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# Cave mountain permafrost environments in the Picos de Europa and their implications

*Ambientes con permafrost de montaña subterráneo en los Picos de Europa y sus implicaciones*

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**Abstract**

The thermal definition of permafrost can be attributed to a wide diversity of periglacial environments, one of which is ice caves. This study analyzes ice caves in relation to the thermal aspect of permafrost with the aim of describing ice caves with permafrost in the temperate high mountain of the Picos de Europa and their implications in the interpretation of ice caves as permafrost indicators. Ice caves provide the environmental conditions of mountain permafrost, with annual mean temperatures below 0ºC over several consecutive years and multiple perennial cryomorphologies. Ice caves are not found at sites where surface environments have permafrost, however endoclimatic features and cryomorphological elements indicate environments with permafrost in the upper part of the cavities currently entirely unrelated to surface climatic conditions. Based on endoclimate data and on landform types and cryomorphic processes, a classification is established unrelated to surface permafrost environments: cave mountain permafrost environment.

**Key words:** Ice caves; permafrost environment; cave mountain permafrost; Little Ice Age; Picos de Europa.

**Resumen**

La definición térmica de permafrost permite atribuirla a una amplia diversidad de ambientes periglaciares. Uno de estos ambientes son las cuevas heladas, que se analizan en este estudio a partir del concepto térmico de permafrost. El objetivo de este trabajo es caracterizar los ambientes con permafrost en cuevas heladas de la alta montaña templada de los Picos de Europa y sus implicaciones para la interpretación de las cuevas heladas como indicadores de permafrost. Las cuevas heladas cumplen con las condiciones ambientales de

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permafrost de montaña en su interior, con temperaturas medias anuales por debajo de 0ºC durante varios años consecutivos, y múltiples criomorfologías perennes. Las cuevas heladas no se localizan en ambientes superficiales con permafrost, sin embargo, las características endoclimáticas y los elementos criomorfológicos indican la presencia de ambientes con permafrost en las porciones más altas de las cavidades, completamente ajenas en la actualidad a las condiciones climáticas de superficie. Basado en los datos endoclimáticos y de los tipos de formas y procesos criomórficos, se establece una clasificación ajena a los ambientes de permafrost superficiales: ambientes con permafrost de montaña en cuevas.

**Palabras clave:** Cuevas heladas; permafrost; permafrost de montaña en cuevas; Pequeña Edad del Hielo; Picos de Europa.



## 1. Introduction

Ice caves are a widespread phenomenon (Perşoiu and Onac, 2012; Mavlyudov, 2018a) and while their importance has been stressed by many authors since the 18th century, their epistemological place in the cryosphere sciences is, nevertheless, vague. Sometimes they are considered within the glacial or periglacial disciplines, or even in definitions that fail to include perennial ice masses (e.g. seasonal ice caves). Despite being well known in the world from the 19th century onwards (Balch, 1900), their study has mainly developed over the last 20 years and fundamentally in specific areas (Citterio and Turri, 2004; Perşoiu and Lauritzen, 2018). The application of new analytical techniques and the collection of paleoenvironmental data from the ice has led to greater depth in their study as an interesting part of the cryosphere and a growing number of monographic manuals and workshops (Citterio and Turri, 2004; Perşoiu and Lauritzen, 2018).

For the purposes of this study, ice caves are defined as natural caves in which a perennial ice mass is preserved deriving from the firnification of accumulated snow and/or freezing water within it (filtered from outside or from internal melting of cryomorphologies). This definition coincides with the more general definition of Perşoiu and Onac (2012): "cave formed in bedrock which contains perennial accumulations of water in its solid phase". These caves have specific karst patterns and climatic conditions, such as temperatures below 0ºC, air circulations, mean and ice accumulations forming stratified ice blocks (perennial cave ice) and cryospeleothems (generally seasonal and non-stratified morphologies). There is now no consensus on specific details, such as: whether the ice conserved must be perennial or only seasonal; the origin of the ice, from snow or from refreezing of infiltrated water; the definition of ice caves and cryomorphologies; the greater or lesser importance of the sublimation processes in mass balances; or indeed if they can be considered to be permafrost environments. All of these are interesting field studies from the geographic point of view because of their widespread global distribution and location in some very specific areas of the high and medium mountain (Colucci *et al.,* 2016; Mavlyudov, 2018b).

From the thermal point of view ice caves are considered a 'thermal anomaly' with respect to outside conditions (Lismonde, 2002; Luetscher and Jeannin, 2004; Luetscher, 2005; Kadebskaya and Tchaikovskyi, 2009; Mavlyudov, 2009; Orvošová *et al.,* 2014) because they are the result of cooling sources located outside the caves. Nevertheless, the fact that ice caves are commonplace means that they cannot be considered anomalous (Mavlyudov, 2018b).

Temperature and hygrometric changes affect ice caves. In the Picos de Europa the fundamental factors in the genesis and mass balance of ice caves are direct snow inputs, which are decisive in feeding the internal ice blocks, the number of entrances to the cave, relative elevation differences, dimensions, altitudinal exposure and siting. Ice caves can be found in regions with continuous, discontinuous or sporadic permafrost, and in those free of permafrost, where the Mean Annual Air Temperature (MAAT) may be around 0ºC (Mavlyudov, 2018b; Dysli and Luetscher, 2003; Perşoiu and Lauritzen, 2018). This means that ice caves have a high ubiquity since they can be found both inside and outside permafrost environments where frost processes are not dominant.

An increasing number of authors are now relating ice caves with permafrost environments (Gómez-Lende, 2015, 2016; Colucci *et al.,* 2016; Obu *et al.,* 2018; Dublyansky *et al.,* 2016; Luetscher *et al.,* 2016; Luhová *et al.,* 2016; Milovský *et al*., 2016), which points to their interest as an indicator of permafrost occurrence even during the Last Permafrost Maximum in the northern hemisphere (Vandenberghe *et al*., 2014; Orvošová *et al*., 2014).

Survey, analysis and inventories of ice caves are still at an early stage due to the low amount of ice caves in relation to the global cryosphere or the difficulties involved in their access, (Maire, 1990; Citterio and Turri, 2004; Kern and Perşoiu, 2013; Perşoiu and Lauritzen, 2018). Direct exploration is the only way to collect data of their presence and their features (Gómez-Lende, 2015; Colucci *et al*., 2016).

In the Picos de Europa, ice caves and ice-patches are the only occurrences of ice. Ice caves are, therefore, very important for environmental characterization and reconstruction due to several reasons: a) there are only five ice patches (González Trueba, 2007; González Trueba *et al*., 2008; Serrano *et al*., 2009); b) ice caves are a good permafrost geo-indicators, as described later; c) the ice blocks inside the caves are the largest frozen bodies remaining in the area; and d) they are of high value for paleoenvironmental information (isotope records, cryogenic cave carbonates —CCC—, pollen and other content for biological analysis).

The three aims of this paper are, firstly to highlight the importance of underground ice masses in surface environments without periglacial processes nor landforms related to permafrost. Second, to establish a specific subterranean permafrost type from the endoclimate parameters of ice caves based on previous authors' information and new data of Picos de Europa ice caves. Finally, to supply new knowledge on the presence of permafrost in the Picos de Europa.

## 2. Study site: Ice caves in the Picos de Europa

The Picos de Europa is a calcareous massif of the Cantabrian Mountains in northern Spain divided in three massifs, the Central (Torrecerredo 2,648 m a.s.l.), Western and Eastern, all separated by deep gorges (Figure 1). Ice caves are located in the high mountain belt and large ice volumes are well preserved in highly diverse cave typologies. The ice caves of the Picos de Europa are mainly concentrated in the Central and Western massifs and there are none in the Eastern massif. Nowadays there are no glaciers, but ice-patches still remain (Serrano *et al.,* 2011*;* 2012; 2018a). The topography, climatic conditions, the thickness of Carboniferous limestones and significant altitudinal gradient provide the conditions for considerable cave development. Caves are mainly of vertical development and include some of the deepest in the world, e.g. Saxifragas (–1,589 m), Cornisa-Magali (–1,507 m) and the Trave system (–1,441 m).

