Overall evaluation

The present study documents the presence of mountain permafrost in a cave of the Pyrenees, in a region where it is generally absent. The authors set out to characterise the permafrost conditions in Devaux ice cave and make a well-structured argument for the occurrence of past and present permafrost in a high elevation cave of the Pyrenees, and this assertion is well supported by adequate monitoring and observations of cryogenic cave sediment or morphologies.

The authors present a clear inventory of cryogenic and ice-related geomorphological features in a glaciated cave and attempt to link their spatial distribution to the various microclimatic or hydrological dynamics of the respective chambers/galleries. Substantial conclusions are reached on the causative mechanisms controlling the different ice morphologies reported in specific regions of the cave. To achieve this the authors use a combination of air, rock and water temperature monitoring to demonstrate the influence seasonal ventilation and hydrological activity in cave sector on the resulting cave ice morphologies. The monitoring set up adequately addresses the complex geometry of the cave, identifying both ventilated and poorly ventilated sections, and the attendant air and rock temperature patterns.

Additionally, the authors successfully demonstrate the cryogenic origin of several types of cave minerals using appropriate major ion geochemical analyses and stable isotope geochemistry. With special emphasis on cave gypsum, the authors explore the spatial relationships of the gypsum crystals with surrounding ice and cryogenic carbonate at both macro- and micro-scale, and provide a convincing first report of cryogenic gypsum in a limestone-bedrock cave.

Overall, the authors present a consistent and well-rounded study highlighting the localised nature of mountain permafrost, and those interpretations are well supported by figures of consistently high quality. This study is timely, it fits within the scope of the cryosphere and should be published with minor corrections, as outlined below.

- ➔ We thanks to referee #2 for the detailed review and the positive comments. We add here our responses while the modifications to the text and figures according to the reviewers' comments will appear in the track-changes version of the manuscript.

Minor comments

A) l90-91: I think this statement could be clarified or rephrased. Because one could argue that ice is also still being preserved at lower elevation sites due to the ventilation-driven thermal anomalies. In the frame of the present study, the main contrast between the mid and high elevation/latitude sites appears to be the contribution of heat conduction to the thermal balance of the cave (positive for the former, negative for the latter).

- ➔ Yes, we agree with the reviewer. The A294 ice cave (cited in the text in the next lines) is a relatively low-elevation cave in the Pyrenees, where the ventilation regime leads to a thermal anomaly that is the cause of the preservation of the ice deposit (Belmonte-Ribas et al., 2014; Sancho et al., 2018). We will rewrite the sentence indicating that ice in high-altitude and high-latitude caves can be preserved also by the presence of permafrost.

B) l98-99: The authors mention a little earlier that often ice caves do not inform about the wider thermal characteristics of the bedrock. When citing the example of ice cave A-294 (Sancho et al., 2018), which is located at an elevation of 2238 m asl with positive MAAT at the entrance, the authors could perhaps point out that this is another observation of sporadic permafrost, driven by the cave geometry, rather than by mountain permafrost as in the sense of this study. I would also suggest rephrasing this sentence (see technical comments).

- ➔ Ok, we will modify the sentence to stress that the A294 ice cave as well as the other Pyrenean caves represent sporadic permafrost occurrences.

C) l83 - here there could be some additional quantitative description of the cave geometries for the reader unfamiliar with cave exploration (include perhaps cross-section dimensions when mentioning narrow passages?). Figure 2B is good, but the blue-grey bedrock colouring is not included in the legend. For the reader, it could be helpful to add items in the legend, and perhaps colour coding the parts of the cave influenced by different thermal regimes, the outer sector and the inner one.

- ➔ We thank the reviewer for his suggestion to improve Fig 2. We will add the approximate dimensions of the chambers and passages named in the text. We will include the cross-section of some passages in the zoomed cave survey. We will remove the grey bedrock colour, will not saturate the figure with colours and we will add colours or symbols for the different thermal regimes. We will also add the limit of active layer, and the possible extension of permafrost from the entrance to the inner part of the cave.

