

1 Mountain permafrost in the Central Pyrenees: insights from
2 the Devaux ice cave

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25

26 **Abstract**

27 Ice caves are one of the least studied parts of the cryosphere, particularly those
28 located in inaccessible permafrost areas at high altitudes or high latitudes. We
29 characterize the climate dynamics and the geomorphological features of Devaux
30 cave, an outstanding ice cave in the Central Pyrenees on the French-Spanish
31 border. Two distinct cave sectors were identified based on air temperature and

32 geomorphological observations. The first one comprises well-ventilated galleries
33 with large temperature oscillations likely influenced by a cave river. The second
34 sector corresponds to more isolated chambers, where air and rock temperatures
35 stay below 0°C throughout the year. Seasonal layered ice and hoarfrost occupy
36 the first sector, while transparent, massive perennial ice is present in the isolated
37 chambers. Cryogenic calcite and gypsum are mainly present within the perennial
38 ice. During winter, the cave river freezes at the outlet, resulting in a damming and
39 back-flooding of the cave. We suggest that relict ice formations record past
40 damming events with subsequent formation of congelation ice. $\delta^{34}\text{S}$ values of
41 gypsum indicate that the sulfate originated from the oxidation of pyrite present in
42 the bedrock. Several features including air and rock temperatures, the absence
43 of drips, the small loss of ice in the past seven decades, and the location of ice
44 bodies in the cave indicate that the cave permafrost is the result of a combination
45 of undercooling by ventilation and diffusive heat transfer from the surrounding
46 permafrost, reaching a thickness of ~200 m.

47 **Keywords:** Ice cave, cave monitoring, cryogenic cave carbonates, cryogenic
48 gypsum, Pyrenees.

49 1. Introduction

50 Mountain areas are among those environments most affected by current climate
51 change (Hock et al., 2019). In the mid-latitudes, high-altitude areas are subject to
52 mountain permafrost, a very sensitive and unstable phenomenon that responds
53 quickly to environmental changes (Harris et al., 2003; Biskaborn et al., 2019) due
54 to the number of factors. Snow cover distribution and thickness, topography,
55 water availability, and surface and rock temperature influence the spatial
56 distribution of mountain permafrost (Gruber and Haeberli, 2009). In light of these
57 processes, multidisciplinary studies including, among others, measurements of
58 rock temperature in boreholes and bottom temperatures of snow cover (BTS),
59 geophysical techniques, and detailed mapping (geomorphology, thermal) are
60 needed to gain a comprehensive understanding of mountain permafrost (e.g.
61 Lewkowicz and Ednie, 2004; Serrano et al., 2019; Biskaborn et al., 2019). On the
62 other hand, integrated studies of paleo-permafrost (e.g. Vaks et al., 2020) and
63 modern permafrost, specifically mountain permafrost (e.g., Supper et al., 2014;

64 Scandroglio et al., 2021), shed light on past, present and future developments of
65 permafrost areas, an issue of vital importance in the context of global warming.
66 Studies of past permafrost require sedimentary records, which are locally
67 preserved in caves located at high altitudes and/or high latitudes. Temporal and
68 spatial changes in past permafrost distribution have been identified using
69 speleothems (stalagmites, flowstones) in high-latitude and polar regions (e.g.,
70 Vaks et al., 2013, 2020; Moseley et al., 2021; Li et al., 2021) as well as in mid-
71 latitude regions (e.g., Lundberg and McFarlane, 2007; Fankhauser et al., 2016;
72 Lechleitner et al., 2020).

73 Ice caves are cavities in rock hosting perennial ice that results from the
74 transformation of snow and/or the freezing of infiltrating water (Perşoiu and
75 Lauritzen, 2018). Cave ice can be dated and used as a valuable paleoclimate
76 archive in non-polar areas (e.g., Stoffel et al., 2009; Spötl et al., 2013; Perşoiu et
77 al., 2017; Kern et al., 2018; Sancho et al., 2018a; Leunda et al., 2019; Munroe,
78 2021; Racine et al., 2022). Recently, coarse cryogenic cave carbonates
79 (CCC_{coarse}), that form during slow freezing of water inside caves, have been used
80 as indicator of permafrost degradation, permafrost thickness, and subsurface ice
81 formation (Žák et al., 2004, 2012; Richter et al., 2010a; Luetscher et al., 2013;
82 Orvošová et al., 2014; Spötl and Cheng, 2014; Bartolomé et al., 2015;
83 Dublyansky et al., 2018; Koltai et al., 2020; Munroe et al., 2021; Spötl et al.,
84 2021).