At least 136 caves with perennial ice have been inventoried in the Cantabrian Mountains, and 125 of these (92%) are in the Picos de Europa, though this number is likely to rise as the inventory is still ongoing (Gómez-Lende and Serrano, 2018a; Serrano *et al.,* 2018b) (Figure 1).

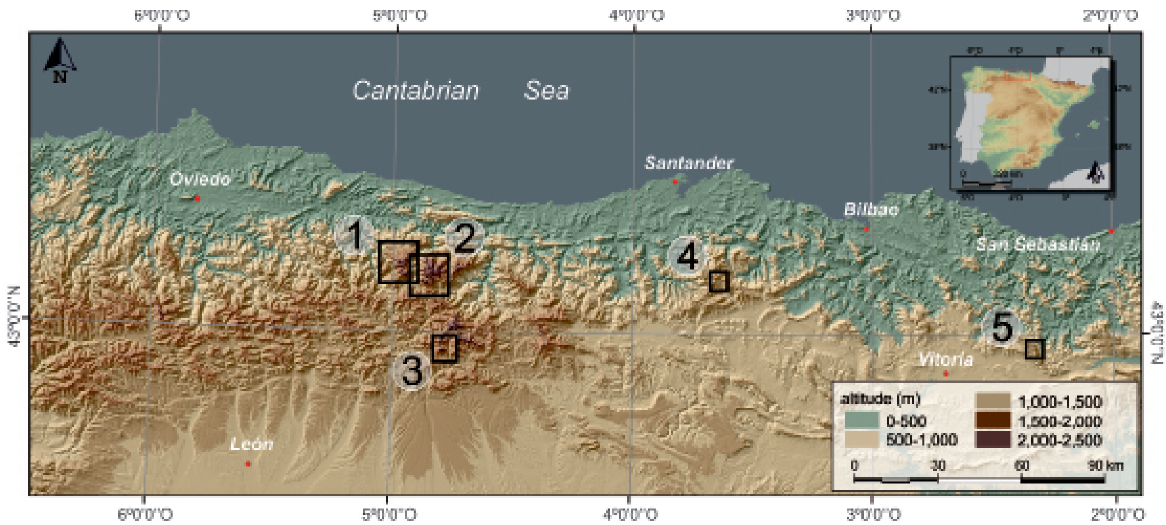


Figure 1. Massifs with ice caves cited in the Cantabrian Mountains and location of the Picos de Europa: 1) Western massif (Picos de Europa); 2) Central massif (Picos de Europa); 3) Montaña Palentina; 4) Valnera massif; 5) Aitzgorri massif (inventory from Gómez-Lende and Serrano, 2018a).

*Figura 1. Macizos con cuevas heladas de la Cordillera Cantábrica y ubicación de los Picos de Europa: 1) Macizo occidental (Picos de Europa); 2) Macizo central (Picos de Europa); 3) Montaña Palentina; 4) Macizo de Valnera; 5) Macizo de Aitzgorri (inventario de Gómez-Lende y Serrano, 2018a).*

The ice caves studied are Peña Castil, Verónica and Altáiz, located above 2,000 m a.s.l. Peña Castil ice cave (IC) (2,095 m), Verónica IC (2,230 m) and Altáiz IC (2,190 m) (Figure 2). The annual mean snowfall is around 1.600 mm, and the snow cover at 2.040 meters of altitude is very unstable, changing from December to March between 0.60 and 3 m thickness, with the mouths remaining blocked for at least two months.

Although ice caves are abundant in the Cantabrian Mountains, systematic studies on their morphology and endoclimate began only a decade ago (Gómez-Lende *et al.*, 2011). Even though the available time series of endoclimatic data and limited number of direct observations do not permit a review of regional endoclimatic patterns, several cryogenic behaviours and thermal regimes have nevertheless been observed.

## *3. Methods*

A multiproxy approach was followed in the ice caves selected, the methods of which included cave monitoring (temperature, humidity, ice changes by Terrestrial Laser Scanner). The difficulty in accessing the Verónica and Altáiz caves limited the use of Terrestrial Laser Scanner (TLS), which could only be used in Peña Castil ice cave. Several surveys have been performed each year in Peña Castil ice cave (Gómez-Lende, 2016), where geomatic data collection (at least twice a year) of variations in the ice level were carried out at the surface of the ice block using a TLS medium range 3D Leica ScanStation C10. This equipment measures distances within a range of 1.5 to 300 m, with nominal precision of +/-6 mm at 50 m distance with normal illumination, scanning 40,000 points per second. The visual field has a scope of 270°x360°. The software used for recording and aligning the clouds of points and data treatment was Leica Cyclone 7.3 ©.

### *3.1. Internal climate monitoring*

Four dataloggers were installed between 2011 and 2020 in different frozen rooms of each of the three caves (Figure 3) to collect

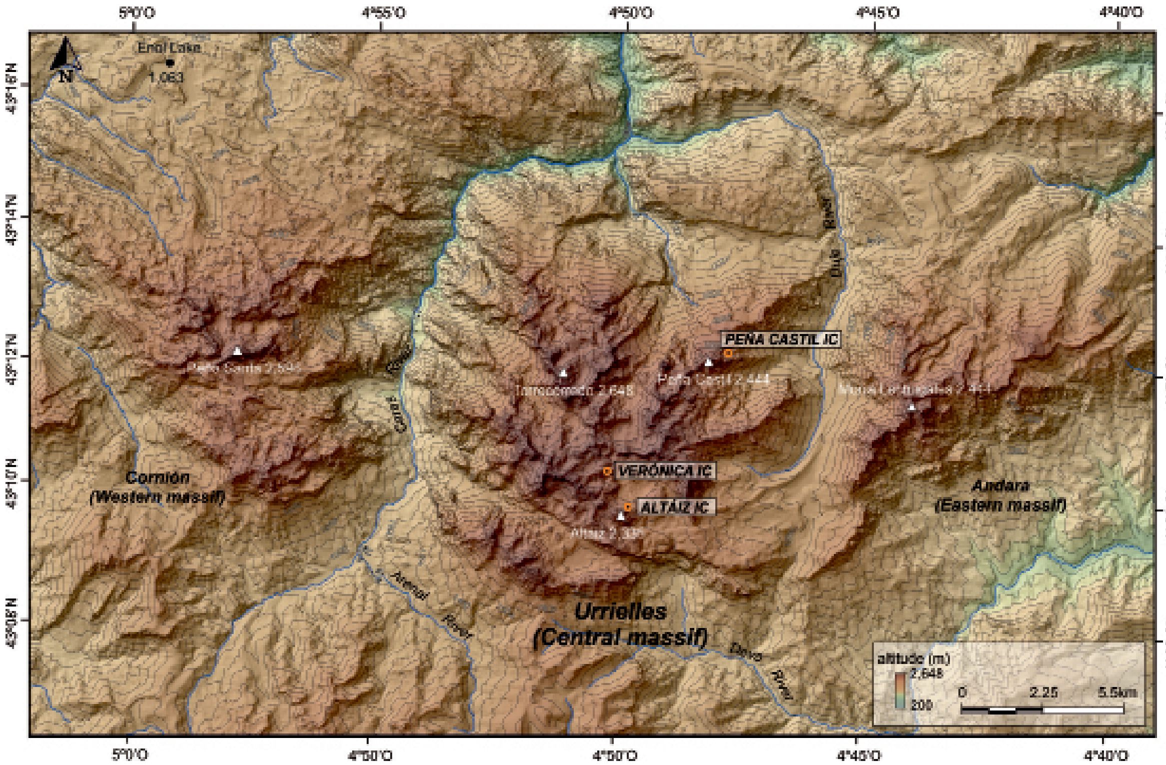


Figure 2. Main studied ice caves in Central massif of Picos de Europa.