D) l506-513, high thermal inertia - how long does it take to erase a climate signal from about 150 years ago, is the bedrock temperature consistent with the approx 1.5°C temperature rise since 1881 at Bigorre station?

- ➔ Coupling all thermal processes involved in heat propagation through a karst system, including diffusive and advective fluxes, is part of our ongoing research and beyond the scope of this article. Assuming heat transfer by diffusion alone, an external warming trend of c. 0.01°C a-1 would rise the cave temperature 200 m below the surface by c. 0.2°C after 150 years, depending on the boundary conditions and physical properties of the rock. These values are remarkably consistent with the Devaux rock temperature of -1.25°C measured at 60 cm depth in the poorly ventilated room D.

E) l315 - figure 5d, the air temperature variations at T11 and T5 (and T2) could be discussed in additional detail (at line 481 for instance). I think that, in summer, the lower correlation between the (T) loggers and the outside air (T) can also be explained by the influence of the outward air flow, whereby air temperature variations are more muted than during the winter inward air flow regime. Could the authors comment on this?

- ➔ Yes, we agree with this comment. During summer, the cold and dense air flows out of the cave due to the temperature difference between outside and inside air. Moreover, the heat supplied to the cave by the river can also modify the cave air temperature, lowering the correlation between both temperature sensors. In winter, although we do not have observations, a chimney effect is expected and relatively warm air masses with respect to the external temperature move towards hypothetic shafts located at a higher elevation than the cave entrance, in the southern face of the Monte Perdido massif. Thus, this process drags cold outside air into the cave. Also, the absence of liquid water in the river would favour fewer thermal disturbances. We will add a sentence about this issue as suggested by the reviewer.

F) l315 - rock temperature sensor R2 is included in the results and discussion with 'well ventilated' parts of the cave, yet it lies in the vicinity of a massive ice body, near the Terminus Devaux, suggesting that there is perhaps little air flow there. Indeed, at line 331, the authors mention that the chamber morphology shields them from the air flow. Perhaps the discussion of its record could be moved to the 'poorly ventilated' section?. Could the authors comment on the lag between the seasonal tock temperature maxima and minima compared to the external and cave air temperature? Given the thermal conductivity of limestone and a sensor depth of 60 cm, does the record support a simple heat conduction model?

- ➔ Temperatures recorded by the R2rock sensor are significantly higher and more variable than in the poorly ventilated room D. These data are also consistent with the measured cave air temperatures and suggest that the cave's ventilation dynamics may affect this area more strongly than anticipated.
- ➔ Regarding the lags between cave air, rock, and external temperatures, it is important to note that in room K (Terminus Devaux), maximum temperatures recorded by the T12air sensor show a lag with respect to the outside maximum temperature ranging from ~31 to ~51 days, while sensor R2rock records the maximum temperature 44 to 82 days later than in the outside atmosphere. For minimum temperatures, the time lag recorded by sensor T12air is ~10 to ~123 days while for sensor R2rock the lag with respect to the minimum outside temperature is ~20 to ~123 days. However, R2rock sensor reaches minimum temperatures around 34 and 62 days before the minimum temperature at the site of sensor T12air. This suggests a complex temperature pattern and a possible lag of more than a year between cave air temperature in room K and rock temperature, calling for extended monitoring to understand how the different heat sources control the temperature variations in Devaux cave.

G) l518 - the only place where perennial hoarfrost is indicated on figure 2B is a small recess appears to be surrounded by ventilated galleries containing seasonal hoarfrost, and as mentioned adjacent to a small ice body of room SPD. This certainly speaks to the frozen nature of the bedrock in this part of the cave, and demonstrates the clear effect of the negative thermal anomaly brought about by the ventilation pattern in the surrounding galleries. But if this is the case, could the authors comment on why there is no perennial hoarfrost in the galleries leading to room D, where such hoarfrost could also have developed?

