Geogr. Fis. Dinam. Quat.
37 (2014), 141-150, 10 figg.

DOI 10.4461/GFDQ.2014.37.13

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MORPHOLOGY, ICE TYPES AND THERMAL REGIME IN A HIGH MOUNTAIN ICE CAVE. FIRST STUDIES APPLYING TERRESTRIAL LASER SCANNER IN THE PEÑA CASTIL ICE CAVE (PICOS DE EUROPA, NORTHERN SPAIN)

ABSTRACT: GOMEZ LENDE M., BERENGUER F. & SERRANO E., *Morphology, ice types and thermal regime in a high mountain ice cave. First studies applying Terrestrial Laser Scanner in the Peña Castil ice cave (Picos de Europa, Northern Spain).* (IT ISSN 0391-9838, 2014).

The Picos de Europa form the highest massif of the Cordillera Cantabrica, northwestern Spain. It is a high mountain belt (1800 to 2650 m) which is characterized by a nivoperiglacial morphodymanic and periglacial conditions in its upper part (above 2200 m). Its sharp topography, climatic conditions, thick carboniferous limestones and large altitude differences provide the environment for a highly developed mainly vertical endokarst in which ice caves are commonplace. Geomorphological studies on ice caves that go beyond topographic descriptions are so scarce as to be practically non-existent.

The application of Terrestrial Laser Scanner (TSL) technology is crucial to monitor cave ice evolution, ice flow and for surveying specific cave morphologies.

Preliminary temperature data obtained for the Peña Castil ice cave by dataloggers inside the cave and from an automatic meteorological stations outside show a static behaviour of the cave with two main periods (open and closed) and two secondary ones (transitional periods). The zonal distribution of temperatures shows differing behaviour in the cave as we move away from the influence of the ice deposit. There is a main ice accumulation period linked to snow cover melt (peaking at the beginning of June) which is characterized by large cryospeleothems and a visible refreezing cap on the ice body surface. In late fall or early winter, the ice body is weakest.

Likewise, we identified different ice structures and cryospeleothems based on their origin and crystallization process, and highlighted those observed for the first time in the Picos de Europa, e.g the radicular crystallization hoarfrost.

KEY WORDS: Ice caves, Thermal regime, Ice morphology, Terrestrial Laser Scanner, Picos de Europa, Cantabrian Mountains.

RESUMEN: GOMEZ LENDE M., BERENGUER F. & SERRANO E., *Morfologías, tipos de hielo y régimen térmico en una cueva helada de alta montaña. Primeros estudios aplicando laser escáner terrestre en la cueva helada de Peña Castil (Picos de Europa, Norte de España).* (IT ISSN 0391-9838, 2014).

Los Picos de Europa son el macizo más alto de la montaña atlántica del suroeste de Europa. Las condiciones topoclimáticas, las masas calcáreas del Carbonífero y los fuertes desniveles configuran un desarrollo endokárstico esencialmente vertical en el que se concentran algunas de las mayores profundidades del mundo. En este contexto existen cuevas heladas, que más allá de reconocimientos topográficos no han sido estudiadas hasta ahora.

La aplicación de Láser Escáner Terrestre (TSL) se muestra decisiva en el control de la evolución y flujo del hielo, así como en el estudio de las características de la propia cueva.

Los primeros resultados climáticos obtenidos para la cueva helada de Peña Castil mediante termorregistradores continuos en el interior de la cavidad y estaciones meteorológicas automáticas exteriores nos indican un comportamiento estático de la cueva en la que se distinguen dos periodos térmicos principales (abierto y cerrado), y otros dos periodos secundarios (periodos transicionales). De igual forma la distribución zonal de las temperaturas registradas, a pesar del escaso desarrollo horizontal de la cavidad, muestra diferentes comportamientos a medida que nos alejamos de la influencia del bloque de hielo. Se distingue también un periodo principal de acumulación de hielo vinculado a la fusión del manto nival con crioespeleotemas voluminosos y una visible capa de recongelación superficial sobre el bloque de hielo. Siendo a finales de otoño y principios de invierno cuando éste se encuentra más debilitado.

Se identifican distintas estructuras del hielo y diferentes crioespeleotemas dependiendo de su origen y cristalización, destacando entre ellas algunas no apreciadas hasta el momento en otras cuevas heladas de Picos de Europa como las cristalizaciones radiculares de sublimación.

PALABRAS CLAVE: Cuevas heladas, Régimen térmico, Morfología de hielo, Láser Escáner Terrestre, Picos de Europa, Montañas Cantábricas.

INTRODUCTION

In the Picos de Europa, ice caves are recognized but rarely go beyond a merely speleological or mountaineering observation, with a few mentions of their geoheritage value in specific cases (González Trueba, 2006). They have not been heavily researched in spite of the long and acclaimed tradition and speleological history of its caves.

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This research was funded by I+D Programme of the Ministry of Science and Innovation (project CGL-2010-19729) and the Ministry of Environment (OAPN-053/2010). We wish to thank CES Alfa and GELL (Grupo Espeleológico La Lastrilla), speleological associations, specially to Javier Sánchez, Emilio Herrera and Enrique Ogando. We are also grateful to Marc Luestcher and anonymous reviewers for their manuscript improvements.

This paper presents the first study of one of them, Peña Castil ice cave, in this high mountain environment and describes its general thermal evolution, relationship with outside parameters, and its most characteristic ice morphologies. In addition laser scanning technology has been used for the first time to obtain topographic models and precise orthoimages to determine relevant quantitative parameters and to monitor their future evolution.