*Figura 2. Principales cuevas heladas estudiadas en el macizo central de Picos de Europa.*

data of thermal regimes every four hours. The dataloggers were iButton DS1921G-F5 with thermal ranges between –40ºC and +85ºC and precision of 0.5ºC. The hygrometric records of the cavities were recorded using one thermohygrometer per cave, the iButton Hygrochron DS1923-F5 with precision in recording humidity of up to 0.04%, a range of thermal functioning between –20ºC and +85ºC and up to 100% humidity. In both cases, OneWireViewer Maxim© was used for programming software and data export. This instrument has been running continuously at the same points for nine years (Figure 3). Temperatures were occasionally recorded manually using thermometers to corroborate the data from the dataloggers by means of individual thermal recordings from the walls, cracks, ice block and cryospeleothems. The manual thermometers used were Hanna, Pt100-HI 9555501 with a precision of 0.1ºC.

### *3.2. Radiocarbon Dating*

Three tracers of vegetation only could be collected from the Altáiz (one location) and Verónica (two locations) ice caves (Gómez-Lende, 2015) by conventional radiocarbon using AMS facility of 14ChronoCenter (Queens University-Belfast) and calibrated using intcal.09.20 (Reimer *et al.,* 2020).

### *3.3. Cryomorphological topographies*

Cartography of cryomorphological elements from the ice caves is used to define the spatial-thermal distribution of ice caves (Gómez-Lende and Sánchez-Fernández, 2018) (Figure 3). An inventory and cartography of cryomorphologies have been done including topography, which allows the description of the different thermal sectors, and to identify permafrost environments within the caves.

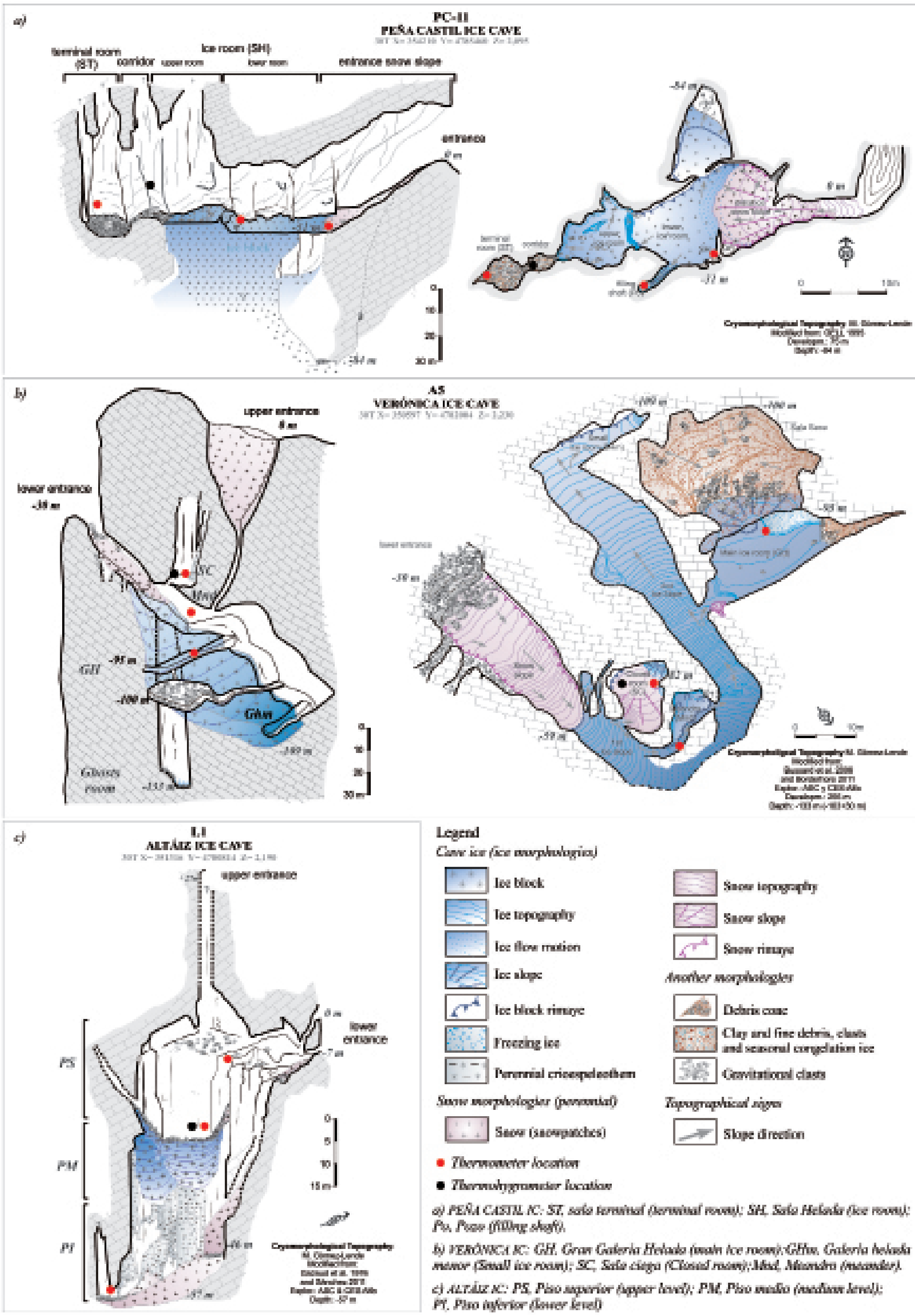


Figure 3. Cryomorphological topographies and datalogger locations in the studied ice caves: a) Peña Castil, b) Verónica, c) Altáiz.

*Figura 3. Topografías criomorfológicas y ubicaciones de los registradores de datos en las cuevas heladas estudiadas: a) Peña Castil, b) Verónica, c) Altáiz.*

### *3.4. Thermal mapping*

Thermal maps of the ice caves were drawn up. Mean annual, estimated for the main chambers of each cave in which the ice blocks are located. Thermal data from continuous dataloggers, manual thermometers, cryomorphological topographies and classical speleological topographies were integrated with a DEM result using GIS techniques in order to generate the thermal topographies (Gómez-Lende, 2016).

## **4. Results**

### *4.1. Temperature regimes below freezing point*

The temperature records show $MAAT_{cave}$ below 0°C in the chambers with ice blocks. February is the coldest month, with mean monthly temperature by year varying between –0.96°C and –3.45°C. Temperatures are influenced by external conditions during winter (namely *open period,* $T_{ext\ cave}<T_{cave}$) when airflow is towards the cave. During this time, a heterothermal regime is predominant. The warmest months correspond to summer (*closed period,* $T_{ext\ cave}>T_{cave}$), in which a homothermal regime close to 0°C predominates and external conditions have no influence. These data show that the evolution of winter seasonal temperatures is a more important factor than summer temperatures in maintaining cave conditions. Furthermore, the predominant temperature range in winter is between 0°C and –2°C (Figure 4).

In the studied caves $MAAT_{cave}<0°C$ are not recorded throughout the totality of the ice cave. These conditions occur around the ice rooms and the chambers and corridors closest to them (Figure 5). The warmest sectors show thermal irregularities with abrupt changes (as can be seen in the proximity of the cave entrance (PS) in the Altáiz ice cave and in the terminal room (ST) in the Peña Castil ice cave, in Figure 4).

