTS measurements and include information deriving from landforms and processes as indicators. The four maps show the distribution pattern of frozen grounds and probable permafrost, possible permafrost, SFG and unfrozen ground. Thermal data and frozen ground indicators were integrated with GIS techniques[37,73]. A DEM that integrates data of altitude, slope, orientation and exposure and the annual solar radiation rate to know the effects of the topoclimatic factors[73], thermal information (BTS and GTS), the 0°C and -2°C isotherms, and the indicative landforms of SFG or mountain permafrost in the Pyrenees (rock glaciers, protalus lobes, debris lobes, frost mounds, patterned ground) were added.

- Geomatic surveys. At sites of frozen ground at different altitudes, surface displacement was monitored by GPS-RTK and Terrestrial laser scanner (TLS)[74,13,75]. Measurements were made on rock glaciers, protalus lobes and debris lobes. Innovation in geomatic techniques has reduced the logistical effort and costs, and raised the quality of the data[76]. The GPS-RTK techniques were applied by monitoring points distributed over the surface of the frozen bodies[77,74] and led to an accuracy of around ±2 cm. The TLS were used for the precise monitoring of rock glaciers and debris lobes[76] in order to observe vertical and horizontal changes with accuracy of ~1-3 cm. A scanning net is first obtained, which leads to the construction of a triangular irregular net (TIN) and a

DEM is finally built, from which annual spatial losses or gains in volume can be calculated[74].

- Altitudinal belts. Finally, the altitudinal relations between landforms indicator of SFG, the thermal regime and annual medium temperatures, the winter temperatures obtained by continuous dataloggers and BTS, and thermal maps information permitted us to establish the periglacial belts at the Pyrenees. In Europe periglacial belts have been established by Chardon[78] and Lehmkuhl[79] in the Alps, Sellier[80] in the European Atlantic mountains, and Lehmkuhl[79] in the Eurasian mountain (Tienshan, Altai, Khangay and Verkhoyansk). This studies have always relied on periglacial landforms, processes and permafrost features, and now thermal data are included to estimate the altitudinal range of periglacial belts.

4. Results

4.1 Landforms and mapping processes

Periglacial active processes in the central Pyrenees were detected in all Pyrenean high mountain areas (Table 3), where a periglacial environment defines the morphogenetic system. Periglacial processes exist at any altitude in the studied areas, and those related to nivation, the freeze/thaw cycle, frost cracking, solifluction and mass wasting were mapped from 2,200 m a.s.l. Nivation and frost cracking were found to be the most common processes from 2,200 m a.s.l. to 3,300 m a.s.l. This is significant, as it permits the most developed geoecological belts in the Pyrenean high mountain to be classified as nivo-periglacial, where nivation processes are dominant, and cryonival, when gelifraction and frozen grounds prevail.

Table 3

The geomorphic processes related to frozen ground are represented in a wide altitudinal rangue between 2,500 m a.s.l. to the west and 2,910 m a.s.l. to the east. A west-east gradient can be appreciated at the lower limit of processes related to frozen ground (Figure 3). Patterned ground, solifluction lobes and rock glaciers have a west-east gradient from 200 m to over 300 m respectively, while the gradient in frost mounds, protalus lobes and patterned ground shows more variability on the eastern side. The upper limits conserve the same tendency but the different altitudes, locations with flat topographies and summit crest development determine the upper limit of frozen grounds.

Figure 3.

Landforms as an indicator of frozen ground are scattered throughout the high mountain above ~2,590 m a.s.l. Rock glaciers, protalus lobes and frost mounds are the most useful indicators of frozen bodies and permafrost. Debris lobes and patterned ground indicate the existence of ice on the ground, but not necessarily permanently frozen ground. There are four rock glaciers and eight protalus lobes in the studied areas, all located between 2,590 and 3,100 m a.s.l. The fronts of rock glaciers are at different altitudes depending on topography, historical evolution and topoclimatic factors, but in all cases their roots are located above 3,000 m a.s.l. They are landforms inherited from past conditions. In the case of Argualas they date from the Holocene, while in Posets they are at least pre-LIA[36,61]. They show degradation features in the lower part of the tongues but, together with protalus lobes, they are the only permanent frozen bodies that flow downhill. From ~2,670 m a.s.l. protalus lobes and frost mounds develop, both related to the existence of permafrost. Processes are distributed according to altitude: in lower areas nivation, gelifraction and mass wasting are dominant, while from ~2,500 m a.s.l. geomorphic processes related to SFG develop, and above ~2,750 m a.s.l. processes are permafrost-related, all of them active up to the highest areas.

4.2. Ground temperatures

MAGT shows a high positive correlation (r=0.87), indicating cooling of the ground with altitude (Figure 4). MAGT < 0ºC are found above 2,800 m, and there are no MAGT <-2ºC, which points to the possibility of SFG above 2,650 m. At lower altitudes MAGT between 2ºC and 6ºC are dominant. The lack of vegetation and the homogeneous and thin coverage and grain size of sediments, commonly till and debris slope, permit us considerate the orientation, altitude and snow distribution as the main factors influencing the MAGT. From 2,800 m a.s.l. there is no clear trend and altitude is no longer the determinant factor of ground temperatures. Thereafter, orientation, accumulation and snow melt become the dominant factors in the distribution of frozen grounds, with a broad range of MAGT between 3ºC and -1.5ºC, which reflects the presence of all types of grounds, without ice, with seasonal ice or with permanent ice.