In this respect and in spite of the fact that the use of laser scanning technology in geomorphological studies has been well tested in many of fields (p.e. Pfeifer & *alii*, 2011), its use in the geomorphological study of caves has, to date, failed to become so widespread (p.e. Roncat & *alii*, 2011; Canevese & *alii*, 2008; 2009; 2011) mainly due to the caves' complexity. Its application has usually been limited to obtaining three-dimensional topographies.

In the Picos de Europa these difficulties in the field work are accentuated by the vertical nature of the caves and there are no previous studies in which terrestrial laser scanner (TLS) has been used. In nearby areas it has been used for palaentological studies in some caves (p.e. Santos Delgado & *alii*, 2012).

The use of these techniques is exploited even less in the study of ice caves, with their use limited to some recent cases mainly oriented to the development of photorealistic digital models and occasional precise calculations of the ice body surfaces of some of the most famous show caves (e.g. Milius and Peter, 2012). In the ice caves of the Tatra Mountains (Poland), Lodowa in Ciemnak, geodesic work has been carried out for 3D reconstructions with differential GPS and for the study of ice block volume (Rachlewicz & Szczuciński, 2006).

The potential of TLS for the study of ice caves, together with the climatic and morphological description of the cave in question, opens a door to new studies leading to a better understanding and explanation of their processes and evolution.

STUDY AREA

The Picos de Europa is the highest massif in the Cordillera Cantabrica in northwestern Spain. It reaches the high mountain belt (between 1800-2650 m) and is characterized by a nivoperiglacial morphodymanic and a periglacial one above 2200 m, where the snow and cold shape an inherited glaciokarstic landscape.

In the present day there are no glaciers but there still remain ice-patches (e.g. Serrano & *alii*, 2011). The topography, climatic conditions, thick carboniferous limestones and significant altitude differences provide the conditions for a considerable endokarstic development, mainly vertical, which house some of the deepest caves in the world: Torca del Cerro del Cuevón-Saxifragas (–1589 m), Sistema de la Cornisa-Magali (–1507 m) and Sistema del Trave (–1441 m) (FEE, 2012). In this context ice caves are common. To date at least 50 caves with perennial ice have been inventoried.

The Peña Castil ice cave is located in the central massif of the Picos de Europa (43°1'21"N/4°47'48"O) in a glacial cirque under the Peña Castil summit (2444 m) and hanging over the Duje valley (fig. 1). The lower entrance is located at 2095 m with an eastern orientation without other entrances worth consideration. Speleological surveys haven´t found another lower entrance, although the cave morphology suggests minor upper entrances (vertical shafts are observed in corridor, terminal room and upper ice room ceilings with dripping) (question marks in fig. 2). The horizontal development is around 65 m and the vertical one is unknown. The cave entrance comprises a sloping ramp (entrance snow slope; *sector 1*) leading to two main ice rooms (lower and upper room; *sector 2 and 3*) in which the ice body is located, and a small terminal room (*sector 4*) after passing trough a narrow corridor (*sector 5*). Both without perennial ice. There is a small filling shaft accessed from lower ice room descending a narrow ramp. The perennial ice deposit surface is 629 m^2 and its thickness, as far as is known to date, is at least –54 m. It involves an estimated ice filling of at least 33.300 m^3 (fig. 2).

METHODOLOGY

For the exploration, research and monitoring of the Peña Castil ice cave systematic field studies are being carried out as well as a study of meteorological parameters provided by two automatic meteorological stations (EMA) near the cave: La Caballar (Sotres, Asturias) and Verónica (Camaleño, Cantabria), belonging to the «Red de Seguimiento de Cambio Global del OAPN».

The field work has been carried out since 2010, adding to the intense and prolonged work of the Grupo Espeleológico de La Lastrilla (Cantabria) in this sector of the Picos de Europa and the explorations of the CES ALFA (Madrid) in October 2011.

The climatic monitoring of the cave is based on temperature and airflow recordings by means of manual instruments, which in addition permits the validation of continuous recordings of temperature obtained with iButton DS1921G thermo dataloggers with measurement intervals set at 4 hours (fig. 2).

The study and analysis of ice structures and their different morphologies with their classification has been performed based on similar classification methods for other ice caves (e.g. Bella, 2006; Persoiu, 2004).

A systematic control (at least twice a year) of variations in the ice level were performed since October 2011, both at the surface of the block and at the different cryospeleothems and their volumes through the use of TLS medium range 3D Leica ScanStation C10. But the results about ice morphologies evolution are waiting to be published. This equipment measures distances in a range from 1.5 to 300 m, with a nominal precision of +/– 6 mm at a distance of 50 m with normal illumination and under conditions of reflectivity, scanning 40000 points per second. The vertical visual field has a scope of 270°x360°. The software used for the recording and alignment of the clouds of points and data treatment is Leica Cyclone 7.3 ©.