### *4.2. Cryomorphologies and frozen features*

In the studied caves 32 cryomorphologies were inventoried, located in environments with seasonal or permanent ice (Figure 3). All of them indicate the permanence of $MAAT_{cave}$ below 0°C. Two types of cryomorphologies were differentiated in the studied ice caves: ice blocks and cryospeleothems. The ice blocks are permanent frozen bodies with stratified ice. The cryospeleothems fall into three main groups: accumulation, generated by ice refrozen; ablation, when ice portions are shaped by melting, dripping or sublimation; and mixed-genesis morphologies. The following cryomorphological processes were detected in all caves studied: refrozen ice, drip, flows, laminar flows, hoarfrost, air flows and standing water forming cryomorphologies as ice cascades, frozen walls, ice mounds, icicles, ice scallops, hoarfrost crystals, frozen lakes and clasts from gelifraction (Gómez-Lende and Serrano, 2018b) (Figure 6).

Other morphologies also indicate periglacial environments within the caves. The most common ones are the walls of the frozen rooms, which are covered with sheets of ice during the open periods (mainly in winter) and the presence of cryogenic clasts fallen from the walls. Sediments deriving from decantation in cold environments, such as Cryogenic Cave Calcite fine (CCCfine) have sometimes been found in caves (Gómez-Lende, 2016). This is calcite precipitate from the segregation of solutes during freezing of water pools at the surface of cave ice deposits.

### *4.3. Chronology of the ice bodies*

The ages obtained from datings were 197±35 a BP for the sample from Altáiz IC, and 176±23 and 594±24 a BP for the two samples from Verónica IC, respectively (Table 1). The ages are very recent, but the ice blocks may be older since samples in the deeper layers could not be obtained. In the case of the Verónica 2 sample, obtained at a depth of –109 m, the ice block is older since

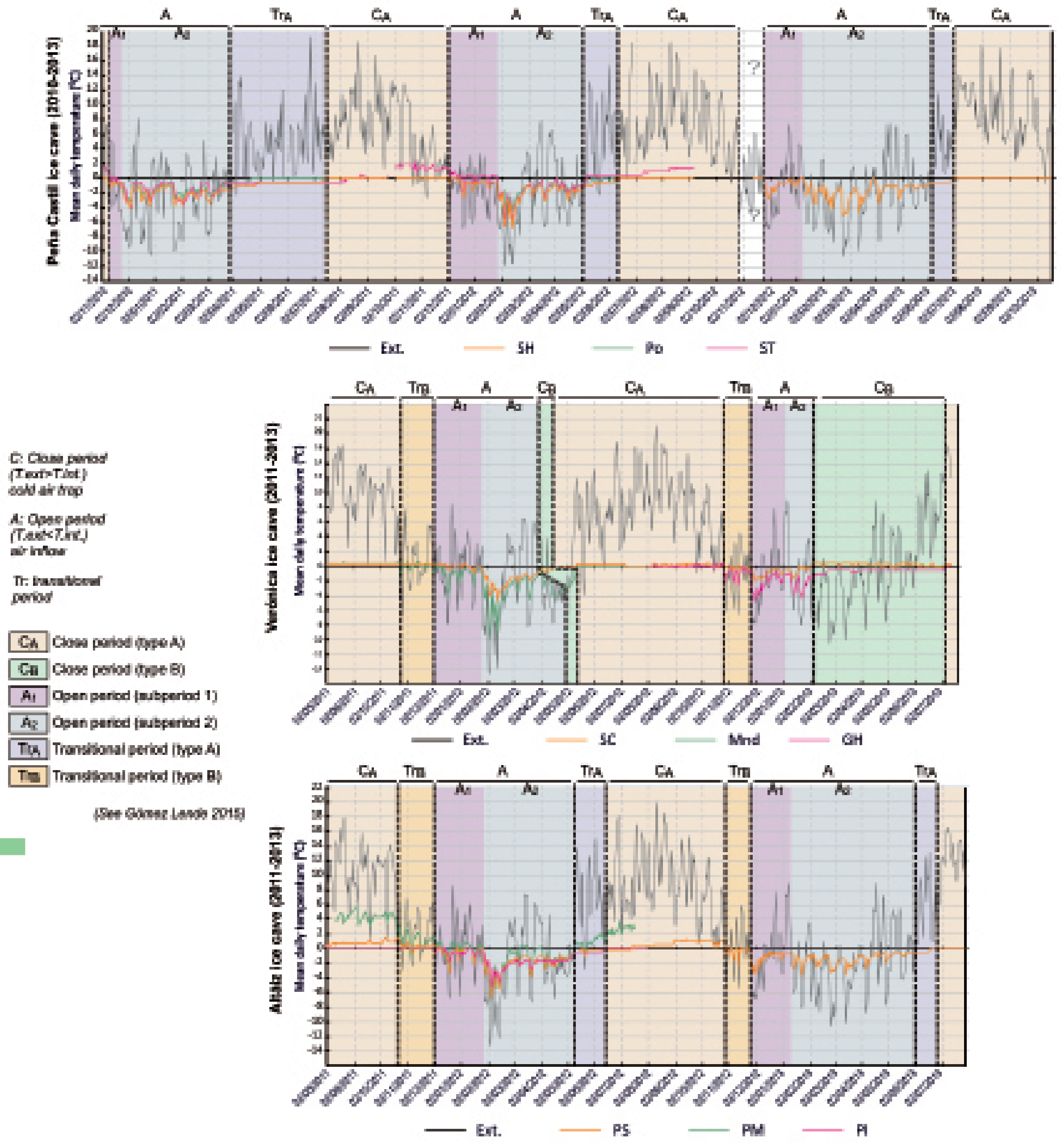


Figure 4. Temperature regimes in the studied ice caves (2010-2013).

*Figura 4. Regímenes de temperatura en las cuevas heladas estudiadas (2010-2013).*

it goes down to greater depths. The datings indicate that the ice block was there before the LIA (Little Ice Age) and is at least as old as the period immediately before the Medieval Warm Period (Table 1).

### *4.4. Cryomorphologies as indicators of subterranean subzero environments*

The ice blocks, understood as perennial cryomorphologies indicative of $MAAT_{cave}$<0ºC,

Table 1. Radiocarbon activity and calibration results of vegetal tracers from Altáiz and Véronica ice caves (Gómez-Lende, 2016).

*Tabla 1. Actividad de radiocarbono y resultados de calibración de los restos vegetales de las cuevas heladas de Altáiz y Véronica (Gómez-Lende, 2016).*

| Code cave | Code Lab. | Material | Depth ice block extraction (m) | $^{14}C$ a BP | Cal a AD 1 SIGMA | AMS $\delta^{13}C$ |
|---|---|---|---|---|---|---|
| Altáiz 1 | UBA-19412 | leaf | 25 | 197±35 | 1660-1681 | -23.0 |
| Verónica 1 | UBA-19413 | leaf | 95 | 176±23 | 1668-1682 | -21.9 |
| Verónica 2 | UBA-19414 | stick (branches) | 109 | 594±24 | 1314-1356 | -26.5 |