85 Many ice caves are located in areas where the mean annual air temperature
86 (MAAT) outside the cave is above 0°C (Perşoiu and Lauritzen, 2018) and,
87 therefore, are highly susceptible to future climate warming (Kern and Perşoiu,
88 2013). These ice caves are local thermal anomalies which are controlled by the
89 cave geometry and the associated ventilation pattern. Their ice deposits
90 represent sporadic permafrost occurrences and do not inform about the wider
91 thermal environment. In contrast, at high altitudes and high latitudes subsurface
92 ice deposits are still preserved by the presence of permafrost under the current
93 climate conditions. There, mountain permafrost is limited to areas where a
94 periglacial belt is present, with $MAAT \leq 0^{\circ}\text{C}$. For example, in the European Alps,
95 discontinuous mountain permafrost is observed above 2600 to 3000 m a.s.l.
96 (Boeckli et al., 2012), while in southern Europe permafrost is generally absent

97 (i.e. not observed even on the highest massif of the Iberian Peninsula, Gómez-
98 Ortiz et al., 2019). In the Central Pyrenees few studies suggest the possible
99 presence of permafrost above 2750 m a.s.l. (Serrano et al., 2019, 2020; Rico et
100 al., 2021), and the presence of a few ice caves has only recently been
101 documented (e.g. Sancho et al., 2018a; Serrano et al., 2018) informing about the
102 occurrence of sporadic permafrost.

103 The aim of this study is to characterize the permafrost conditions in Devaux cave,
104 a high-altitude ice cave in the Central Pyrenees. We monitored air, water and
105 rock temperatures and used cryogenic cave deposits to i) document the
106 distribution of permafrost within this cave, and ii) to study the processes that
107 resulted in perennial cave ice bodies and associated cryogenic mineral
108 occurrences.

109

110 **2. Study site**

111 Devaux cave opens at ~2838 m a.s.l. in the NE cliff of Gavarnie cirque (France)
112 of the Monte Perdido massif (MPm) in the Central Pyrenees (Fig. 1a). The cave
113 is located between the Parc National des Pyrénées (France) and the Parque
114 Nacional de Ordesa y Monte Perdido (Spain). Named after Joseph Devaux who
115 discovered and explored it in 1928, the cave was later investigated with respect
116 to its hydrogeology and microclimatology and preliminary descriptions of its
117 deposits were reported (e.g., Devaux, 1929; 1933; Rösch and Rösch, 1935;
118 Rösch, 1949; du Cailar and Dubois, 1953; Requirand, 2014).

119

120 The area is dominated by limestones and dolostones ranging from the Upper
121 Cretaceous to the Eocene-Paleocene. MPm is the highest limestone karst area
122 in Europe reaching up to 3355 m a.s.l. (Monte Perdido peak) (Fig. 1b). The
123 nearest peaks to Devaux cave are Marboré (3248 m a.s.l.) and the three Cascada
124 peaks (3164 m, 3111 m, and 3098 m a.s.l.). The limestone thickness above the
125 cave varies between ~200 and 250 m (Fig. 2a). In Devaux, the galleries follow
126 the axis of a NW-SE striking syncline (Fig. 1b). A river runs along the cave (Fig.
127 2a, b). The cave has two known entrances: the lower one corresponds to the
128 main outlet of the cave river (Brulle spring, North 1, ~2821 m a.s.l.), while the

129 upper entrance is known as the “Porche” (South, ~2836 m a.s.l.) (Figs. 1c and
130 2b). Between these two entrances, a small gallery (Spring North 2) opens +1.2 m
131 above Brulle spring (Fig. 1c). Brulle is one of the main springs in the Gavarnie
132 cirque. This spring drains a catchment of ~2.6 km² (polje) located on the southern
133 face of MPm between ~2850 and 3355 m a.s.l. (Figs. 1b and, 1d). Major water
134 flow is observed during late spring and early summer when snowmelt occurs in a
135 catchment characterised by shafts, sinkholes and small closed depressions (Fig.
136 1d). The water of Brulle spring feeds, together with some other springs located a
137 few hundred meters below, the Gavarnie waterfall (Fig. 1b). A tracer experiment
138 (du Cailar et al., 1953) indicated that part of the water of the Gavarnie waterfall,
139 and thus likely also from Brulle spring, comes from a ponor in the Lago helado
140 (lake, Fig. 1e) located ~2.3 km to the east of Devaux cave (Figs. 1b and 2a). The
141 Gavarnie waterfall (Fig. 1b) turned green within ~21 hours after injection of the
142 tracer but the water at Brulle spring was not directly checked (du Cailar et al.,
143 1953). During the colder months, the spring as well as the Gavarnie waterfall
144 freeze.

145 The geomorphology of the area is dominated by karst, glacial and periglacial
146 landforms. The area was strongly glaciated during the last glacial period on both
147 sides of the massif (e.g., Reille and Andrieu, 1995; Sancho et al., 2018b;
148 Bartolomé et al., 2021). Today, only two glacier relicts covered by scree deposits
149 are present in the Gavarnie cirque (Fig. 1b): 1) the Cascada dead-ice which is
150 located several hundred meters below Devaux cave, and 2) a dead-ice
151 accumulation in the NE wall of the cirque. Till present close to Brulle spring, on
152 the access to Devaux and in the Cascada glacier, point to a much larger glacier
153 extent in the past, maybe corresponding to the Little Ice Age or even the
154 Neoglacial advance recognized in the nearby Tucarroya (Fig. 1b) and Troumouse
155 cirques (Gellatly et al., 1992; González Trueba et al., 2008; García-Ruiz et al.,
156 2014, 2020).