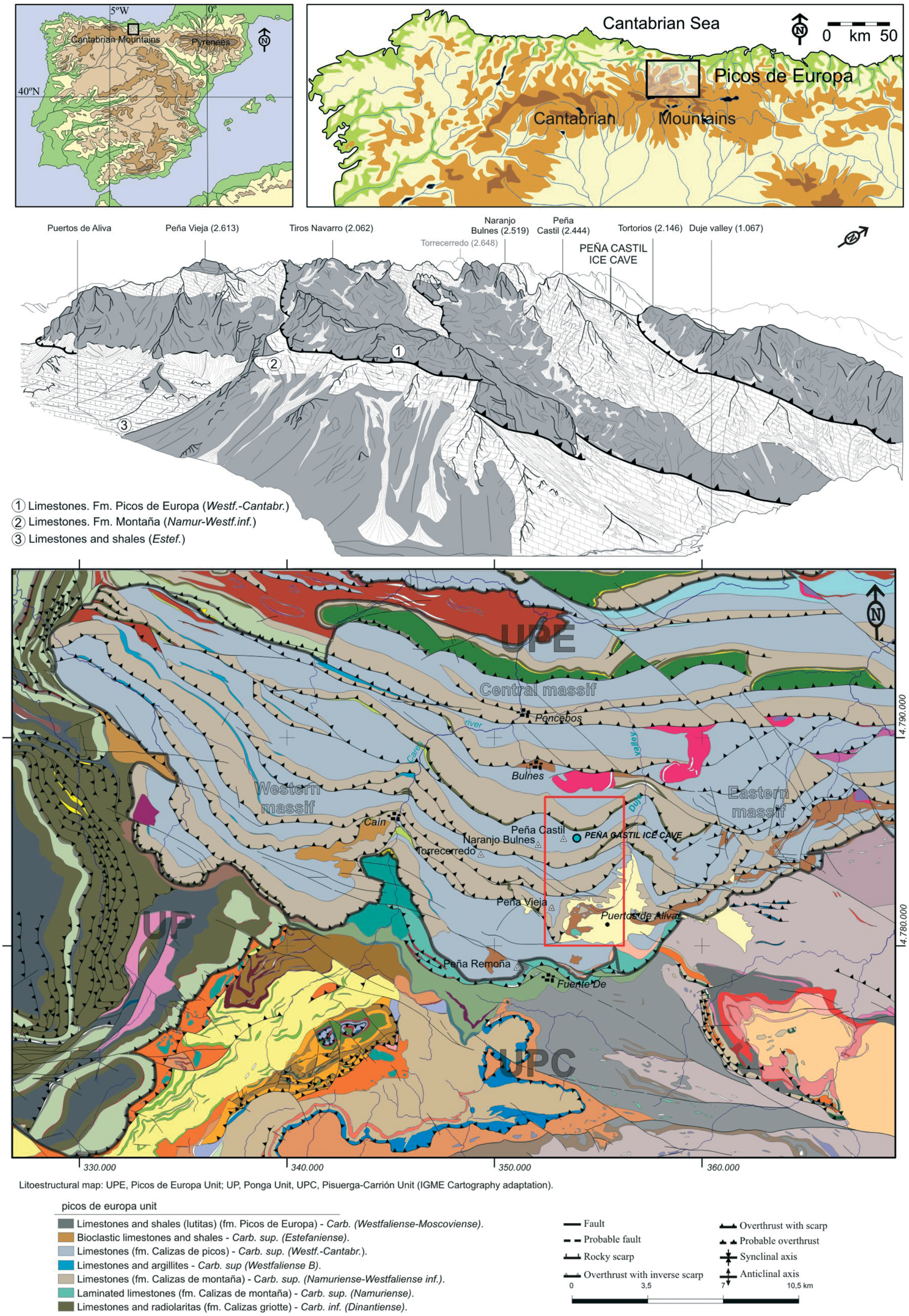

FIG. 1 - Location of Peña Castil ice cave.