- ➔ A possible explanation for the absence of hoarfrost in rooms D (and also G) is that these chambers are insufficiently ventilated. Devaux (1929) indicated the presence of ice crystals on the ceiling at the entrance of room D. In the same way, du Cailar and Dubois (1953) showed a schematic cross-section of room D, where ice crystals are present to the mercury thermometers (Fig 1). These historical reports suggest that these chambers were probably more ventilated in the past, possibly related to a major rise of the water level (later freezing) due to the blockage of the Brulle spring. Those seasonal changes of the river base level might have favoured air circulation towards room D. The blockage of the Brulle spring, as well as the elevation of the base level, provoked seasonal geomorphological changes in the passages. This situation might have favoured a more intensive ventilation of room D.

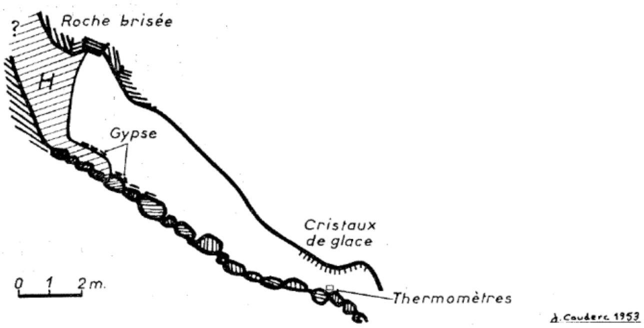

Figure 1: Schematic cross-section of room D, where hoarfrost (Cristaux de glace) appears to form close to mercury thermometres. Modified from du Cailar and Dubois (1953)

H) Could the authors elaborate on why CCC or CCG related ice, rich in air inclusions could be related to the formation in a subaqueous environment?

- ➔ Cryogenic Cave Carbonates (CCC) are crystals that form when water freezes inside caves (e.g. Žák et al., 2004, 2012). At low freezing rates, water ponds start to freeze from the surface, thus isolating and preserving liquid water in a closed system (pool-model) (Žák et al., 2004). The progessive freezing of the pond provokes the loss of CO_2 and the segregation of solutes (Killawee et al., 1998). Once supersaturation is reached, CCC start to crystallize. Thus, liquid water is necessary for CCC formation. CCC are characterized by a different isotopic composition ($\delta^{13}C$, $\delta^{18}O$) than regular speleothems (e.g., stalactites, stalagmites). Although we are currently working on the isotopic characterization of CCC from Devaux,, the CCC morphologies show the same shapes as those found in other ice caves (e.g. Luetscher et al., 2013; Žák et al., 2012, 2018). Also, we find these carbonates trapped within the ice indicating a subaqueous environment as suggested by other studies (Bartolomé et al., 2015; Colucci et al., 2017).

  The relation between CCC and ice rich in air inclusions (bubbles) is difficult to study in comparison with other caves containing CCC since only very few sites have been found where CCC are still present within the ice and detailed studies are lacking. Most of the CCC are found on blocks long after the ice has disappeared (e.g. Koltai et al., 2020; Spötl et al., 2021; among others). In Sarrios 6 ice cave (southern slope of the Monte Perdido massif), CCC were found within the ice (Bartolomé et al., 2015), and the CCC are also surrounded by bubbles (Fig.2a in Bartolomé et al., 2015), similar to those found in Devaux. The forthcoming analyses of these gas inclusions may provide additional information with respect to CO_2 degassing during the freezing process, leading to the precipitation of CCC. On the other hand, gypsum crystals appear as single crystals and also used CCC as nucleation points.

I) l689: the authors mention that 'exceptional insights' into the origin of mountain permafrost are gained by the study of the Devaux ice cave deposit. In this study, three potential mechanisms are put forward, which all go some way to explain the permafrost conditions at the site. 1) negative thermal anomalies due to cold air advection in winter, 2) negative radiative anomaly due to the mountain topography/orientation and 3) inherited past cold climate signals, not entirely erased by current warming due to thermal inertia. In the discussion, the authors could comment on a ways to quantify the potential contributions of each to the current thermal state of the cave?