157 The study area lies at the transition between Atlantic and Mediterranean climate,
158 with generally cold and dry winters and warm and dry summers. In MPm, the
159 annual 0°C isotherm is located at ~ 2900 m a.s.l. (López-Moreno et al., 2016;
160 Serrano et al., 2019). The wet seasons are fall and spring. The annual
161 precipitation at the Góriz meteorological station (2150 m a.s.l. and 3 km SE of the

162 cave) averages 1650 mm. However, mass balance calculations of the nearby
163 Monte Perdido glacier, where more than 3 m of snow (density 450 kg/m³)
164 accumulates between November to April, indicates a minimum amount of 1500
165 mm water equivalent, therefore the total annual precipitation in high parts of the
166 massif exceeds 2500 mm (López-Moreno et al., 2019). In the MPm,
167 discontinuous permafrost is present between ~2750 and ~2900 m a.s.l. and
168 becomes more frequent above ~2900 m a.s.l. on the northern side (Serrano et
169 al., 2019). Periglacial activity is characterized by rock glaciers, solifluction lobes
170 and patterned ground (Feuillet, 2011).

171

172 **3. Material and methods**

173 **3.1 Cave survey and mapping**

174 A survey of Devaux cave was conducted using a compass and clinometer as well
175 as a laser distometer (Disto-X, Heeb, 2014). In addition to cave ice, chemical and
176 clastic deposits were mapped in the cave (Fig. 2b). The labelling of the cave
177 chambers (A to K) follows the nomenclature introduced by Devaux (1929) and
178 Rösch and Rösch (1935).

179 A map of potential solar radiation (RAD) of the MPm was obtained using an
180 algorithm which considers the effects of the surrounding topography on
181 shadowing considering the position of the sun. RAD was calculated for every
182 month and was then averaged to obtain an annual mean. Details of this
183 computation can be found in Pons and Ninyerola (2008).

184 **3.2 Cave monitoring**

185 The cave consists of large rooms (e.g., room F, and those located beyond SCAL
186 chatière) connected by small galleries (Fig. 2b), locally with narrow passages
187 (e.g., galleries close to SPD room or SCAL chatière, Fig. 2b). 15 stations were
188 installed in the outmost ~350 m of the cave to monitor air (11 sensors), water (2
189 sensors) and rock temperature (2 sensors) (Fig. 2b). Cave air temperature
190 variations were recorded using different devices (Hobo Pro v2 U23-001 (accuracy
191 ±0.25°C, resolution 0.02°C), Tinytag Talk 2 (accuracy ±0.5°C, resolution, 0.04°C)
192 and ELUSB2 (accuracy ±0.21°C, resolution 0.5°C)). The cave river temperature

193 was recorded at two points. The first site (W7) was located close to the Brulle
194 spring (Fig. 2b; Hobo TiDBit V2, accuracy $\pm 0.21^{\circ}\text{C}$, resolution 0.02°C) and, the
195 second site (W6) was located in room F (Fig. 2b; Hobo UA-001-08; accuracy
196 $\pm 0.53^{\circ}\text{C}$, resolution 0.4°C). Both sensors were installed at a water depth of 20
197 cm. Finally, the rock temperature was recorded at two sites (R1 and R2 in room
198 D and K, respectively) using a Hobo U23-003 device (accuracy $\pm 0.25^{\circ}\text{C}$,
199 resolution 0.02°C). Each sensor has two external temperature probes (channels
200 1 and 2, Ch1-Ch2). These temperature probes were installed in two horizontal
201 drill holes of 60 cm depth, ~ 1.5 to 2 m from each other.

202 We monitored sporadically the cave during different intervals between 2011 and
203 2015, while a continuous monitoring was carried out between July 2017 and July
204 2021. Maximum, minimum and mean temperatures as well as the number of
205 frost/warm days were obtained for each sensor and site (Fig. 2b). Changes in the
206 ice morphology were evaluated using wall marks measured at four points since
207 2013 in room G and using one point during 2020-2021 in room SPD (Fig. 2b)
208 using a digital sliding caliper.

209 The outside temperature was measured at the “Porche” entrance (~ 2836 m a.s.l.)
210 and on the southern face of MPM at ~ 2690 m a.s.l. For comparison, these
211 temperature records were corrected assuming an adiabatic lapse rate of 5.5°C
212 km^{-1} (López-Moreno et al., 2016; Navarro-Serrano et al., 2018) to an elevation of
213 ~ 2850 m a.s.l., corresponding approximately to the lower limit of the hydrological
214 catchment area of Devaux. In both cases, the temperature was measured using
215 Tinytag Talk 2 sensors equipped with a radiation shield. These data were
216 compared to the temperature record from the Pic du Midi de Bigorre
217 meteorological station (PMBS; 2011-2020) (2860 m a.s.l., ~ 28 km N of Devaux)
218 obtained from Météo-France. Moreover, the homogenised data available since
219 1882 from PMBS (Bücher and Dessens, 1991; Dessens and Bücher, 1995) were
220 used to identify long-term temperature trends.

221 **3.3 X-ray diffraction, ion chromatography and sulfur isotopes**

222 X-ray diffraction (XRD) analyses were performed on sulfate and carbonate
223 crystals from rooms G, D and K, as well as on sulphide and oxidized crystals
224 thereof from the host rock (Fig. S1). The analyses were performed at the

225 Geosciences Institute in Barcelona (GEO3-BCN-CSIC) using a Bruker-AXS
226 D5005 powder diffractometer configured in $\theta/2\theta$ -mode (e.g. Rodríguez-Salgado
227 et al., 2021).