Figure 4.

Mean ground temperatures in March show a lower correlation with altitude (r=0,66), though they have the same structure as MAGT (Figure 4). This structure is characterized by three behaviours differentiated by altitude: between 2,200 m and 2,500 m; between 2,500 m and 2,850 m; and over 2,850 m a.s.l. (Figure 5A and B).

- At the lower altitudes, below 2,500 m a.s.l., winter temperature increases with altitude with the highest correlation (r=0.66), and the thermal range lies between 3ºC and -2ºC.
- Between 2,500 m and 2,850 m a.s.l. ground cooling with altitude has a lesser gradient and very low correlation (r=0.007). All records show temperatures >-2ºC, indicating possible permafrost and SFG. Only one record points to a mean March ground temperature >2ºC, and this is in the Monte Perdido massif.
- From 2,850 m a.s.l. temperatures show a higher though rather low correlation with altitude (r=0.12) and a greater thermal gradient. All the temperatures show records below -2ºC, except one located on the south side of Astazou, and those below -4ºC are

dominant (78%), with one record >0ºC. The thermal records clearly show the dominance of permafrost, both possible and probable, though with the presence of SFG. The cold season ground temperature points to the presence of frozen grounds from 2,300 m a.s.l. in La Maladeta, but as a whole they are only dominant between 2,580 m and 2,850 m a.s.l.

Figure 5.

Data from GTS and its annual evolution show three ground thermal regimes in the studied massifs: “Thermal regime dependent on atmospheric temperature”, “Thermal regimes of grounds dependent on the snow cover” and "Frozen soil thermal regimes". The first type is located at the lower limit, where ground temperature has a high correlation with air temperatures. The second type is characterized by stable cold season temperatures (~0ºC for 6 to 8 months) and negative temperatures in autumn (0 to -3ºC), showing the absence of frozen ground up to 2,785 m. The third type reflects either a long period with ground temperatures below 0ºC under atmospheric influence, or the presence of permafrost.

4.3. Basal temperature of the snow measurements

BTS measurements show a certain similarity with the thermal ground records (Figure 5). The correlation between altitude and temperature in the ground is lower than observed for ground temperatures (r=0,61), but a similar pattern can be seen. Ground temperature falls with altitude up to ~2,500 m and thereafter the thermal range in the ground broadens slightly to go from ~2º at 2,350 m a.s.l. to 6.5ºC at 2,500 m a.s.l., 8ºC at 2,700 m a.s.l. and 10.5ºC at 3,000 m a.s.l.

Above 2,650 m a.s.l. BTS measurements remain between 0ºC and -4ºC and from 2,700 m a.s.l. between 0ºC and -8ºC. Above 2,650 m a.s.l. BTS measurements remain between 0ºC and -4ºC and from 2,700 m a.s.l. between 0ºC and -8ºC. Above 2,700 m a.s.l.

records with temperatures <-2ºC are dominant (76%), and above 2,975 m a.s.l. 60% of temperature records are <-6ºC. Between this altitude and up to 3,020 m a.s.l. the BTS measurements have a greater thermal range, with ground teperatures between 0ºC and -2ºC (Figure 5C). Therefore there is SFG, possible and probable permafrost, and from 3,020 m a.s.l. all BTS records are <-2ºC. Hence, between ~2650 and 3050 m a.s.l. there is a patchy spatial pattern of discontinuous permafrost with SFG. This all indicates an environment with continuous permafrost wherever there are no vertical crests, which, above this altitude, only happens at the Monte Perdido, Maladeta and Posets massifs, and only over a small area (~700 ha).

The number of freeze/thaw cycles has a low correlation with altitude (r=0.28), so it is not among the factors that drive them (Figure 5D). There are areas with a very low number of freeze/thaw cycles (<20) between 2,200 m a.s.l. and 3,020 m a.s.l. From 2,500 m a.s.l., two distinct behaviours are recorded: a very low number of freeze/thaw cycles that reach 3,000 m a.s.l.; and a gradual increase in freeze/thaw cycles with altitude, which reach a maximum at 2,900 m (300 cycles) before falling away at greater altitude. Above 2,850 m freeze/thaw cycles is highly variable (between 150 and 300).

4.4. Geomatic surveys

The displacement and dynamics of several landforms (four rock glaciers, a protalus lobe and a debris lobe), located in the Infierno-Argualas, Posets and Maladeta massifs, were measured by geomatic techniques. All of them are above 2,700 m a.s.l., an altitude at which there is permafrost and processes are related to solifluction and permafrost creep. All analyzed landforms show activity with a wide range of displacement between 1 and 32 cm a^{-1} [74,36,60,61,75].

Debris lobes are located at 2,760 m a.s.l in the Alba cirque, Maladeta massif. The thermal environment is located at the MAAT 0ºC and MAGT of 0.9ºC. It is a SFG, frozen for six months from January to June and its thermal regime is determined by snow accumulation (Figure 6). Mass displacements have been measured between 37 and 10 cm a^{-1}, a slow activity related to frozen ground and water availability by snow melt from April to July.

Figure 6.