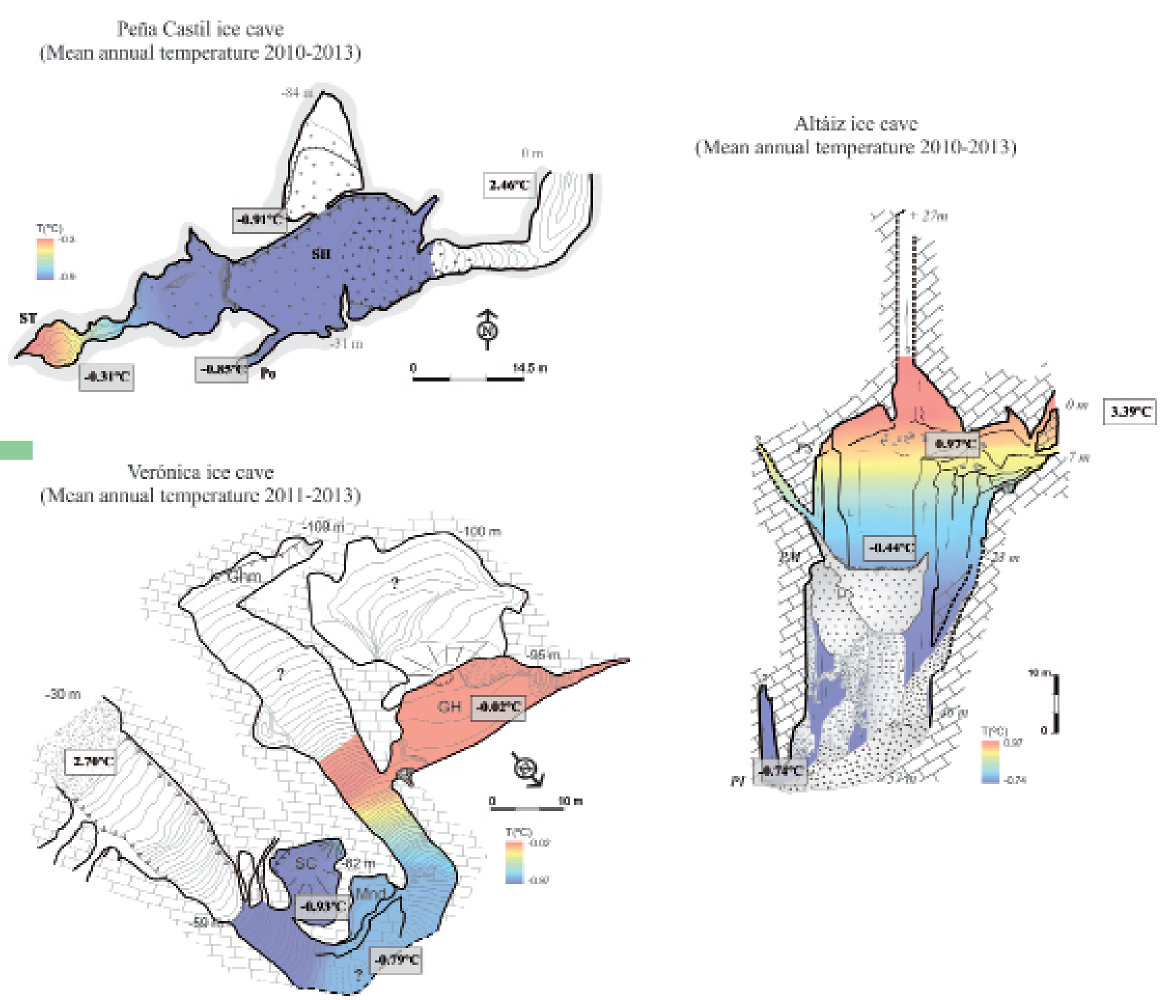


Figure 5. Thermal zones in the studied ice caves (2010-2013).

*Figura 5. Zonas térmicas en las cuevas heladas estudiadas (2010-2013).*


Figure 6. Some perennial cryospeleothems can be considered as indicators of permafrost environments by remaining frozen for several consecutive years (ice cascades in photos 1 y 2). Others one are indicators of periglacial environments (clasts from gelifraction and with certain sorting in photo 3; and frozen walls in photos 4 and 5).

*Figura 6. Algunos crioespeleotemas perennes pueden ser considerados como indicadores de ambientes con permafrost si permanecen congelados durante varios años consecutivos (cascadas de hielo en fotos 1 y 2), y otros son indicadores de ambientes periglaciares (clastos de gelifracción y con cierta clasificación en foto 3; y paredes congeladas en las fotos 4 y 5).*

are housed at different depths. In the case of Altáiz IC the depth reached is –40 m, whereas in Peña Castil IC it is –84 m and in Verónica IC, –109 m. Greater depths are reached in other ice caves of the Picos de Europa, as in the case of the HS4 ice cave, where ice blocks have been explored down to –260 m. Sediments deriving from decantation in cold environments, such as Cryogenic Cave Calcite, probably fine (CCCfine), have sometimes been found. CCCfine have been found in in the ice block of Peña Castil ice caves inside ice pools, on ice scallops and rocky scallops, and inserted within the ice block at –54 m, in the Peña Castil ice cave at –33 m and within fine ice layers of the HS4 ice cave at –260 m (Figure 7).

## 5. Discussion: ice caves and permafrost

### *5.1. On the concept of permafrost and its presence in ice caves*

CCCs are considered permafrost morphologies indicators within ice caves due to their formation in freezing environments, and


Figure 7. Cryogenic calcite (CCCfine) located in several sector of Picos de Europa ice caves: 1 and 2) cryogenic calcite in ice pools; 3 and 4) cryogenic calcite in different scallops (-33 m in Peña Castil ice cave).

*Figura 7. Calcita criogénica (CCCfine) ubicada en varios sectores de las cuevas heladas de Picos de Europa: 1 y 2) calcita criogénica en depresiones de hielo; 3 y 4) Calcita criogénica en diferentes scallops (-33 m en la cueva helada de Peña Castil).*

their isotopic analyses have been used to establish past environmental conditions during the Pleistocene, known as the Last Permafrost Minimum (Orvošová *et al.*, 2014; Vandenberghe *et al.,* 2014). These authors considered ice caves to be permafrost environments. Richter *et al*. (2010) also refers to this type of CCC pool sedimentation as an indicator of permafrost periods. CCC coarse and CCC fine genetic conditions are very different. While CCC coarse is related to permafrost environments, not always the CCC fine, because a fast freezing of water can generate CCC fine by sudden temperature oscillations without a permafrost environment (Koltai *et al.,* 2021; Spötl *et al.,* 2021; Munroe *et al*., 2021).

Such indicators, in the studied ice caves and the permanent ice blocks in an environment where the $MAAT_{cave}$ is <0$^{o}$C for several years, support the argument that these are permafrost environments. The concept of permafrost from the thermal point of view and the results of the present study lead to the consideration of ice caves as indicators of permafrost presence in the Picos de Europa. Permafrost plays a role, at least in the case of the caves studied, as one of the most prominent factors defining mountain permafrost.

The ice caves studied have environments with $MAAT_{cave} \leq 0^{o}C$. The climate has changed several times since their genesis due to endokarstic configurations and topoclimatic changes, and the importance of water and heat transfer —the air and water circulation systems— has become primordial. The cold environment in the ice caves, remains due to the null solar radiation, the high degree of humidity, the perdurability of accumulated snow and air currents. These latter are fundamental in maintaining the negative 'thermal anomaly' with respect to the $MAAT_{ext.cave}$ within the ice caves (Lismonde, 2002; Luetscher and Jeannin, 2004; Luetscher, 2005; Kadebskaya and Tchaikovskyi, 2009; Mavlyudov, 2009). All of them are essential for maintaining permafrost conditions and they are the factors that differentiate them from the multiple non-ice caves nearby. Many of the ice caves studied were a permafrost feature until the last decades of the 20th century (Morard *et al.,* 2012; Richter *et al.,* 2010; Harris and Brown, 1978, 1982; Haeberli, 1978; Harris, 1979, 1982; Pissart *et al.,* 1988; Urdea, 1993, 2004; Ohata *et al.,* 1994), although in most cases they were interpreted as such due to the lack of specific studies (Harris, 1979), rather as an atypical phenomenon of permafrost that did not quite fit into the categories traditionally considered. Haeberli (1978) referred to the "special feature of perennially frozen ground"; Urdea (1993) to the "special form of the permafrost's existence", and French (2007) included them generically as "other types of ice" within the category of "ground ice" (Figure 8). Harris (1979, 1982) consid-