228 Samples of cave drip water, ice and river water were analysed for major ions by
229 ion chromatography (IC) at the laboratories of the Pyrenean Institute of Ecology
230 (Zaragoza). Carbonate alkalinity was determined by titration within 24 hours after
231 sampling.

232 Sixteen samples, including sulfate crystals, dissolved sulfate and pyrite crystals
233 were selected for sulfur isotope analysis at the Godwin Laboratory for
234 Paleoclimate Research of the University of Cambridge (UK), following the
235 methodology of Giesemann et al., (1994). For gypsum samples, ~5 mg of
236 powdered gypsum were dissolved in deionized water at 45°C overnight. Then, a
237 BaCl₂ solution (50 g/L) was added to induce BaSO₄ precipitation. In the case of
238 water samples, BaCl₂ was added directly to the sample. Subsequently, 6M HCl
239 was added to remove any co-precipitated carbonate minerals and the BaSO₄
240 precipitate was rinsed several times with deionized water. Finally, BaSO₄ was
241 dried at 45°C overnight. Sulfate dissolved in water were precipitated using the
242 same method.

243 Isotope measurements were carried out using a Flash Elemental Analyzer (Flash-
244 EA) at 1030 °C. The samples were folded in tin capsules. After sample
245 combustion, the generated SO₂ was measured by continuous-flow gas source
246 isotope ratio mass spectrometry (Thermo Scientific, Delta V Plus). Samples were
247 run in duplicate and calibration was accomplished using NBS-127. The
248 reproducibility (1σ) of $\delta^{34}\text{S}$ was better than 0.2‰, similar to the long-term
249 reproducibility of the standard over the run (0.2‰). $\delta^{34}\text{S}$ isotope values are
250 reported relative to VCDT (Vienna-Canyon Diablo Troilite).

251

252 **4. Results**

253 **4.1 Devaux cave description**

254 Devaux cave is ~2500 m long and comprises three distinct levels (Fig. 2b). The
255 lower and the middle levels correspond to the Brulle spring (0 m), and the
256 “Porche” entrance (~+14.5 m), respectively. The third one comprises chambers

257 and galleries +21 m to +29 m above the Brulle spring (Fig. 2b). In the inner part
258 of the cave, some unexplored vertical chimneys may connect to sinkholes in the
259 catchment above the cave (Fig. 2a). The main ice deposits are located in rooms
260 D, G, SPD and K (Fig. 2b). Except for SPD, these chambers located above the
261 Porche entrance (between ~+1 and +7 m) can be accessed via ascending
262 passages.

263 During the cold season, the cave river starts freezing at the spring and the ice
264 then expands backward into room F (Fig. 2b). The ice totally or partially clogs the
265 main gallery and dams the water inside the cave forming a small lake (cf. also
266 Rösch and Rösch, 1935). This process is important for the seasonal ice extent
267 as the flooding of the cave depends on whether the springs (North 1 and North
268 2) are frozen or not (e.g., Rösch and Rösch, 1935). Webcam observations
269 (Gavarnie, Oxygène hut) suggest a possible freezing of the Brulle spring from
270 late November to mid-May simultaneous with the freezing of the Gavarnie
271 waterfall. Moreover, historical photos (e.g., Devaux, 1929; Rösch and Rösch,
272 1935) and our own observations show that snow during winter and spring can
273 reach the Brulle entrance - a situation that also favours the blocking of the
274 springs. As a result of such flooding events, slackwater deposits formed in the
275 cave entrance zone, but locally also further into the cave (e.g., in rooms I, J, K
276 and SCAL chatière, along the main gallery; Fig. 2b), while silty sediments are
277 found at elevated positions with respect to the river level (e.g., in rooms D and
278 G). Sandy sediments dominate in the large rooms located beyond the SCAL
279 chatière. Two such successions (~1 m thick) comprising hundreds of rhythmic
280 fine sand and silt layers are present in elevated areas with respect to the current
281 river, witnessing major events of back-flooding.

282 Observations made during summer show a dominant air-flow direction from the
283 inner to the outer parts of the cave, exiting through the Brulle and Porche
284 entrances. Conversely, the opposite is expected for the cold season (chimney
285 effect). When the Brulle spring is partially clogged by ice during early summer
286 forcing the stream to flow below the ice, air flows from room F to C (Fig. 2b) (e.g.,
287 summer 2021). The air flow is imperceptible in rooms D, G, and close to K located
288 away from the main cave passages.

289 **4.2 Climate setting of Devaux cave**

290 The MAAT at the elevation of Devaux cave is ~ 0 °C (-0.04 °C; 2017-2021). On
291 the other hand, a positive MAAT (1.8 °C) is recorded on the southern side of the
292 MPm at a similar altitude (Fig. 3a). Maximum and minimum air temperatures
293 outside the cave vary between 24.5 °C and -17.2 °C (hourly values, 2017-2021).
294 The PMBS MAAT record (Fig. 3b) shows a warming trend of around $+1.5$ °C since
295 the beginning of the measurements in 1882. Before 1985, temperatures below
296 0 °C dominated the annual cycle, while positive MAATs became more frequent in
297 recent years. Minimum temperatures also show a increasing trend of $\sim +2.5$ °C,
298 while the maximal annual temperatures do not show a clear trend. The north-
299 facing Gavarnie cirque is associated with a clear RAD anomaly (Fig. 4). Values
300 lower than 215 kWh/m² are observed at ~ 2000 m and between ~ 2800 and 2900
301 m a.s.l., corresponding to the cirque bottom, the area located behind La Torre
302 peak and the surroundings of Devaux cave. At the cave entrance the RAD value
303 is only 390 kWh/m², in stark contrast to the summit areas and surroundings where
304 the RAD often exceeds 1500 kWh/m² (Fig. 4).