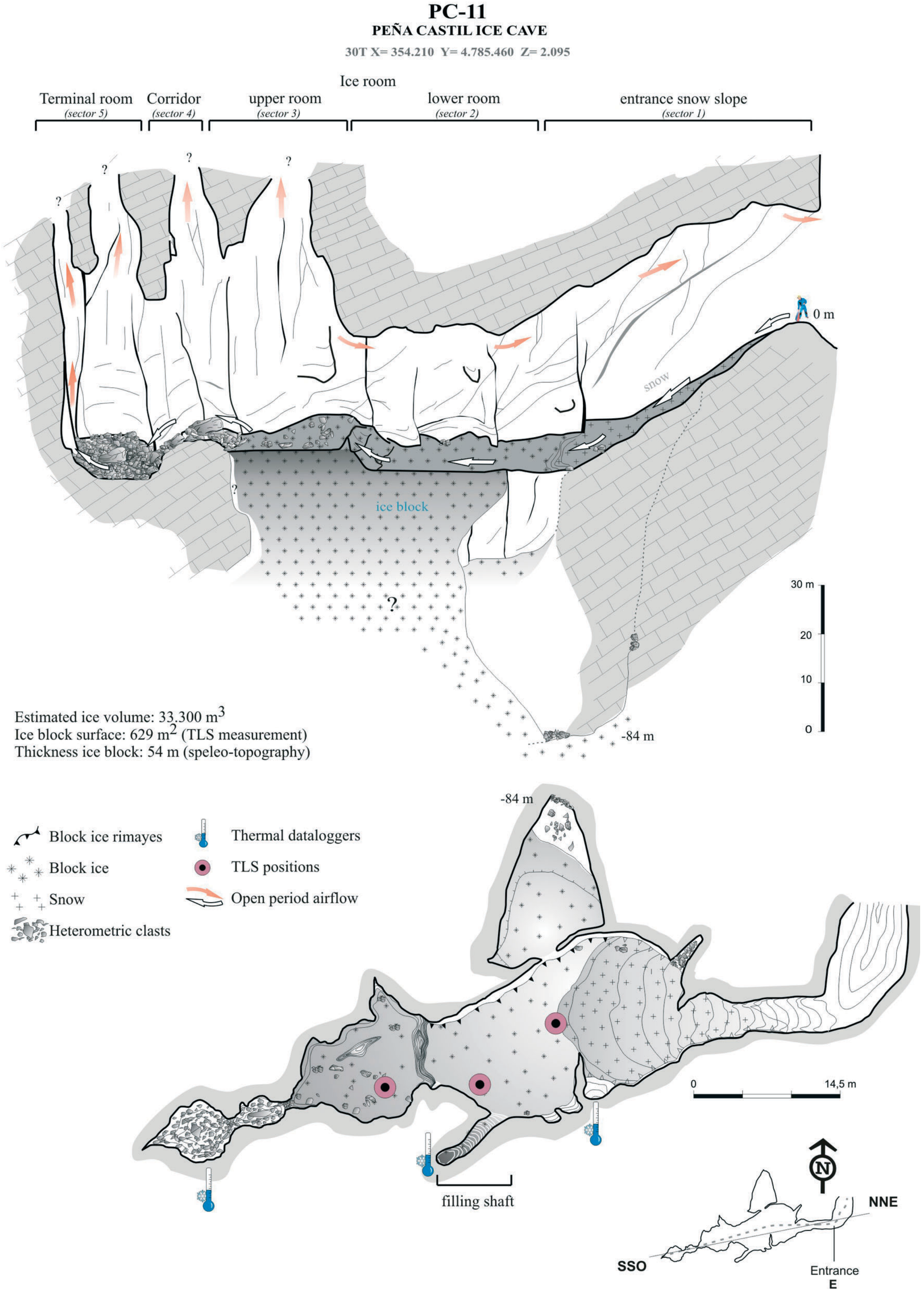

FIG. 2 - Peña Castil ice cave topography (ice block depth modified from Ogando, 1995). Coloured arrows show the inside seasonal airflow (only in winter time): upper ones are warm air masses, lower ones are cold air masses.

TLS measurements were taken at the entrance, in the ice rooms and in the most nearby ones in the Peña Castil ice cave. In order to minimize effort, time and avoid occlusions gaps, it was necessary to plan the number of scans and their location previously. Also wall irregularities determined the position and the number of scans needed. With a total of three scans at medium resolution and a total duration of 7.5 minutes each a cloud of 76,178,580 points was obtained. Following a process of cleaning, regulating and triangulation of the cloud of points a 3D model of the cavity was obtained, from which true orthoimages were derived (not obtained by rectification) in which the relief effect is corrected. The result of these models of spherical field of view (V270-H360º) is that the vertical topographical component, one of the factors very important for ice caves but often omitted from cave studies, is easily and accurately mapped. Both walls and ceilings, which in many of the cavities of the Picos de Europa are very difficult if not impossible to access.

In this case, Peña Castil ice cave, the opacity of the ice interface is appropriate to consider no penetration depth or reflexion in TLS signal and the measurements have a good behaviour at the ice surface.

Anyway, the TLS method and the orthoimages obtaining for Peña Castil ice cave are explained more fully in Berenguer & *alii* (2014) (differential rectification method of orthoimage generation, correct process, or relief effect).

RESULTS

THERMAL REGIME

The first climate results obtained by dataloggers inside the cave and exterior meteorological stations show a static behaviour of the Peña Castil ice cave (e.g. Luetscher & Jeannin, 2004). Two main thermal periods can be differentiated, an open period between November and February characterized by the influence of external conditions (heterothermal regime predominance), and a closed period free of external influences and with stable temperatures close to freezing point (homothermal regime predominance), taking place between May and September. There are also two transitional periods. In these cases the temperatures are increasing or descending progressively until they have adjusted to those of the main periods.

The mean annual air temperature inside the cave (MAAT inside) doesn´t rise above 0ºC in any room during the control time, recording –4ºC at the coldest and exceptionally +2ºC at the highest (daily mean temperatures), which was only reached in the terminal room during some days in autumn (fig. 3).

Seasonal transition

The cave MAAT recorded during the 2010-2011 cycle did not exceed 0ºC, although in the terminal room (ice-free) the maximum values were above 0ºC for 26 days, particularly in October (fig. 3.a).

During the open period the lowest temperatures ranged between –4º and –3ºC and are provided, at certain times, by a cold air inflow inside the cave resulting from a marked fall in the exterior air temperature (below 0ºC) (fig. 3.b). At this time there is a good correlation between inside and outside temperature variations, although throughout the whole period the correlation between both evolutions is not so good due to large increases in exterior temperature. During the closed period the outside temperature did not influence the inside cave temperature.

The temperature time series shows a negative trend in winter and displays a slow and stepwise increase in early