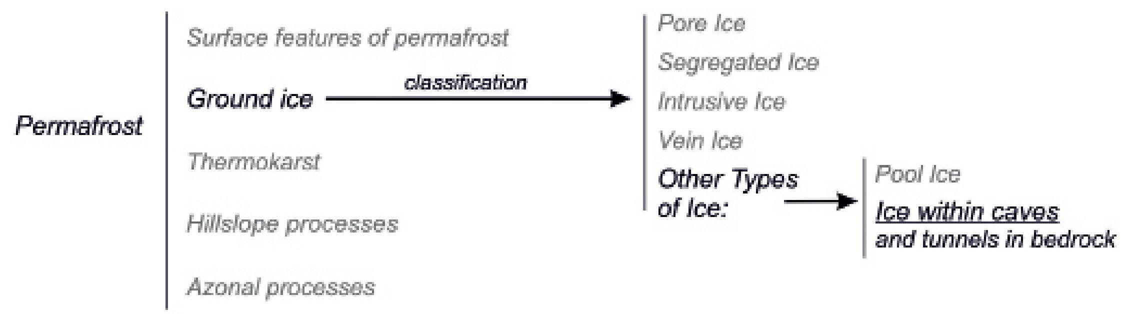


Figure 8. Types of permafrost according to French (2007). Ice caves are placed in a category that classifies them in a catch-all generic group and gives rise to ambiguity.

*Figura 8. Tipos de permafrost según French (2007). Las cuevas heladas se clasifican en un grupo genérico general y da lugar a ambigüedades.*

ered ice caves to be one more element of permafrost environments, commonly located in continuous and discontinuous permafrost areas, or sporadically, and always in environments with mean temperatures below +5ºC. In other studies, ice caves were considered as permafrost environments because of the permanence of ice blocks (Holmlund *et al.,* 2005; Perşoiu and Onac, 2012). Silvestru (1999) stated that "for perennial ice to accumulate it is essential that the Annual Mean Temperature remains below 0ºC"; and Yonge (2004) considered the siting of the cave in a permafrost area (high latitudes or altitudes) to be the reason why its walls are also subject to freezing temperatures. The Swiss Geomorphology Society considered ice caves to be manifestations of the cryosphere situated in the interphase of glacial and periglacial domains and as examples of sporadic permafrost. The denominations used have been highly varied, and difficulties arise when trying to include them within some of the pre-existing expressions due to local factors and not to zoning rules (Table 2).

The presence of ice caves has also been used as an indicator of mountain permafrost (Serrano *et al.,* 2009) in the Spanish Pyrenees, and as "*permafrost in caves*" in the Cantabrian Mountains (Pellitero, 2012). The endoclimatic and cryomorphic studies in the Picos de Europa ice caves show the importance of endoclimatic factors rather than exoclimatic, and the disconnection between to surface and subterranean thermal conditions. Although continuous and depth permafrost can condition the thermal regime in caves, we can prove that the cave factors are determinant. These factors are the snow feed, cave morphology and airflow that generate an endokarstic permafrost environment with annual medium temperatures around 0ºC, independently of the surface environment. Therefore, it may be related to a 'special feature', 'local', 'isolated' or 'patchy', but the ice caves environment remain independent of permafrost type and ground thermal conditions outside the cave. On the specific nature of the studied environments, we can define this type of permafrost environment as a cave

Table 2. Denominations of types of permafrost and ice caves according to different authors

*Tabla 2. Denominaciones de tipos de permafrost y cuevas heladas según diferentes autores*

| **Terminology** | | **Cited by authors** |
|---|---|---|
| **Permafrost** | **Ice caves** | |
| Local | Special feature of perennially frozen ground | Haeberli (1978); Žák *et al*. (2004); Richter and Riechelmann (2008); Richter *et al*. (2010); Luetscher *et al*. (2016) |
| Extrazonal | Special form of permafrost's existence | Urdea (1993); Morard (2011) |
| Ground ice | Other types of ice | French (2007) |
| Non-conventional | | Ford and Williams (2007) |
| Isolated or sporadic | | Luetscher *et al.*(2003); Urdea (2004); Stoffel *et al.* (2009), Luetscher and Bourret (2010), Morard (2011) |
| Patchy | | Mihevc *et al.* (2016) |
| | Preserved due to permafrost conditions | Holmlund *et al.* (2005); Perşoiu and Onac (2012) |
| Permafrost in caves | | Pellitero (2012) |
| | Cryospheric interphase between glacial and periglacial domains under discontinuous alpine permafrost | Swiss Geomorphological Society |

mountain permafrost environment, the most suitable for unequivocally denominating the ice caves located in the mountains.

*5.2. On the concept of ice caves as permafrost from the morphogenetic point of view.*

An added difficulty in qualifying ice caves as permafrost comes from the morphogenetic conception (permafrost as sub-surface frozen material). To consider an ice block to be permafrost is not correct. In some cases, it appears more a glacial mass than a periglacial feature or a type of thermal permafrost. When the ice block housed within the cave has the characteristics reflected in Figure 9, fundamentally its ice motion, it has often been denominated a subterranean glacier (Maire, 1977; Eraso and Pulina, 1994; Perşoiu, 2005; Tulis and Novotný, 2006; Andrejchuk, 2009). For ice blocks without ice motion resulting from successive re-freezing of underground lakes, such a name is incorrect. Under the definition of ice cave used in this study, the ice block is