305 While the mean daily air temperature (MDAT) at the cave entrance (purple line in
306 Fig. 5) and the temperature series from PMBS (pink line in Fig. 5) agree in their
307 absolute values, the variability of MDAT at the Devaux entrance is lower than at
308 the PMBS. This pattern could be related to local topographic conditions leading,
309 for instance, to less RAD, or to the position of the sensor in the cliff (less night
310 emissivity). Given this radiation contrast, warmer temperatures prevail on the
311 southern side of the MPm (Fig. 4), favouring early snowmelt in spring and early
312 summer, while at the same time the temperature stays below 0 °C in the cave's
313 surroundings.

314 **4.3 Devaux cave temperature variations**

315 The cave can be separated into distinct areas depending on their thermal regime:
316 ventilated galleries (rooms A, B, C, F and the main gallery from SPD to SCAL
317 chatière)) and poorly ventilated parts off the main air flow path (rooms D, G, K -
318 Figs. 2b, 5).

319 **4.3.1 Well-ventilated cave parts**

320 Air ($T_{2\text{air}}$, $T_{5\text{air}}$, $T_{10\text{air}}$, $T_{11\text{air}}$) and water ($W_{6\text{water}}$, $W_{7\text{water}}$) temperature data show
321 large seasonal oscillations. All sensors except $T_{11\text{air}}$ show a few days of positive
322 temperatures during summer. Sensor $T_{2\text{air}}$ (2011-2012, Fig.5a), which is also the
323 closest to the Porche entrance, shows the highest correlation (r) with the external
324 temperature (0.73, $p < 0.001$). Sensor $T_{5\text{air}}$ (2017-2021, Fig. 5d) in room B also
325 shows a high correlation and significant correlation (0.82, $p < 0.0005$) with the
326 outside temperature. During the major cave cooling that takes place between the
327 end of October and May and the correlation is significant and ranges between
328 0.68 to 0.84. During summer and part of fall, the correlation decreases notably (-
329 0.23 to 0.76). Sensor $T_{11\text{air}}$ (2018-2021, Fig. 5d) is partly protected from the air
330 flow and shows lower a correlation (0.69, $p < 0.001$) despite being located in a
331 well-ventilated gallery (SPD room). Also during the winter months, the
332 correlations are lower (0.49-0.62, $p < 0.001$) than in $T_{5\text{air}}$. Sensor T_{10} (2014-
333 2015, Fig. 5c) does not show any significant correlation with the external
334 temperature.

335 Sensors $W_{6\text{water}}$ and $W_{7\text{water}}$ (Figs. 5b, c) recorded water temperature variations
336 during the years 2012-2013 and 2014-2015, respectively. Both sensors record a
337 continuous temperature decline from the end of November to mid-January until
338 the water freezes. At $W_{7\text{water}}$, the temperature ranges between -0.3 and -5.8 °C
339 between the end of fall and the beginning of winter, while the temperature stays
340 close to 0°C between January and the beginning of June. At $W_{6\text{water}}$, the
341 temperature reached a minimum of -1.7 °C and shows smaller variations than at
342 $W_{7\text{water}}$. No significant correlation was found between the external air temperature
343 and the river water temperature. Only $W_{6\text{water}}$ shows a weak correlation with the
344 external temperature when ice is absent (0.39 $p < 0.001$ and 0.40 $p < 0.001$).

345 For each monitored interval, the mean annual cave temperature at the $T_{2\text{air}}$, $T_{5\text{air}}$
346 and $T_{11\text{air}}$ sensors is lower than the outside mean temperature (by 0.4°, 2.0°, 3.3°
347 C, respectively). The $W_{6\text{water}}$, $W_{7\text{water}}$ and $T_{10\text{air}}$ sensors show mean
348 temperatures higher than the external mean temperatures (by 1.6°, 2.6°, 2.5° C,
349 respectively). The periods 2011-2012 and 2017-2018 (at $T_{2\text{air}}$ and $T_{5\text{air}}$,
350 respectively) represent the coldest cave years of the monitoring period.