The Maladeta protalus lobe (42°38′51″N–0°38′30″E) is located between 2,850 and 2,960 m a.s.l. It is 113 m in length with a N-NE orientation and characterized by large granite blocks on the surface. It is in the altitudinal zone between -4°C and -2°C MAAT in the possible permafrost belt and the MAGT is -1.3°C. The measured displacement of the protalus lobe is between a maximum mean annual displacement of 10.8 cm a^{-1} and a minimum of 3.8 cm a^{-1}. The displacement recorded in the protalus lobe diminishes progressively towards the central area where the slope decreases, and the displacement at the front increases once more, where instability is greater[36,75]. The recorded dynamic defines a periglacial landform with low activity and interannual variations.

The Argualas rock glacier (42º46´22´´N/ 0º16´16´´W) is located between 2,590 and 3,032 m a.s.l. It is 750 m long, oriented to the NW and made up of metamorphic blocks and fine sediments organized in furrows and arches of around 1-3 m depth (Serrano et al. 2006 47). It is in the possible permafrost belt with MAAT around -1.5ºC/-2°C. Its measured displacement is between 17.7 cm a^{-1} and 32 cm a^{-1}, and rates for the lower part tend to be greater, reaching 40 cm a^{-1}[30,36].

La Paúl rock glacier (42º39´40´´N/0º26´34´´E) is between 2,830 and 2,950 m a.s.l. It is 400 m long, oriented to the N and made up of granitic and metamorphic blocks with fine sediments organized in arches and eroded by the growth of the La Paúl glacier during the LIA. The rock glacier lies between the probable and possible permafrost belts, with MAAT around 0.73°C and BTS measurements of 2.8ºC at the front and between -3ºC and -4.6ºC in the main body. The measured displacement during the last four years is 30 cm a^{-1} at the front with velocities between 31 cm a^{-1} to 45 cm a^{-1} in the central body.

The Posets rock glacier (42º39´27´´N/0º26´39´´E) is between 2,830 and 3,000 m a.s.l. and has a length of 400 m and is oriented east-north-east. The surface is made up of fine sediments and small blocks of slates and schist, with large blocks scattered on the surface. MAGT is between -0.5ºC and -1.5ºC and BTS measurements on the rock glacier show temperatures of -6ºC, though measurements lower than -3ºC are the most common, indicating conditions at the lower limit of the permafrost environment. The mean horizontal displacement rates in the central axis and lower part are around 9 cm a^{-1}, and the fastest movements are recorded in the central part where the displacement rate is 10.9 cm a^{-1} [30,60]. Increases in displacement rates are observed from the root to the central area, decreasing towards the front. The rock glacier shows a dynamic characteristic of very low and attenuated activity rock glaciers and has been classified as distinctive of marginal periglacial mountain environments.

The Maladeta rock glacier (42º39´19´´N/0º37´37´´W) is located between 2,910 and 3,010 m a.s.l. It has a length of 210 m, is oriented to the N and is made up of large granite blocks[75]. It is located within the possible permafrost belt with MAAT between -4°C and -2°C. MAGT is between -2°C and -6ºC and BTS measurements on the rock glacier show temperatures between -3.6 and -8.4ºC in a permafrost environment determined by atmospheric and ground temperatures. The measured displacement is between 13.8 cm a^{-1} and 12 cm a^{-1}, an active movement showing debris transport with high-relief slope processes in the high mountain cascade system. On the surface the deep hollows and depressions point to permafrost degradation processes.

4.5. Thermal mapping

The maps of the distribution of frozen grounds reveal the differences between the massifs of Infierno and Monte Perdido, where the altitudinal distribution is a patchy pattern, and those of Posets and Maladeta, where the altitudinal gradient determines the distribution of frozen grounds (Figure 7). The patchy pattern shows differences by orientation, with the presence of unfrozen grounds to 2,750-2,800 m a.s.l. Above 2,650 m a.s.l. SFGs are common, such that there is a very moderate altitudinal range in which SFGs predominate and there are unfrozen grounds (at 2,625-2,650 m a.s.l. in northern orientations and at 2,625-2,780 m a.s.l. in southern ones). In this altitudinal range the presence of processes such as frost-cracking, nivation, solifluction, gelifluction and cryoturbation point to high periglacial morphodynamic effectiveness.

Figure 7.

Between 2,650 m and 2,825 m a.s.l. in northern and 2,780 m and 2,900 m a.s.l. in southern orientations the presence of SFG, unfrozen grounds and sporadic permafrost also confers a patch-patterned spatial distribution. Above this altitude discontinuous permafrost is dominant and from 2,900 m a.s.l. there is potential continuous permafrost from the thermal data, though the geomorphological data show the presence of processes and landforms not associated with frozen grounds. The presence of crests and summit edges without permafrost in their upper regions, which occurs at over 3,000 m a.s.l., leads us to think that the distribution of discontinuous permafrost and SFG reaches the summits (Figure 7). All areas show a wider frozen ground altitudinal range in northern orientations than in southern ones.

Overall, the evidence indicates that on northern slopes mountain permafrost is dominant from 2,750 m a.s.l. to the watershed crests (3,000-3,100 m a.s.l.). On southern slopes SFG is dominant in a broad range between ~2,600 m a.s.l. and at the summits (3,000-3,400 m).

4.6. Pyrenean periglacial belts and limits.

The Pyrenean periglacial landsystem can be divided into three main belts with systematically characteristic features according to the thermal data -MAGT, cold season temperatures, BTS measurements, freeze/thaw cycles- and landform distributions:

- **The infraperiglacial belt**.