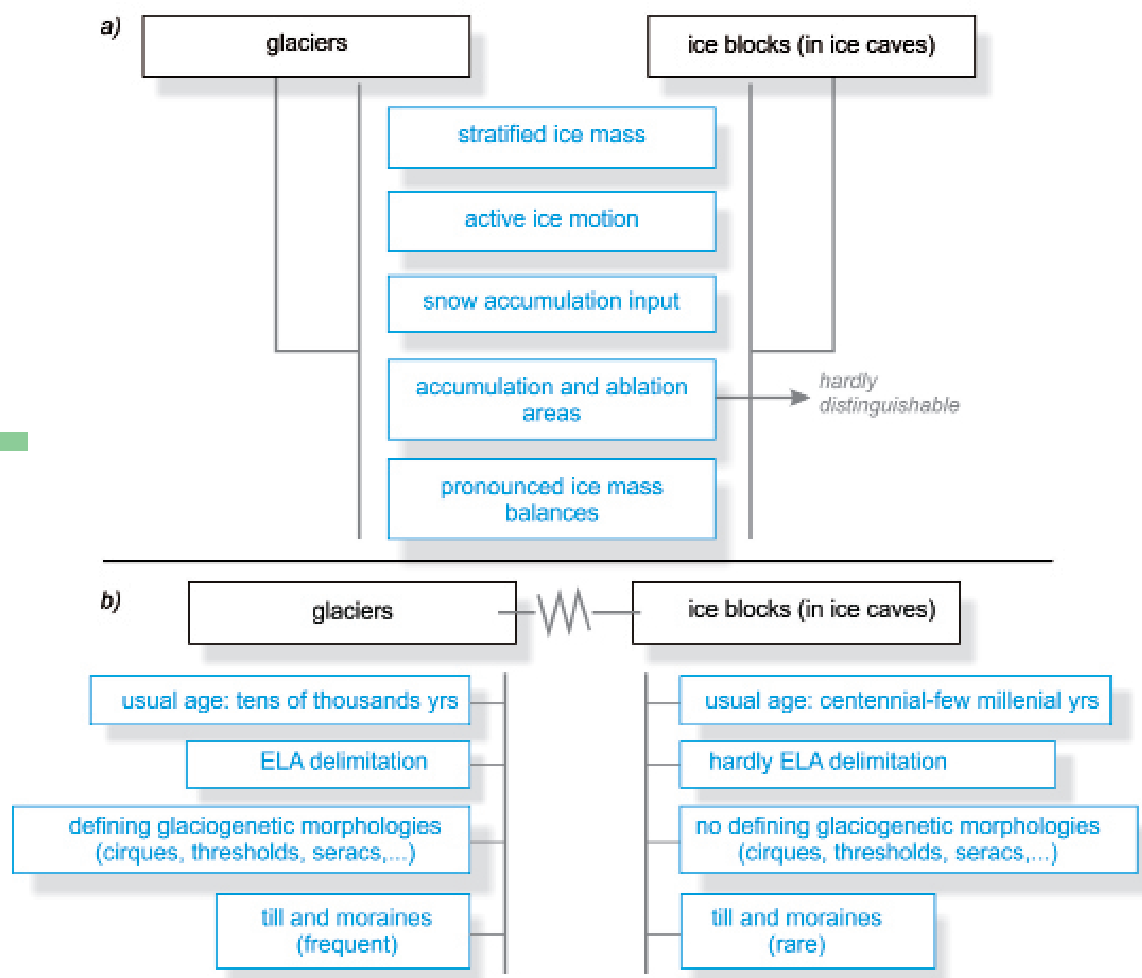


Figure 9. Ice caves versus glaciers: similarities (a) and differences (b).
*Figura 9. Cuevas heladas versus glaciares: similitudes (a) y diferencias (b).*

not considered as a type of permafrost itself, but rather as a permafrost environment indicator, whether it has ice motion or not, and only some parts of the ice cave would have a permafrost environment (Figure 10). Certain characteristic processes of surface periglacial environments, such as gelifraction, cryoturbation and frost shattering can be generated in ice caves. There are also landforms such as flowstones, ice needles, patterned ground, and clay hummocks under periglacial conditions (Luetscher *et al.*, 2005; Bella, 2006; Mihevc, 2009; Kosutnik, 2011; Morard, *et al.*, 2012; Zák *et al.*, 2012; Mihevc, 2014; Colucci *et al.*, 2016).

In the studied caves, around thirty classified cryomorphologies, both perennial and seasonal, and related to periglacial processes have been inventoried, including the precipitations of calcite. Both are located between the ice strata and the surface of some ice blocks, and on scallops on the walls. In the Picos de Europa CCC they are located between –10 and –280 m depth inside the ice caves and at altitudes between 2,180 m and 2,350 m. The CCCcoarse are deposits developed in permafrost environments, as a consequence they are used as the altitudinal limit of permafrost (Žák *et al.,* 2004, 2012; Richter and Riechelmann, 2008; Richter *et al.,* 2010; Luetscher *et al.*, 2016; Orvošová *et al.,* 2014).

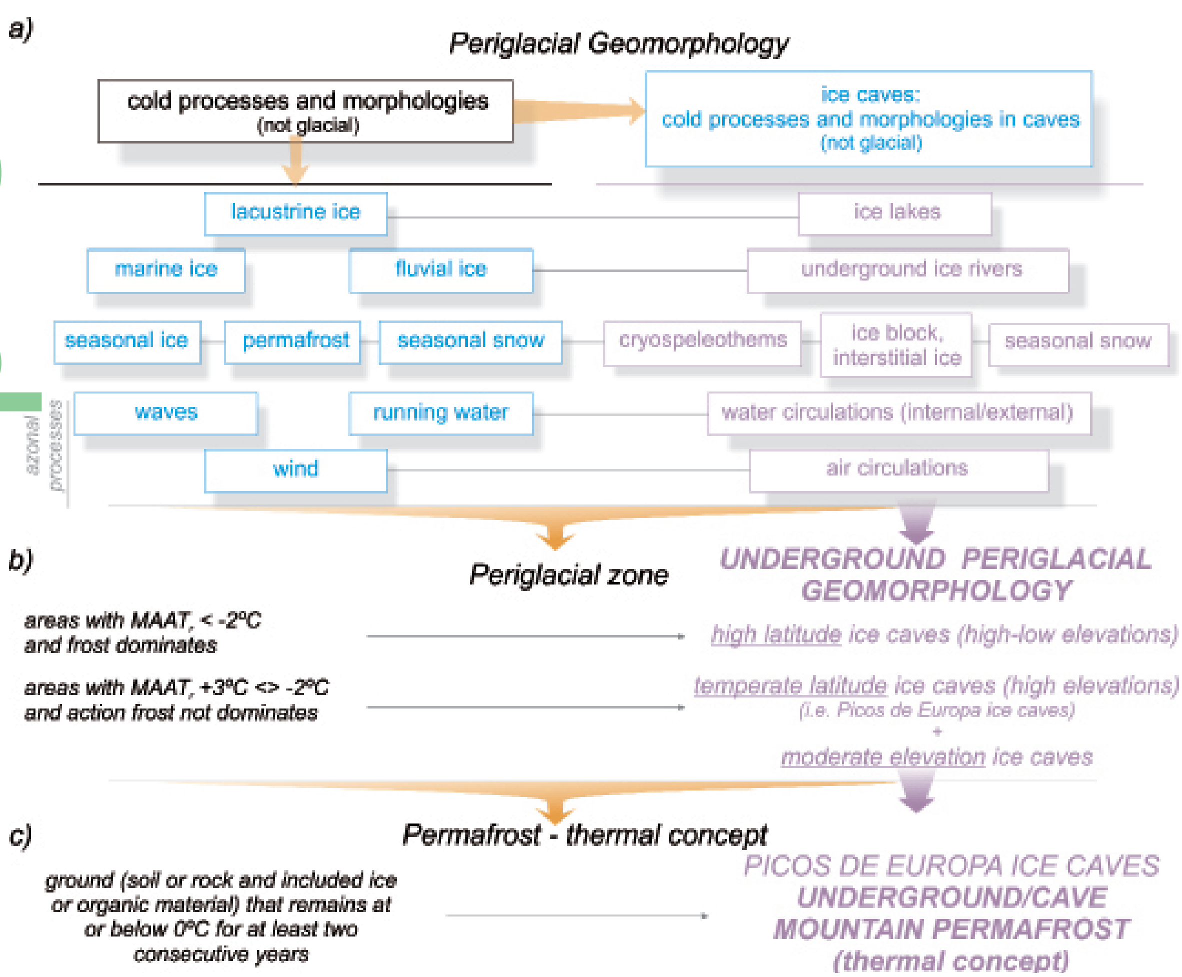


Figure 10. Ice caves in periglacial geomorphology.

*Figura 10. Las cuevas heladas en la geomorfología periglacial.*

### *5.3. On the ages of ice blocks and their implications on the cave mountain permafrost environment in the Picos de Europa*

We have already seen how the cold environment remains because of the accumulated snow and airflow, the fundamental processes that maintain the negative 'thermal anomaly' with respect to the $MAAT_{ext.cave}$ (Lismonde, 2002; Luetscher and Jeannin, 2004; Luetscher, 2005; Kadebskaya and Tchaikovskyi, 2009; Mavlyudov, 2009). If we consider the ice caves as a periglacial element indicator of permafrost environments during the LIA, as the datings point to, several implications on the potential altitudinal changes of periglacial belts can be established.

The 0ºC isotherm at the surface during the LIA has been estimated at 2,341 m in the more favourable topoclimatic areas, and the lower altitude of the fronts of the LIA glaciers was at over 2,190 m (González Trueba, 2007). Not all cavities above 2,100 m are ice caves and the LIA glacier fronts were located below this altitude. Some subsurface ice blocks are located at around 300 m depth in some caves, such as the Hs4, whose entrance is at 2,350 m. The ice blocks, therefore, did not reach the lower altitude of glacier fronts until the LIA or more recently. The 0ºC isotherm cannot be estimated from the altitude of the ice caves studied, neither for that time nor for the present because they denote thermal anomalies as we have already stated. The existence of ice caves, in greater numbers during the LIA, would confirm a thermal anomaly at around 100-200 m below the 0ºC LIA isotherm. As not all the caves are located at similar elevations, this fact does not imply a general reduction of the altitude of the surface isotherm.