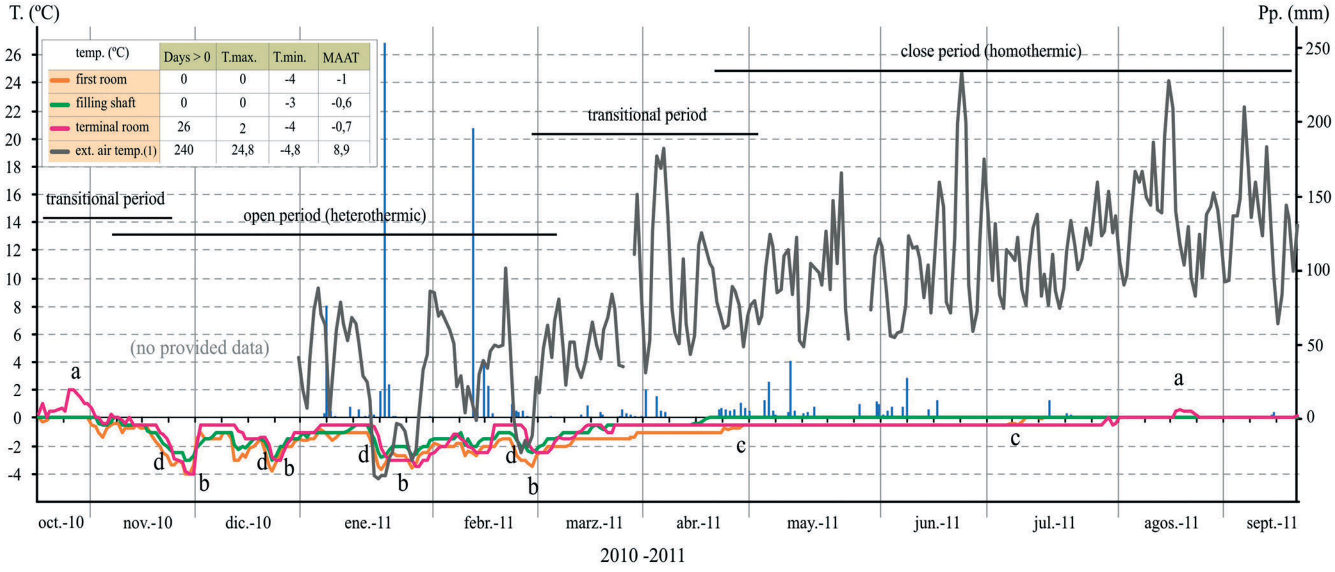

FIG. 3 - Thermal regime in Peña Castil ice cave. (1) Referencial Authomatic Meteorological Station: La Caballar-Sotres 1257 m a.s.l (Asturias, P.N. Picos de Europa).

spring to reach 0ºC, and then a slow and stepwise decrease in November. During the summer months temperatures remain stable, close to 0ºC without remarkable variations (fig. 3.c).

Spatial transition

The cave MAAT recorded in the ice rooms is lower (–1ºC) than in the terminal room and the filling shaft (both without ice body) and more days were recorded at the lowest temperatures than in the other rooms (8 days with –4ºC in the ice room whereas there were only 4 days in the terminal room and none in the filling shaft). In the monitored zones the recorded MAAT are slightly higher: –0.57 ºC in the filling shaft and –0.69ºC in the terminal room.

The spatiotemporal evolution inside the cave reveals slight thermal delays depending on the area. For example, several times a year temperature changes in the terminal room occurred exactly one day after similar changes in the first rooms (ice rooms) (fig. 3.d).

Morphologies and structural ice types

Inside the Peña Castil ice cave there is an ice body and several seasonal cryospeleothems distributed throughout the cave.

The ice body's width is not known accurately nor is its volume owing to the fact that the lower cave part is still not accessible (estimated ice volume at least 33.300 m^3). The ice body surface is divided in two distinct sectors. In the first clastic sediments are not observed, but there are organic material patches (branches, leaves, lichens, etc) and fine sediments accumulate in ablation morphologies (especially in early winter). In the second sector of the ice body, the upper ice room, there are abundant heterometric clasts and sunlight no longer affects it. In this sector it is sometimes difficult to estimate the ice body surface due to numerous clasts on the ground. Cryoturbation can be observed in finer sediments (sand and gravel) (fig. 4). Nowhere in the cave have been found evident periglacial morphologies, like sorted stone circles, polygons or stripes. The ice body shows multiple strata, some of them with fine sedimentary inter-stratification. There are some particularly wide layers of around 50 cm with clear ice in which air bubbles and internal microfractures can be observed. Descending along a rimaye permits the observation of ice scallops produced by air fluxes as well as horizontal/subhorizontal melt channels and bridges (fig. 5). The whole ice body structure has a noteworthy massive disorganized polygonal pattern. The ice is covered with a layer of external water and re-frozen with a filamentous aspect perpendicular to the arrangement of the strata.

FIG. 4 - Weak fine sedimentation movement caused by refreezing water (left photos); and fine sediment accumulation in ablation morphologies (right photo).

FIG. 5 - Melt channels and bridges inside the ice body.

Meanwhile, cryospeleothems are widespread in the cave, especially in certain periods and zones. Among the cryospeleothems that we have been able to distinguish in the Peña Castil ice cave are (fig. 6):

a) infiltrated water cryospeleothems which can be formed: (a.1) by dripping (like stalagmites, stalactites, clear icicles, opaque icicles, ice pearls, bamboo-stalagmites, ice mounds); (a.2) by water flow (ice columns or icefalls); (a.3) by rock sheet water flow (ice curtains, organ tubes or ice flags); (a.4) or by thin frozen sheet water on the ground (flat ice floor, pond ice).

b) sublimation cryospeleothems as sublimation stars that have only be seen in specific areas of the cave and not in other studied ice caves in Picos de Europa. These have a small size and only appear attached to rockwall scallops.

The field observations of cryospeleothems in the Peña Castil ice cave demonstrate that most are seasonal morphologies which form every year. Only the presence of sublimation stars is difficult to ensure every year due to their fragility. We appreciate that in late May-early June cryospeleothems represent a considerable ice volume. These periods are the optimum moments for cryospeleothem formation, after which they disappear completely in October/November, when the open period comes and temperatures begin to drop. At that moment there are very common clear icicles and ice pearls (dripping and ablation morphologies).

The size of the ice crystals changes depending on the shape and the cryomorphology. Characteristic polygonal crystals can be observed in many cryospeleothems (ice curtains, falls), typical concentric crystallizations in the stalagmites or stalactites, or ice structures with oxygen bubbles. Normally, the shape or size of the polygons or bubbles varies depending on the cave ice structure. We also observed, for example, different type of icicles depending the speed of its development and the load of mineral concentration: very sharp icicles probably caused by rain infiltrated water in November with a very swift development and they are clearer than others probably due to reduced sediment load.

3D SURVEYING AND MODELS

Using this technical surveying we´ve obtained an approximation of the exact reality which could not, until now, be achieved using traditional techniques (e.g. zenithal views or mapped vertical walls or ceilings) (fig. 7).

We develop 3D models from which we obtain orthoimages (fig. 8) and allow to work at millimetric scales, and observe angles and perspectives which are often impossible to be obtained within the cave itself. Together with the orthoimages, this facilitates the photo-interpretation of geomorphological features that would otherwise, if they were at all possible, be imprecise (figs. 9, 10).