The thermal data show a belt between ~1,800 m a.s.l. and ~2,500 m a.s.l. where the MAAT is around 4ºC and 2.5ºC, with the cold season annual isotherm of 0ºC located at 1,785 m a.s.l.[20]. The 0ºC isotherm is the thermal indicator of the beginning of the periglacial belt at ~1,800 m a.s.l. when ice in the ground can be present even though the snowpack protects the ground from atmospheric temperatures. The MAGT is between 2.5ºC and 6ºC and the frozen season temperature between 3ºC and -0.5ºC indicating the possibility of freeze/thaw cycles and nivation processes. The BTS measurements show a narrow thermal amplitude, with a maximum of 6.5ºC (Figure 5C). The thermal regimes are "dependent on atmospheric temperature", with and without snow cover or with thin snow covers; and "dependent on the snow cover", with cold season temperatures stable at around 0ºC for 6 to 8 months. Negative temperatures only appear in autumn and are generally moderate. Ground insulation by the snow cover indicated the absence of SFG and permafrost. Therefore, there is only unfrozen ground and cold associated processes, though sporadic permafrost was detected at low altitudes, and only above 1,800 m a.s.l. at exceptional sites related to snow avalanche channels in north-facing aspects[81].

Processes are also highly varied, mainly those associated with nivation and ground freeze-thaw cycles, although there are also solifluction and frost-cracking processes in this belt. The snowpack generates nival pavement, nivokarst landforms (in the Monte Perdido and Posets massifs), and protalus ramparts. Landforms deriving from frost weathering are directly related to air temperature and direct insolation on the substrate forming debris talus and cones. Finally, solifluction lobes and sheets, and terracettes, the latter with its upper limit at 2,200 m a.s.l., are very common and allow the lower limit of the periglacial belt to be established.

- **The middle periglacial belt**,

From ~2,500-2,600 m a.s.l. to ~2,900 m a.s.l. a dozen thermoregisters show homogenous temperatures with MAGT between 5ºC and -1ºC, the MWGT between 3ºC and -2ºC, and a thermal rank from BTS measurements between 4ºC and 8ºC. This belt coincides with the MAAT between 2.5ºC and -0.5ºC, and the 0ºC isotherm is found between 2,750 and 2,950 m a.s.l. depending on the massifs considered[82,13,49]. Thermal regimes that are dependent on the snow cover and frozen soil regimes are dominant at these altitudes. It is the main domain of SFG, above 2,650 m a.s.l. and reaching 2,800-2,900 m a.s.l., although there is also unfrozen ground up to 2,750-2,800 m a.s.l. and permafrost above 2,650 m. Discontinuous permafrost occurs predominantly in the highest part of the belt, appearing over 2,760 m a.s.l. On the other hand, on the crests, walls and mountain passes topoclimatic conditions are not favourable to permafrost, as is common in alpine models[2].

In the middle periglacial belt there are processes related to frozen as well as unfrozen ground. Cryoturbation is an important indication of continuous or seasonal frozen ground, although frost mounds are not very common in the Pyrenees[36,45,83,13] and patterned grounds, developing from 2,530 m a.s.l. to 3,050 m a.s.l., are not necessarily related to frozen ground. Rock glaciers and protalus lobes are only found on slopes with northern orientations.

- **The supraperiglacial belt.**

The upper belt is developed above 2,900 m a.s.l. The MAAT is between -1ºC and -2ºC, and the -2ºC isotherm is between 3,130 m a.s.l. and 3,360 m a.s.l. depending on the massifs considered[13,49], in nearly all cases above the summits. The MAGT is between 3ºC and -1.5ºC, and the cold season temperature between 0.5ºC and -8ºC. The BTS temperatures show a thermal rank around 10ºC always with temperatures below 0ºC. The thermal regimes in the belt are varied. The least represented is the "Thermal regimes of grounds dependent on atmospheric temperature", which only occurs at the highest altitudes above 3,000 m a.s.l. The high correlation with air temperatures is triggered by windy conditions that clear the snow cover from the ground. The "Thermal regimes of grounds dependent on the snow cover" occur in the lowest part of the belt, which points to permafrost not being present and the insulation of the ground by the snow cover. Finally, the most widespread is "Thermal regimes of frozen grounds", influenced by air temperatures, the presence of permafrost and the arrival of the cold wave from the ground, but this thermal regime also points to the occurrence of SFG.

The SFG is very scattered and discontinuous permafrost is dominant, although the thermal conditions of crests, walls and summits prevent the development of continuous permafrost on massifs lower than 3,330 m a.s.l. There is frost-cracking and nivation at these altitudes, but the dominant processes are permafrost creep, solifluction and cryoturbation. A wide range of landforms are present, but the commonest are the subtract outcrop together with protalus lobes and rock glaciers on the slopes and patterned ground and frost mounds in flat areas.

5. Discussion on processes and thermal distribution.

Data from the four studied areas show a complex topography with geomorphic altitudinal belts and a patchy pattern of frozen grounds, factors which are consistent with the occurrence of permafrost and SFG[84,2].

The four massifs analyzed are fairly homogenous in their behaviour, with differences related to their differing altitudes rather than to geographical or local climate issues. All of them point to general conclusions for the entire Pyrenean mountain range.