351

352 **4.3.2 Poorly ventilated cave parts**

353 Sensors located in rooms D ($T_{3\text{air}}$, $T_{4\text{air}}$, $T_{8\text{air}}$), G ($T_{9\text{air}}$), K ($T_{12\text{air}}$) and rock
354 temperature ($R_{1\text{rock}}$, $R_{2\text{rock}}$) show air temperatures below 0 °C during the
355 monitoring period with small oscillations and a weak and/or insignificant
356 correlation with the external air temperature. Sensor $R_{1\text{rock}}$ (Fig. 5) recorded rock
357 temperatures consistently below 0°C during the entire monitoring period. This
358 sensor shows constant rock temperatures (-1.24 °C and -1.27 °C for channels 1
359 and 2, respectively), similar within error to the cave air temperature ($T_{3\text{air}}$, $T_{9\text{air}}$;
360 2019-2021). All sensors except for $T_{3\text{air}}$ (2011-2012, Fig. 5a) show mean air and
361 rock temperatures lower than the mean external temperature during the same
362 period (by 0.59 °C to 2.47°C). The muted temperature variations in these
363 chambers reflect reduced heat exchange compared to the well-ventilated parts
364 of the cave. Sensors $T_{12\text{air}}$ and $R_{2\text{rock}}$ are located in room K, and similar to $T_{11\text{air}}$,
365 the chamber morphology shields them from the air flow. Rock temperature sensor
366 $R_{2\text{rock}}$ shows a slightly more variable temperature ranging between -0.19°C and
367 -0.28°C (mean of -0.24 and -0.23°C for channel 1 and 2, respectively). Sensor
368 $T_{12\text{air}}$ shows a low correlation with the external temperature ($r^2=0.35$, $p<0.001$
369 (2018-2021)), and the same is observed for $T_{\text{ext}} - R_{2\text{rock}}$ ($r^2=0.35$, $p<0.001$ (2019-
370 2021). Meanwhile the correlation between $T_{12\text{air}}$ and $R_{2\text{rock}}$ is high but not
371 significant ($r^2=0.93$, $p>0.005$ (2019-2021)).

372

373 **4.4 Cave deposits**

374 **4.4.1 Ice**

375 Congelation ice formed by freezing of water within the cave is the most abundant
376 type of ice, and four main ice deposits are located in chambers D, G, SPD, and
377 K (Fig. 2b). The most relevant feature of these ice bodies is their high
378 transparency and massive aspect, i.e. the lack of layering (Figs. 6a, b).
379 Transparent ice is present on the ceiling, blocking chimneys, galleries and
380 fractures. The local loss of transparency is related to the presence of cryogenic
381 cave minerals and/or air inclusions (Figs. 6a, b, c, d).

382 A highly transparent ice deposit covers the southwest wall of room D and blocks
383 the access to a gallery (Fig. 6a). The height of this deposit reaches ~6 m, and its
384 base is located ~20 m above the Brulle spring. The thickness of this ice deposit
385 ranges from 4.5 to 14.5 m (horizontal laser measurements across the ice in the
386 gallery blocked by ice) and the estimated volume ranges from ~350 to ~710 m³.
387 Three unconformities marked by cryogenic minerals were identified in this ice
388 body.

389 In room G, an ice body (~25.8 to 29.6 m above the Brulle spring) is present on
390 the ceiling (Fig. 6b) and the estimated ice volume is ~180 m³. A comparison with
391 a historical photograph shortly before 1953 (Casteret, 1953) suggests that the ice
392 body has not changed significantly during the last ~69 years (Figs. 7a, b). Ice-
393 rock distances measured at four points, however, reveal small changes at three
394 of them. The first has retreated 9.8 mm since 2014 (mean 0.9 mm a⁻¹, n=2), the
395 second has retreated 19.2 mm since 2014 (mean 0.6 mm a⁻¹, n=5), and the third
396 one has retreated 15.8 mm since 2013 (mean 2.2 mm a⁻¹, n=7). At ~80 m from
397 the entrance, a small descending room (SPD) (Figs. 2b, 6c) hosts a small volume
398 of ice. Measurements between 2020 and 2021 indicate a retreat of 20 mm a⁻¹
399 (n=1). A last major ice deposit is present ~280 m from the entrance (room K),
400 where transparent and massive ice (~15.5 m above the Brulle spring) currently
401 fills a cupula or chimney (Figs. 2b, 6d). Additional ice bodies are present behind
402 the SCAL chatière in the upper gallery (Fig. 2b), but they have not been studied.

403 In contrast to these massive ice deposits, layered ice of seasonal origin is present
404 in small chambers adjacent to the river (E and F rooms) (Fig. 6e). This ice forms
405 sheets of about 10-15 cm in thickness which are present in room F and nearby
406 areas (Fig. 6f). This ice is related to the damming and freezing of water inside the
407 cave when the Brulle spring freezes. Our visits from 2017 to 2021 revealed that
408 most of the damming and subsequent ice formation in room F took place during
409 winter and spring 2017-2018 corresponding with the coldest months (both inside
410 the cave and outside) of the monitoring period (Fig. 5d). These ice slabs are
411 characterized by flat surfaces on both sides and obviously record incomplete
412 freezing of the dammed water. The ice sheets largely disappeared during
413 summer and fall, and only strongly degraded ice remained in elevated areas of
414 room F.

415 On the other hand, ice sheets associated with earlier episodes of river damming
416 and freezing have disappeared, and only linear colour changes remained as
417 witnesses of such events on the walls of the room E (Fig. 8d). A historical
418 photograph exemplifies these ice levels in the access between rooms F and E
419 (Fig. 8a). In August 1984 the ice was close to the ceiling and nearly 1 m thick
420 (Fig. 8a; Marc Galy, pers. comm.). This contrasts with the low ice level in recent
421 years (Fig. 8b). In total, three ice-level marks were identified in relation to back-
422 flooding and subsequent freezing of ponded water (Figs. 8c, d). They appear at
423 a lower elevation than the Porche entrance (c.+9.5, +9.2, +8.8, m with respect to
424 the Brulle spring).