Likewise, its accuracy has allowed us to calculate the surface ice body and estimate its volume, which would be at least 33.300 m^3. In making 3D models we might also estimate the total ice volume, calculating seasonal cryomorphology volumes observed in the ice cave at the end of open period. And its evolution. Future research inside the ice cave is planned to control and calculate this evolution and seasonal volumes.

TLS software gives colour to the orthoimage based on the main materials that recognizes, with different colour intensities (fig. 7 and 8).

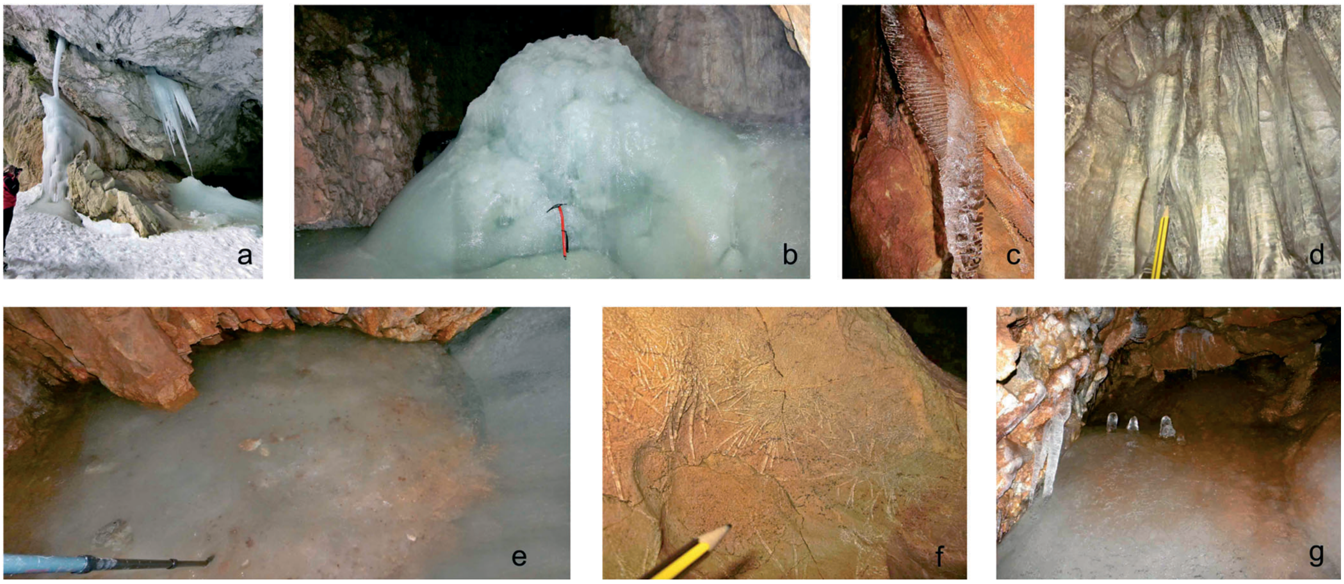

FIG. 6 - Some cryospeleothems in Peña Castil ice cave. a) ice stalactites, columns and icefalls by dripping and flow water in lower entrance and ice room; b) ice mound located between lower and upper ice room; c) small ice flags spread over many rockwalls; d) ice organ tubes caused by rock sheet water flow; e) pond ice in the small filling shaft; f) sublimation ice stars attached to rocky scallops in upper ice room; g) small bamboo-stalagmites over an icefall.

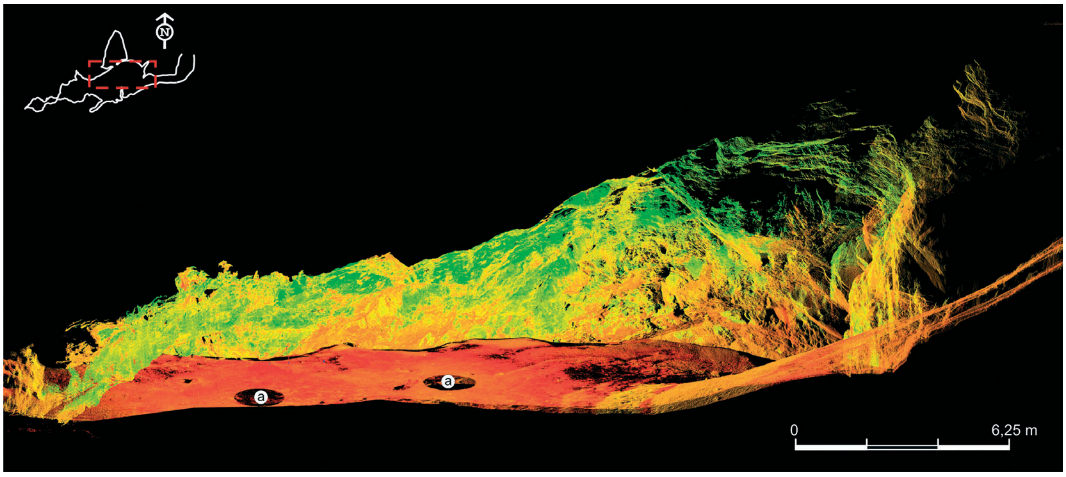

FIG. 7 - Lower ice room TLS cross-section. a) TLS positions.