Snow is the main morphodynamic factor in the Pyrenean periglacial belt since it determines water availability, freeze/thaw cycles and the thermal regime of grounds, mainly in the lower parts of periglacial environments. The moderate activity and high variability of freeze/thaw cycles is due to the atmospheric thermal regime at low altitudes, where it does not cool often below 0ºC, and to the accumulation and duration of the snow cover at the higher ones, as it protects the ground from freeze periods from early autumn to summer. The existence of a high number of freeze/thaw cycles (>120 and up to 200) at low altitudes indicates the importance of topoclimatic factors.

The periglacial landforms, patterned ground, debris lobes and sheets, are always scattered across areas with water availability in periods without nival protection and the periglacial dynamic is changeable due to the high interannual variability of the snowpack, steered by the complex interactions among climate, topography and blowing snow[120]. Annual snow accumulation and snowpack duration clearly show sensitivity to warming and in the central Spanish Pyrenees both will decrease dramatically over the next century by up to 78% of the maximum accumulated snow water equivalent, while the duration of the snow cover may shorten significantly at low altitudes[85]. The warming influence on the snowpack decreases with increasing altitude, although changes in the dynamic of the snowpack will be greater on those slopes that received intense solar radiation, those of the S, SE and SW[85, 86]. This is of significance to the near future as the effectiveness of periglacial processes in the lower areas as well as the higher ones can be assumed to increase as a result of permafrost degradation.

These records place them within the frame of displacements commonly found in protalus lobes[87,36,60]. In all cases, protalus lobe displacements are slower than those of active rock glaciers.

In the Central Pyrenees the main areas with unfrozen grounds reach 2,750-2800 m a.s.l., even though there are SFG above 2,650 m a.s.l. The altitudinal range of SFG and unfrozen grounds is therefore only between 2,600 and 2,880 m a.s.l. in southern orientations and in the upper belts SFG and permafrost are dominant, though there are also unfrozen grounds on crests and peaks. At these altitudes there is high periglacial efficiency in generating landforms deriving from the interrelationships between diverse processes such as frost-cracking, nivation, creep and cryoturbation. Also, the geophysical surveys showed evidence of frozen bodies above 2,590 m a.s.l.[33,59,34,36,37,39], and sporadic permafrost at exceptionally low altitudes, as in the Telera massif, at around 1,850-2,000 m a.s.l.[88].

The previous data points to a complex spatial thermal distribution, a patchy pattern, in which all kinds of thermal conditions on the ground appear between 2,650 and 2,800 m a.s.l. in northern orientations, and between 2,800 m a.s.l. and 2,900 m a.s.l. in southern ones (Figure 8). Discontinuous permafrost is dominant between 2,750 m a.s.l. and 2,900 m a.s.l. in northern aspects, but between 2,850 m a.s.l. and 2,950 m a.s.l in the southern faces where the altitudinal range is reduced.

The altitudinal range of frozen grounds is always lesser in southern orientations that in northern ones. The most sensitive to current changes by permafrost degradation environment is found at above 3,050 m a.s.l. There is potential thawing due to the increase in atmospheric temperatures and the altitudinal rise of isotherms disturbing walls and crests. As common in alpine models, the crests, walls and mountain passes topoclimatic conditions are not favourable to permafrost, and natural hazards are increased[2], as this also occur in the Pyrenees[86,89,52]. They are no such environments in the Infierno massif because of its lower height, but the area of permafrost is very considerable in Aneto-Maladeta, the Posets massif and Monte Perdido, where more than 300 ha, 160 ha and 180 ha respectively are located above 3,000 m, all of them highly frequented during summer.

Figure 8.

Continuous permafrost may occur above 3,000 m a.s.l., but the summit crests and edges are not favourable to frozen ground development due to the high solar radiation on both slopes[90,2]. As in the Alps, summit areas in the Pyrenees probably have a patchy pattern with SFG and permafrost.

The altitudinal organization of periglacial processes and landforms seems to be a sign of a well-established periglacial landsystem in the Pyrenean high mountain. In the mountains the periglacial landsystem has been divided into belts or sub-belts in which the altitudinal range directs dynamic changes and MAAT has been used to delineate the altitudinal belts with permafrost and active processes[91,80,79,13]. The geomorphic periglacial belts included in the periglacial mountain landsystem are of great geoecological interest in the development of functioning models of high mountain environments, ecological relationships and forecasting human-induced or climate changes in the environment.

Periglacial belts and limits in European mountains have been established since Chardon[78] proposed a division in the western Alps between the “infraperiglacial” belt (~1800-2400 m a.s.l.), the “periglacial-type” belt (~2400-3100 m a.s.l.), and the “supraperiglacial” belt (~3100-4000 m a.s.l.). These were later simplified and divided into two sub-belts: the inner periglacial sub-belt, defined by the lower limit of active solifluction between 2,200 and 2,350 m a.s.l., and the upper periglacial sub-belt, dominated by blockfields, patterned ground, bare bedrock, rock glaciers and solifluction with permafrost environments, at altitudes above 2,400-2,500 m a.s.l.[79]. Lower limits were indicated by Sellier in the Atlantic mountains defined by the lowest solifluction limit[80] and in the Rondane massif (Norway) where three periglacial belts were differentiated, all with sporadic to continuous permafrost occurrence[192,93,94]. Several proposals have been made to divide the periglacial belt in the Pyrenees, all of which have distinguished three or four belts (Table 4).