➔ That is an interesting point, but probably too complex and exceeds the scope of this paper. Quantifying every factor that influences the thermal state of the cave is a multifaceted issue that would require a heat-flow model coupling heat and mass transfer between rock and air in ventilated caves (Sedaghatkish et al., 2022). Eventually, once the age of the ice bodies has been determined, the relative importance of the individual processes may become clearer and help reconstructing the thermal history of the inherited permafrost. We will add a sentence indicating these points in the conclusions to discern the contribution of the different factors in the modern permafrost.

Technical comments (T: suggested typographic correction, R: suggested rephrasing)

➔ We will include all technical comments suggested below.

l55-57: (R) snow cover distribution and thickness, topography, water availability, surface and rock temperature all influence the spatial distribution of mountain permafrost

l57-61: (R) In light of these processes, [...] are needed to gain a comprehensive understanding of mountain permafrost.

l98-99: (T) the presence of a few ice caves has only recently been documented

l315: I think this could be reformulated, as the authors list water, and rock T sensors together with the air T sensors.

l357: I think R1 could be dropped from the list in parentheses, as it is not an air temperature sensor.

l396: (T) transparent and massive ice (~15.5 m above the Brulle spring) currently fills a cupula or chimney

l452: (T, American English spelling) milliliter

l453: (T) in room SPD, CCC and CCG

l456: for the sake of consistency, I would drop the s at the end of CCC here.

l501: (T) with more continuous permafrost starting at 2900 m asl

l535-536: massive ice is formed by slow freezing - there should perhaps be a reference here.

l568: (T) The cave ice bodies [...] therefore represent

l596: (T) which contrasts with

l615: for the sake of consistency, drop s at the end of CCG here.

l636: (T) related to hydrocarbons

l666-667: (T) is the size and well-developed shape of the crystals

l718: (T) rich in air inclusions

l724: (T) in Devaux cave

Figure 2A: could it be helpful to indicate on the cross-section the assumed extent of mountain permafrost (200 m thick, over 350 m in an E-W direction)?

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Here we reply to an email received with some questions about the manuscript:

Regarding precipitation, I noticed a small error in your manuscript *"annual precipitation next to the cave may exceed 2500 mm, as the snow depth measured in early May exceeds on average 3 m"*
3 m snow depth is not 2500 mm precip (water equivalent) but rather 1000-1500 mm w.e. even at the end of winter when the snowpack is dense.
Note that there are winter precipitation measurements (i.e. coincident snow depth and density measurements) done by Moraine in late May on Ossoue glacier, the average over a 21 year period is 2700 mm w.e. (max 2000 mm w.e., min 3700 mm w.e.)

- ➔ These precipitation data are derived from measurements performed at the end of April, when snow depth was ~3.2 m on average and snow density was close to 450 kg/m^3. The average snow depth could even be larger due to the strong winds that remobilize and compact the snow during winter in this sector. These measurements would thus represent a minimum amount of 1500 mm w.e (López-Moreno et al., 2019), while the rest of the precipitation would correspond with rainfall between May and October. Data from Góriz hut (2150 m a.s.l, 1984-2020), located in the South face of the Monte Perdido massif, indicate the total precipitation between May to October ranges from 331 to 1415 mm, with a mean of 884 mm. Moreover, this precipitation would increase with altitude. We will rephrase the sentence in the revised version, to clearly indicate which part of the total precipitation comes from snow and which one from rainfall.

Recompute the radiation map with a better digital elevation model, there are weird staircase-like artefacts on Fig 4.

- ➔ We computed the radiation map using a 5 m resolution DEM from the Aragón Service of Cartography (https://boletinagrario.com/f296,sitar-sistema-informacion-territorial-aragon.html, last visit 21/09/2022). To our knowledge this is one of the most accurate DEM available for the Pyrenees. Those staircase-like artefacts may be due to the extreme slope that forms the Gavarnie cirque. We are confident that the use of a different DEM would not affect the main message of this figure which is to indicate the great radiation anomaly in the Gavarnie cirque.

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