425 Another important feature is the presence of hoarfrost, which was observed in
426 rooms A, B, C, E, F and along the gallery between SPD and J (Figs. 2b, 7g, h).
427 The crystal size varies from few mm to 4 cm and appears to be upholstering some
428 galleries and cupolas, forming aggregates that hang from the ceiling (Fig. 6h).
429 Finally, seasonal ice formations (e.g., icicles and ice stalagmites), as well as drips
430 are restricted to the outmost ~15 m, in the vicinity of both entrances, and in the
431 innermost part of the cave (~ 500 m from the entrance). Seasonal ice formations
432 are absent in cave sectors where transparent ice bodies and hoarfrost are
433 present. Firn deposits derived from snow are restricted to the Porche entrance.

434

435 **4.4.2 Mineral deposits**

436 They comprise mainly cryogenic cave minerals. XRD analyses of samples from
437 rooms D, G and K yielded gypsum and calcite, while the sulfide crystals and their
438 oxidation products present in the host rock were identified as pyrite and goethite,
439 respectively. The presence of cryogenic gypsum in Devaux was already reported
440 by du Cailar and Dubois (1953). In room D, gypsum was observed within the ice
441 and on boulders (Figs. 9a, b, c). A total of three gypsum levels (lower, middle and
442 upper, located at ~21.4, ~22.6 and ~23.9 m, respectively, with respect to the
443 Brulle spring) were identified in the ice (Fig. 9a). Due to the progressive retreat of
444 the ice body, some of these crystals are now present on the ice surface. Gypsum
445 levels comprise large single crystals (0.5-1 cm in diameter), aggregates forming
446 rafts (10 cm) up to 1 cm in thickness (Fig. 9b), as well as a fine crystalline fraction.

447 Examination of the fine fraction using a binocular stereo microscope indicates the
448 presence of cryogenic cave carbonates and gypsum (CCG) including globular,
449 single and twin morphologies <1 mm in diameter (Fig. 9d).

450

451 In room G, gypsum and carbonates crystals are present in the lower part of the
452 ice deposit (Fig. 10e) and on blocks. There, CCC are larger (>10 mm) than in
453 room D and include globular shapes and raft-like aggregates, similar to those
454 reported by Žák et al. (2012). Some of these CCC show gypsum overgrowths
455 (Fig. 9f). Across the ice surface, patches of globular CCC (sub-millimetre size)
456 have been released by ice sublimation (Figs. 7a, b). In room SPD, CCC and CCG
457 (≤ 2 mm) are present within and on the ice (Figs. 2b, 7c). Finally, in room K, only
458 few CCC were still present within the ice, while most of them form heaps of loose
459 crystals covering blocks. Some of these CCC exceed 5 mm in diameter. Crystal
460 morphologies include rosettes, skeletons and rhombohedrons similar to those
461 reported by Žák et al. (2012) as well as white tapered crystal aggregates. Beyond
462 room K, regular carbonate speleothems (i.e. stalagmites, stalactites and
463 flowstones) are present. Gypsum coating walls or ceilings was not observed.

464 **4.5 Cave water chemistry and sulfate isotopic composition**

465 The chemical composition of water in Devaux cave is dominated by calcium and
466 bicarbonate with relatively high Mg concentrations and locally also elevated
467 sulfate concentrations (Table 1). Total dissolved solids (TDS, n=7) vary from 57
468 to 315 mg l⁻¹. Devaux's dripwater has higher mean sulfate concentrations (65 mg
469 l⁻¹) than the cave river (11 mg l⁻¹) and massive and seasonal ice (2.8-18 mg l⁻¹).
470 The $\delta^{34}\text{S}$ value of dissolved sulfate in the dripwater is -14.4‰ (n=1), which is
471 significantly higher than in cave river water (-28.5‰ to -27.3‰, n=2; Table 2).
472 Gypsum crystals in room D show $\delta^{34}\text{S}$ values ranging from -15.1‰ to -15.8‰
473 (n=7), while in room G they range from -12.3‰ to -11.9‰ (n=5). A pyrite sample
474 from the host rock yielded a $\delta^{34}\text{S}$ value of -12.7‰ (n=1).

475 **5. Discussion**

476 **5.1. Processes controlling the thermal regime in Devaux cave and the extent of** 477 **permafrost**

478 A complex spatial distribution and a high degree of heterogeneity are among the
479 main characteristics of mountain permafrost (Gruber and Haeberli, 2009). In
480 Devaux cave the existence of permafrost can be related to a combination of two
481 processes: i) cave atmospheric dynamics, and ii) conductive heat transfer
482 through the rock.

483 Devaux cave is characterized by mean air and rock temperatures lower than the
484 external mean annual temperature (Fig. 5). The low cave temperatures in winter
485 lead to an inward airflow and an associated negative thermal anomaly behind the
486 entrance zone. On the contrary, during summer the cold and dense air flows out
487 of the cave due to the temperature difference between outside and inside air. The
488 heat supplied to the cave by the river also influences the cave air temperature by
489 exporting thermal energy from the cave during winter. Similar seasonal ventilation
490 patterns have been observed in ice caves elsewhere (e.g., Luetscher et al., 2008;
491 Colucci and Guglielmin, 2019; Perşoiu et al., 2021).