Table 4

The periglacial belts in the Pyrenees are divided into three units, the infraperiglacial belt (~1,800 to ~2,500 m a.s.l.); the middle periglacial belt (~2,500-2,600 to ~2,900 m a.s.l); and the supraperiglacial belt (above 2,900 m a.s.l.). The infraperiglacial belt was defined by Serrano et al.[95] and González-García[13], though the upper limit is now at lower altitudes due to the high ground temperatures, which are always above 2ºC. It includes the nival and nivoperiglacial belts[13] and the subnival and nival belts[135] because distinctions are not made by nivation processes and there is no evidence of different thermal regimes. More thermal data and dynamic knowledge on activity and inherited elements are necessary to subdivide the infraperiglacial belt. The middle periglacial belt is located at lower altitude than the “periglacial” and “periglacial-type” previously proposed[95,13,96], in which the dominance of frozen ground (SFG and permafrost) implies a lowering of the upper and lower altitudinal limits. The supraperiglacial belt is in agreement with the supraperiglacial belt proposed by Serrano et al.[95] and González-García[13], though the lower limit has now been set 200 m lower because of the new recording at 2,900 m a.s.l. The winter season ground temperatures at this altitude are lower than -6ºC and are close to those of permafrost related landforms.

The current active periglacial environments in Iberian mountain ranges are located in the upper parts of the highest mountain ranges and are mostly related to seasonal frost dynamics[58]. Marginal permafrost conditions have only been detected in sporadic patches close to the summits of Sierra Nevada and the Cantabrian Mountains and are related to LIA moraine complexes, today undergoing a rapid degradation of permafrost. At the same altitude as in the Pyrenees, seasonal frost has been detected in the high parts of the Central Range, NW Ranges and the Cantabrian Mountains[42]. The complexity of the periglacial belt in the Pyrenees is not found in other mountains of the Iberian Peninsula. The most common processes are solifluction, characterized by very slow deformation rates (less than 1 cm yr^{-1}), needle-ice activity and miniature patterned ground, all associated with diurnal frost cycles[42]. Nival processes are also common in the Iberian Mountain, and the Pyrenees is no exception. The occurrence of seasonal frozen ground and mountain permafrost in the Iberian Peninsula seems, nevertheless, to be limited by altitude, and only the Pyrenees and Sierra Nevada reach altitudes that support cold environments. Between the two ranges the latitudinal difference is appreciated in the altitudinal distribution of periglacial processes, with frozen ground around 200 m higher. Only in the Pyrenees are there well developed frozen bodies such as rock glaciers and protalus lobes, which define the Iberian high mountain. Changes related to warming will have significant consequences in the periglacial belt of the Iberian mountains, largely driven by changes in snow depth, spatial variability associated with variations in surface runoff, in soil thermal regimes, and geomorphological processes[86,42,52].

Within the Mediterranean framework permafrost conditions generally increase with altitude towards the eastern part of the region and from north to south[43]. In the western and central Mediterranean, permanently frozen ground is rarely found below 2,500 m, discontinuous permafrost is generally detected between 2,500 and 2,800-3,000 m and continuous permafrost is distributed in ice-free environments above this level[43]. The altitudinal range observed in the Pyrenees, above 2,600 m in northern aspects and 2,800 m in southern ones, is higher than in the southern Alps (above 2,400 m) and Rila mountains (above ~2,350 m), but lower than in the southeastern ones, such as Mount Olympus, ~2,700 m, NE Turkey and central Anatolia, above 2,800 m[97,98,99]. To the south permafrost is only found in sporadic patches above 3,000-3,100 m in Sierra Nevada and the Atlas[100, 101]. Latitude seems to be the most determinant factor in the distribution of Mediterranean periglacial belts for massifs of similar altitudes.

Oliva et al.[42] have pointed out that in the near future periglacial activity in Iberian mountains will become restricted to higher elevations. Furthermore, the pronounced future annual and seasonal climate projections would lead to an ascent of permafrost conditions and rapid degradation process, possibly triggering large slope and mass wasting processes with important socio-economic impacts, which have already begun in the Pyrenees[43,52].

6. Conclusions

The central Pyrenean high mountains offer a broad periglacial belt in which significant morphodynamic variations can be seen. The lower limit of frozen grounds is at ~2,650 m a.s.l., although below this level there may be sporadic permafrost or SFG depending on local factors such as topography, slope morphology, aspect, hydrology or thickness and duration of the snow cover. Possible permafrost appears above 2,650 m a.s.l. in northern and southern orientations and probable permafrost is dominant above 2,900 m a.s.l., but unfrozen grounds reach 2,900 m a.s.l. as do frozen grounds. The distribution of unfrozen and frozen grounds points to the presence of a patchy pattern throughout the periglacial belt.

The thermal data reveal that the most widespread frozen grounds in the temperate high mountain of the Pyrenees are SFG, which alternate with unfrozen grounds at the lowest altitudes, where the snowpack is the most important element. The snow cover, its thickness and duration determine thermal processes, such as the freeze/thaw cycles on the ground, frost and thermal regimes, and geomorphic ones, such as nivation, the most extended morphogenetic system expressed in a varied representation of landforms such as nival pavements, nivation hollows, nivation dolines and lapies, protalus ramparts, supra-snowpack and sub-snowpack small mudflows, or avalanche snow cones and paths.