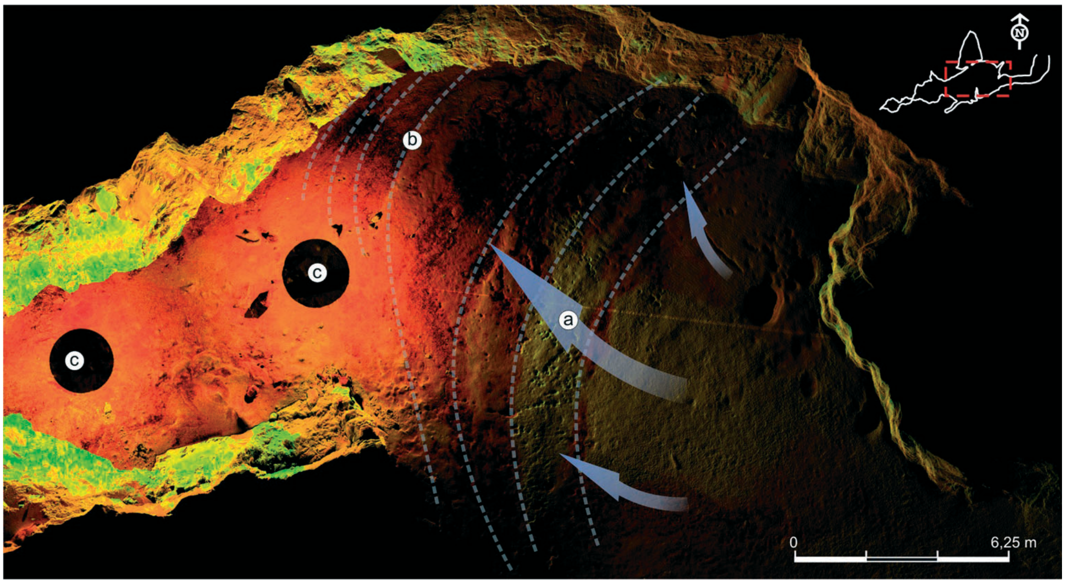

FIG. 8 - TLS orthoimage (zenithal view); blue marks show thrust (a) arcs on slope entrance (snow) and (b) arcs on ice body (ice). Arrows indicate the direction flow; c) TLS positions.

On one hand, the 3D model of the cavity allows the observation of how one of then main inputs in the feed to the ice block (the direct supply of snow from the exterior) exerts pressure on it by pushing it towards the interior of the cavity. fig. 8 shows an orthoimage of the three-dimensional model with a vertical perspective, practically impossible to obtain in the field of work. On the image pushing arches can be seen generated by the intrusion of the large snow mass of the cave's entrance. These arches are observed both at the ends of the snow slope and in the ice block, showing pressure exerted upon the block that implies a flow towards the interior of the cavity both horizontally and in depth. This flow is corroborated by the morphology and disposition of some grooves found in one of the walls of the ice room. In addition to this, the millimetric detail of the TSL models allows the geometrical monitoring of an internal fissure that crosses the ice body from one side to the other (fig. 9). Despite not having been possible to check it in the interior of the block (due to the sealing off of the ice) we assume that this was due to possible internal weakening of the block itself and/or of a pressure fracture and its displacement.

CONCLUSIONS AND OUTLOOK

The Peña Castil ice cave is a static cave with a large main entrance and its ice body is both a direct and an indirect consequence of snow. The direct one is the major factor, with snow accumulation and recrystallization from the first snowfall in winter to later ones in May. The indirect consequence provides decisive contributions of endogenous ice with water infiltrated cryospeleothems derived mainly from snowmelt in late spring (when exterior MAAT is high and cave MAAT is close to 0°C), although exterior

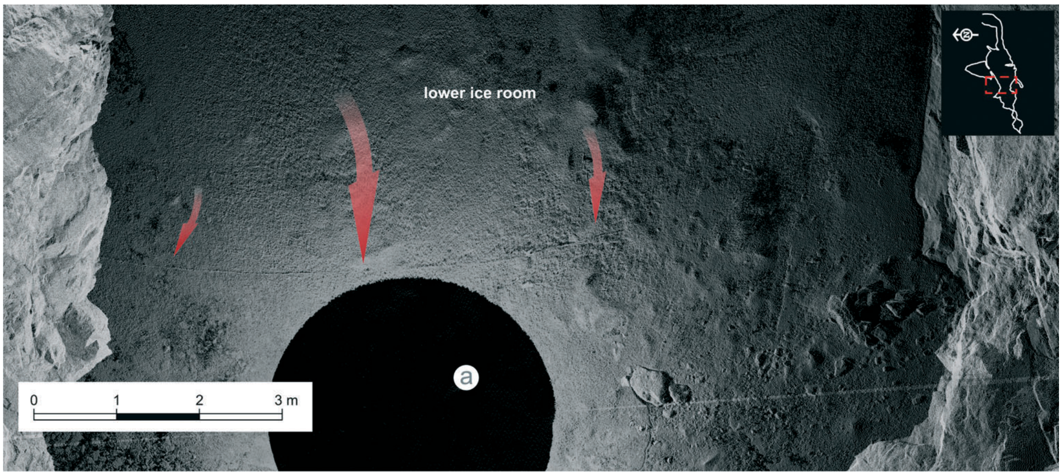

FIG. 9 - Accuracy TLS detail example. It shows a small intraglacial fissure inside the ice body. Arrows indicate the fissure. (a) TLS position.

snowpatches can sometimes remain throughout the year. At the bottom of entrance slope is preserved snow throughout the year and superficial snow cover evolution is an essential factor for the Peña Castil ice cave.

External climate factors are reflected in the cave climate during the open period, especially when the external temperature drops below 0ºC. During the closed period temperatures dissociate and cave MAAT remains stable. Both periods are separated by two intermediate trends of cave temperatures increasing (from mid-March to July) or decreasing (mid-October to late November). Thermal anomalies are recorded on certain dates and only in certain cave zones. We hope to confirm their causes in future studies.