The lowest limit of surface sporadic permafrost is located at 2,230 m in the Jou Negro cirque. If we consider the altitude of frozen chambers with permafrost environments and the altitude of ice cave vents, all located above 2,100 m altitude, the lower limit of the permafrost would be lower, falling by approximately 100 to 150 m, clearly in discordance with surface thermal conditions.

Finally, if during the MWP the mean temperature were 1ºC higher than the LIA mean temperature, it would imply an altitudinal increase in the regional paleo-MELA (2,700-2,750 m). The necessary conditions for the genesis of glaciers were not met, although this could have been otherwise under the surface. As we consider that the Verónica ice block may have generated prior to the beginning of the LIA (Table 1), the conditions necessary for the generation of ice bodies within the caves of Picos de Europa began before the LIA glaciers, and the subsurface ice bodies are still preserved today (Figure 11).

The existence of subterranean ice bodies in the caves of Picos de Europa disagree with surface thermal conditions during the LIA and those at present, as it is a thermal anomaly; and processes inside the ice caves are independent of ground and surface processes and thermal regimes, all of which support the existence of a permafrost environment partially disconnected from surface environments and typical of temperate high mountain karst systems with distinctive permafrost environments.

## 6. Conclusions

The Picos de Europa ice caves are located in the high mountain above 2,000 meters. The ice caves are understood as natural karst caves (geomorphological element) in which a perennial ice mass is housed (periglacial cryological element) under a climate directed by its endokarstic condition with a $MAAT_{cave}$<0ºC for at least two consecutive years. These conditions are only present around the existing ice masses between the first 200-400 m depth. Water and snow circulation are the fundamental hydrological elements in the feed and persistence of the ice blocks, and air circulation is the fundamental thermal element in the maintenance of the mean sub-zero temperatures. Both are the defining

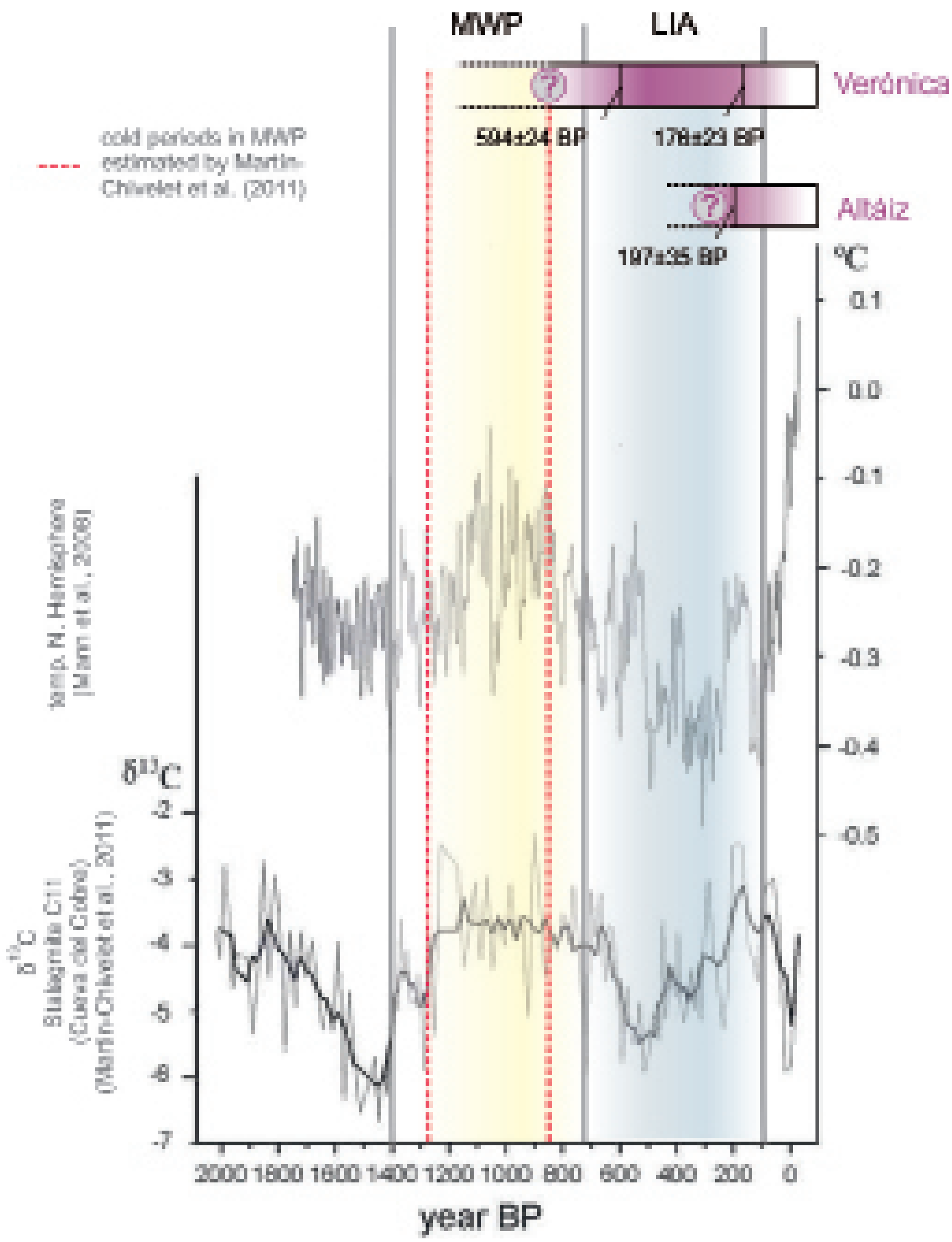


Figure 11. Time of the Altáiz and Verónica ice blocks related to the chronologies and paleotemperatures estimated for MWP and LIA. Paleotemperatures are estimated for the Northern Hemisphere (Mann *et al.,* 2009), the accumulated series of δ13C are taken from the geochemical analysis of a stalagmite in the Cueva del Cobre (Montaña Palentina-Cantabrian Mountains) by Martín-Chivelet *et al.* (2011). (Modified from Martín-Chivelet *et al.,* 2011).

*Figura 11. Período abarcado por los bloques de hielo de Altáiz y Verónica dentro de las cronologías y paleotemperaturas estimadas para el Periodo Cálido Medieval y la Pequeña Edad del Hielo. Las paleotemperaturas son estimadas para el hemisferio norte (Mann et al., 2009), las series acumuladas de δ13C se toman del análisis geoquímico de una estalagmita en la Cueva del Cobre (Montaña Palentina-Cordillera Cantábrica) (Modificado de Martín-Chivelet et al., 2011).*

elements in ice caves and permafrost environments. These features permit ice caves to be defined as indicators of permafrost environments regardless of the environmental conditions on the surface. Ice caves can be located both in surface permafrost environments and in periglacial ones without permafrost. This is the case of the Picos de Europa high mountain, where the ice caves are located in periglacial environments without permafrost, but the caves contain cave permafrost environments.

Due to the widespread existence of this type of environment in many regions, mainly at medium latitudes and in the calcareous High Mountain, and to the difficulty in framing them in permafrost environments, for this type of permafrost we propose the term "cave mountain permafrost environments". This terminological proposition is supported by its endokarstic nature in a mountain environment, the exchanges of air masses between the exterior and the interior of caves with an alternation of open and closed periods, the $MAAT_{cave}$<0°C and an important snow feed.

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