The degradation of the permafrost is visible in rock glaciers and protalus lobes, as well as on the walls, crests and summits, which indicates an increase in the probability of rock-falls and slope slides over 3,000 m a.s.l. This is a narrow altitudinal margin of moderate extension, but is highly visited on the most attractive summits (Maladeta-Aneto, Posets, Monte Perdido massifs), which increases risk. It is also possible to foresee changes to the lower parts related to changes in the duration and thickness of the snow cover, which means an increase in the activity of periglacial processes in the lowest and highest parts of the periglacial belt in the near future.

The high mountain area can be divided into periglacial geomorphic sub-belts: the infraperiglacial belt, the middle periglacial belt, and the supraperiglacial belt. The most developed one is the lowest, which has the greatest altitudinal range and surface area, though it is the least active due to the atmospheric thermal conditions between the 4ºC and 2.5ºC isotherms and the protective factor of snow cover on the ground. The middle periglacial belt is the most geomorphologically active as it contains all kinds of thermal behaviours in the ground: unfrozen, SFG and mountain permafrost; generating a combination of geomorphological processes and a great capacity for erosion and transport. The upper belt possesses a highly variable altitudinal amplitude among the different massifs due to the varying altitude of its summits. Although the processes and landforms involved are fewer and simpler in their behaviour than those of the lower belts, it is the most active belt due to its topography, dominated by steep slopes, topoclimatic conditions, location above the 0ºC isotherm, a highly irregular snow cover in windy areas and degradation of permafrost.

The large number of processes and landforms that are involved and their altitudinal and spatial organization make up a complex environment that determines the geoecological dynamic of the high mountain. For this reason and because most of the periglacial high mountain forms a part of the Natural Protected Areas of the Spanish State or the Autonomous Community of Aragon, they must be considered in order to understand high mountain ecosystems and habitats. In particular, changes occurring in the near future associated with projected changes in temperature and precipitation are likely to have a significant influence on high mountain snow cover and permafrost.

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FIGURES:

Figure 1. Location of massifs studied in the Pyrenees. 1, Infierno (3,175 m a.s.l.). 2, Monte Perdido (3,355 m a.s.l.). 3, Posets (3,375 m a.s.l.). 4, Maladeta (Aneto peak, 3,404 m a.s.l.).

Figure 2. Sketches of the areas studied with the main glacial and periglacial landforms.

Figure 3. Periglacial landforms distribution by altitude in the Pyrenees.

Figure 4. A, relation altitude/medium annual ground temperatures (MAGT) and B, altitude/medium March ground temperatures (MMGT). It is possible differentiate between the periglacial belts and in the case of MMGT the less correlation existent in each periglacial belt.

Figure 5. Altitudinal distribution of MMGT (A), MAGT (B) BTS measurements (C) and number of Freeze/Thaw cycles (D). SPB, supraperiglacial belts. MPB, middle periglacial belt. IPB, infraperiglacial belt.

Figure 6. Air and ground thermal regime (hydrologic year 2009-2010) on the debris lobe in Maladeta massif at 2920 m a.s.l.

Figure 7. Frozen ground distribution maps and isotherm altitude (red dotted line) of the areas studied.

Figure 8. A, altitudinal distribution of frozen ground in the areas studied. NFG, unfrozen ground. SFG, seasonal frozen ground. PoP, possible permafrost. PrP, probable

permafrost. B, synthesis on altitude distribution of frozen ground and periglacial belts (IP, infraperiglacial belt; MP, middle periglacial belt; SP supraperiglacial belt).

TABLES:

Table 1. Permafrost typology by factors.
Table 2. Data used in this work
Table 3. Periglacial processes and landforms analyzed in the Pyrenean high mountain area.
Table 4. Studies on periglacial belts in the Pyrenees

Table 1. Permafrost typology by factors

Typology	**Permafrost classification**			**References**
Thermal	Cold (MAGT<-0,5°C never equal to ~0°C)	Temperate (MAGT=~0°C)	Semi-temperate (MAGT>-0,5°C occasionally values ~0°C)	Delaloyé, 2004
Thermal rule-based	Probable (MAGT >-2ºC)	Possible (MAGT -2/0ºC)	Improbable (MAGT > 1ºC)	Haeberli, 1985
Environmental	stable	metastable	instable	Harris, 1986 Oberman y Mazhitova, 2003
Spatial (mapping)	Continuous	Discontinuous	Sporadic	Barsch,1978; Harris, 1986
	Potential extensive	Potential local		Foen, 2005
	In rarely all conditions	Mostly in cold conditions	Only in very favourable conditions	Boeckli et al. 2012

Table 2. Data used in this work

Data		Infierno			Monte Perdido			Posets[59]			Maladeta			TOTAL	
		Nº	Date	Altitude	Nº	date	Altitude	Nº	Date	Altitude	Nº	Date	Altitude	Nº	Alt.
Ground temperature		3	2010-2011	2730 2360	13	2015-2017	3075 2585	5	2009-2011	2970 2285	11	2009-2011	2919 2173	32	3075 2285
BTS measurements		119	2011	2810 2350	56 (154)	2016	3075 2585	72	2001[59]	3155 2620	80	2010	3155 2210	323	3155 2210
Mapping		Geomorphological map, Thermal map, Permafrost distribution map. Frozen ground map 1/10,000 scale												--	--
Indicators landforms	SFG	Debris lobes Patterned ground			Debris lobes Patterned ground			Debris lobes Patterned ground			Debris lobes Patterned ground			Debris lobes Patterned ground	
	Permafrost	Protalus lobe			Protalus lobe Frost mounds			Rock glaciers[29,35,37,60,61] Protalus lobe Frost mounds			Rock glaciers Protalus lobe Frost mounds			Rock glaciers Protalus lobe Frost mounds	

Table 3. Periglacial processes and landforms analyzed in the Pyrenean high mountain.