Regarding ice mass balance, field observations lead to the conclusion that major ice formation is produced during spring when the superficial snow cover melt begins marked by an external temperature increase together with a cave temperature close to the freezing point. Also, spring rainfall contributes to the snow cover melt. In these dates large sublimation stars attached to wall scallops are observed, but we don´t know if they´re a remnant of the winter form or have formed in this period. Probably the first is right. When the closed period has been established infiltrated water decreases and cryospeleothems begin their slow melt, but the entrance slope permanence snow, which supplies certain inputs of fusion water and some thermal protection. Here water flows into the cave (infiltrated and snow ramp melt) are appreciable, and most ablation morphologies (moulins, bedieres, etc) begin to emerge. This situation reaches a peak around November when there is minimum water circulation (weakened and dried ice body) and the seasonal cryospeleothems are completely melted, only the large ones remaining (interannual cryospeleothems). Only in early autumn, with rain and weak snowfalls and decreasing temperature, do we observe accumulation ice morphologies such as clear icicles and accumulation/ablation ice morphologies such as ice pearls. During the open period, scarce inputs (direct input of snowfall incorporated through the exposed entrance) and lower temperatures prevent ice fusion or a fluid water stream.

TLS measurements reveal certain morphologies related to the ablation dynamics inside the ice body (internal fissures) and a direct push by slope snow with thrust arcs. Also, using this technology allows a precise monitoring of the surface ice body and the cryospeleothem volumes making it possible to obtain accurate ice mass balances (total width of the ice body unknown).

This study has shown that TLS measurements and models are very useful in geomorphological studies of ice cave. In the coming years these techniques will allow the surveying of exact variations of rimayes (fig. 10), cracks, fissures and changes in the ice surface as well as cryospeleothem volumes, and may support the accurate monitoring of the ice mass balance in the Peña Castil ice cave among others. It will also be possible to monitor the curvature of arches and fissures in the ice body, which may indicate ice flow, displacement or fragmentation.

Likewise, it may determine the evolution of morphologies of ice accumulation (mainly volumes) and snow slope volume, which could help to estimate exterior climate conditions and their annual evolution and correlation with processes inside.

The potential of these tools in the measurement of ice morphologies will provide an important source of knowledge concerning variations in surfaces, volumetries and ice thicknesses both intrannually and interannually. It will become decisive in calculation of ice mass balance. Without doubt, one of the greatest advances with the application of this type of technique is that it is an important step forward for the quantitative knowledge of the mass balance of an ice cave, a fundamental factor in the evolution of an underground ice block.

Future research inside the Peña Castil ice cave is planned to study these processes and evolutions, and to improve our understanding of the periglacial environment of the Picos de Europa.

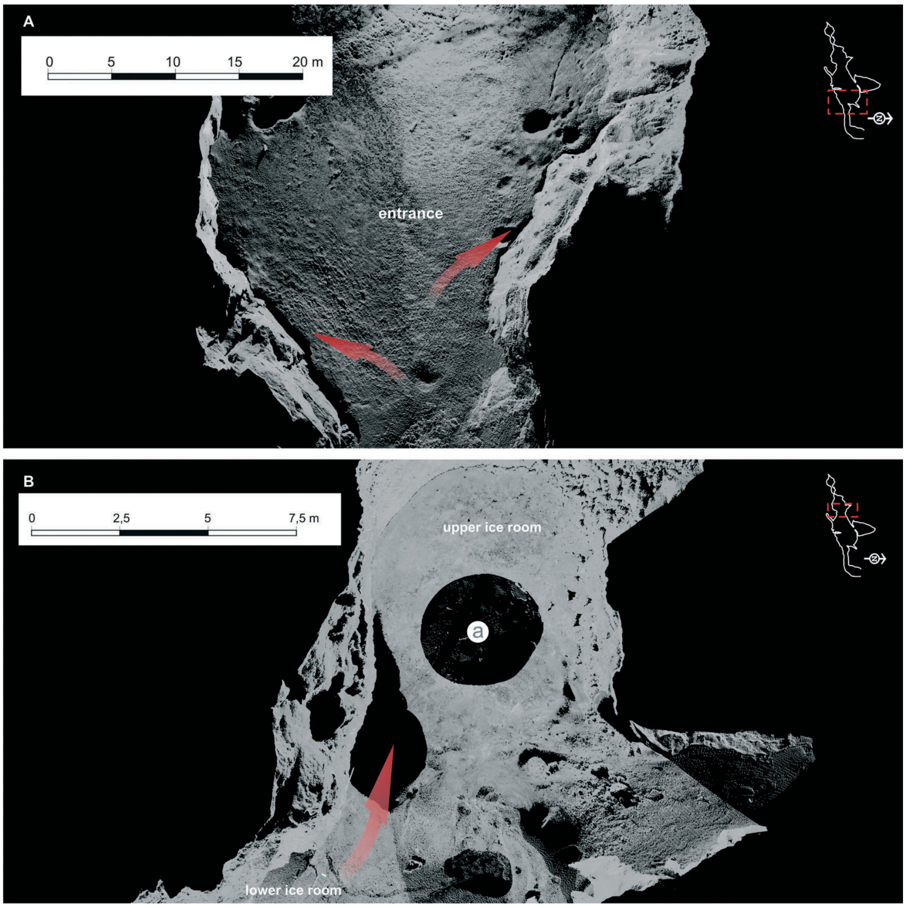

Fig. 10 - Evolution of "rimayes" can be measured accurately. Arrows indicate some rimayes: entrance rimayes (A) and block ice rimayes (B). (a) TLS position.

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(Ms. received 11 September 2013; accepted 30 April 2014)