Processes	**Landforms**	**Infierno**			**Monte Perdido**			**Posets**			**Maladeta**			**TOTAL**		**Indicators**
		Nº	**Altitude m**	**Or.**	**Nº**	**Altitude m**	**Or.**	**Nº**	**Altitude m**	**Or.**	**Nº**	**Altitude m**	**Or.**	**Nº**	**Altitude m**	
Frost cracking	Debris talus and cones	--	3000 2400	N, S, E	-	3040 2555	N, S	-	3100 2300	N, W, E.	--	3050 2200	E, N, W, NW, NE	--	3100 2200	Freeze-thaw
	Crest and ridges	--	3100 2600	--	--	2700 3300	--	-	3300 2900	--	--	3200 3000	--	--	3300 2600	Freeze-thaw
Nivation	Nival pavements	-	2900 2400	-	--	2950 2500	--	--	3100 2600	--	--	2700 2470	--	--	3100 2400	Freeze-thaw
	Nivokarst landforms	--	--	--	--	3100 2500^*	--	--	--	--	--	--	--	--	--	No frost
	Protalus ramparts	7	2690 2450	N, E NE,	-	--	--	1	2750 2700	NW	2	3000 2970	N	**10**	**3000 2450**	**No frost**
Mass movement	Debris flow	16	2500 2450	NE	3	2700 2500		16		E, N	3	2500 2300		38	2700 2300	No frost
	Solifluction lobes	--	2400 2200	--	-	-	-	-	2600 2200	--	-	2500 2100	-	-	2600 2100	Freeze-thaw
	Terracettes	--	2450 2200	-	-	2650 2490	N, S, E	-	2700 2200	E, W	-	2650 2200	N, S	-	2700 2200	Freeze-thaw
Gelifluction and frozen ground creep	Debris lobes	-	2700 2500	-	8	3030 2520	N, NE, NW, SE	3	2900 2650	W, E	--	2920 2700	N, E	**11**	**3030 2500**	**SFG**
	Rock glaciers	1	2730 2590	NW	-	-	-	2	3050 2780	N, NE	1	3110 2910		**4**	**3100 2590**	**Permafrost**
	Protalus lobes	1	2700 2680	N	1	2900 2850	N	4	3000 2775	N, W NW,	2	2960 2750	NW, NE	**8**	**3000 2680**	**Permafrost**
Cryoturbation	Frost mounds	--	--	--	4	2850 2760	--	10 (6)	3050 2670	--	7 (2)	2920 2900	--	**21**	**3050 2670**	**Permafrost**
	Patterned grounds	-	2600 2430	-	**20 (5)**	2790 2530	--	**36 (11)**	**3050 2800**	**--**	**(2)**	**2900 2500**	**--**	**~60**	**3050 2530**	**SFG**

Or., Orientation. SFG, seasonally frozen ground.

Table 4. Studies on periglacial belts in the Pyrenees

Authors	**Area**	**Periglacial belts**		**Altitude m a.s.l.**	**Periglacial processes**	**Frozen Ground**
Serrano et al. 2000	Central Southern Pyrenees	Supra-periglacial	Glacionival	> 3000-3100	Frost cracking Gelifluction Cryoturbation	Continuous permafrost
		Periglacial	Cryonival	~3100 2600-2700	Frost cracking Gelifluction Cryoturbation	Disc. permafrost Cont.permafrost
		Infra-periglacial	Nivo-periglacial	2600-2700 ~2100	Nivaton Solifluction Frost cracking Gelifluction	Sporadic permafrost
Feuillet, 2010	Central Northern Pyrenees	Atlantic mountain periglacial		>2850	--	Con. permafost
				>2650	Cryoturbation	Disc. permafrost NFG
				2620 2300	Gelifluction Cryoturbation	SFG NFG
		Lower limit		2250-2300	Solifluction	--
González-García, 2013	Central Southern Pyrenees	Supra-periglacial	Glacionival > 3100	~3400 3000-3100	Nivaton Frost cracking	Prob. permafrost >2900
		Periglacial	Cryonival	3000-3100 2600-2700	Nivaton Solifluction Frost cracking Gelifluction Cryoturbation	Poss. permafrost > 2800 m a.s.l. Prob. permafrost >2900 m a.s.l.
		Infra-periglacial	Nivo-periglacial	~2600 ~2300	Nivation Solifluction Gelifluction	Spor. Permafrost
			Nival	~2300 ~2000	Solifluction Runoff Nivation	Seasonal ice
Fernandes et al. 2017	Upper Garona bassin	Periglacial/cryonival		~2800 ~2300	Cryoturbation Solifluction Talus slopes Nivation	--
		Nival		~2300 ~1900	Nivaton Cryoturbation Solifluction Talus slopes	--
		Subnival		~1900 ~1500	Peat development Talus slopes	--

Cont. permafrost, continuous permafrost; Disc. permafrost, discontinuous permafrost; Spor. permafrost.sporadic permafost; NFG, unfrozen ground; SFG, seasonal frozen ground; Prob. permafrost, probable permafrost; Poss. permafrost, possible permafrost.