492 On the other hand, positive temperatures are observed both in the cave river and
493 in the air at the entrance (Fig. 5), reflecting heat advected by water (river) and the
494 influence of the external temperature (cf. Luetscher et al., 2008; Badino, 2010).
495 The lack of correlation between the external and internal temperatures and the
496 small temperature variability in rooms D, G, and K reflect their thermal isolation
497 from well-ventilated cave parts. There, the apparent thermal equilibrium between
498 the rock and the cave atmosphere ($T_{\text{rock}}=T_{\text{air}}$) supports the notion that heat
499 exchange is dominated by conduction through the bedrock.

500 The MAAT at the altitude of the cave is $-0.04\text{ }^{\circ}\text{C}$ (2017-2021) suggesting that the
501 $0\text{ }^{\circ}\text{C}$ isotherm is located close to the cave. Using an array of techniques (geomatic
502 surveys, temperature monitoring, temperature at the base of the snowpack (BTS)
503 and geomorphological and thermal mapping), Serrano et al. (2019) observed
504 mean annual ground temperatures between -1 and $-2\text{ }^{\circ}\text{C}$ on the northern slope
505 of the MPM suggesting that discontinuous permafrost is present between 2750-
506 2900 m a.s.l., with more continuous permafrost starting at 2900 m a.s.l. The
507 orientation of the Gavarnie cirque, as well as the high slope angle, and shadow
508 from the surrounding peaks favour the preservation of permafrost at lower
509 elevations (e.g., Gubler et al., 2011).

510 Given the high thermal inertia of the rock, the permafrost temperature at depth is
511 still under the influence of past climate conditions (e.g., Haeberli et al., 1984;
512 Noetzli and Gruber, 2009) and, therefore, part of the current permafrost in the
513 area could be inherited from previous colder times (e.g., Colucci and Guglielmin,
514 2019). In particular, the low mean annual temperatures recorded at PMBS in the
515 late 19th century were favourable conditions for permafrost development. We
516 surmise that the current permafrost could be inherited from colder periods of the
517 Little Ice Age.

518 In well-ventilated ice caves hoarfrost is the most dynamic ice formation on
519 seasonal time scales. The presence of perennial hoarfrost is, however, indicative
520 of a continuously frozen bedrock and thus representative of caves within the
521 permafrost zone (e.g. Luetscher and Jeannin, 2018; Yonge et al., 2018). In
522 Devaux cave, perennial hoarfrost is observed in rooms where the bedrock is
523 surrounded by small ice bodies (e.g., gallery close to SPD room, Fig. 6g). Devaux
524 (1929) indicated the presence of ice crystals on the ceiling at the entrance of
525 room D. In the same way, du Cailar and Dubois (1953) showed a schematic
526 cross-section of room D, where ice crystals are present at the beginning of the
527 room. These historical reports suggest these areas were probably more
528 ventilated in the past, which favoured the hoarfrost formation. On the other hand,
529 seasonal hoarfrost is present in ventilated galleries (A, B, C, F and between SPD
530 and J). Seasonal hoarfrost in room B and C, and in the area between H to J,
531 disappears at the end of summer, probably because of the heat delivered by the
532 cave river, as recorded by the T5 sensor (Fig. 5).

533 The presence of permafrost in Devaux's catchment is supported by the absence
534 of drips and/or seepage in the investigated cave passages (e.g., Luetscher and
535 Jeannin, 2018; Vaks et al., 2020). Active drips and seasonal ice formations are
536 limited to the first ~15 m of the cave as well as to the inner part (beyond room K).
537 Mountain permafrost thus penetrates ~350 m longitudinally from the eastern cliff
538 of the Gavarnie cirque to the southern side of the massif. On the other hand,
539 given the elevation of the cave and the topography above the cave, the current
540 maximum permafrost thickness on the southern side of the MPm is ~200 m
541 (without taking into account the active layer).

542

543 **5.2. The origin of ice in Devaux cave**

544 The transparent and massive character of Devaux's cave ice, as well as the
545 presence of CCC, which formation requires low congelation rates (Žák et al.,
546 2004), suggests that this ice formed by slow freezing of water dammed by ice at
547 the spring. This model is consistent with the climate of the Gavarnie cirque, cave
548 geomorphological observations, cave air and water temperatures as well as
549 historical reports. The cave water level can rise by several meters as indicated
550 by slackwater deposits upstream of the Brulle spring.

551

552 The distribution and characteristics of ice bodies in Devaux cave indicate that the
553 hydraulic head rose by at least ~ 15 - 29 m, which is the elevation of the ice bodies
554 in rooms G, F and K. This situation requires that all springs (including Porche)
555 are blocked for a sufficiently long time to allow for complete freezing of these cave
556 lakes. The lack of important unconformities in this massive ice (e.g., detrital
557 layers), which are usually related to seasonal ablation (e.g., Luetscher et al.,
558 2007; Stoffel et al., 2009; Hercman et al., 2010; Spötl et al., 2013), suggests that
559 the ice deposit in room G it is the result of a single flood event. On the contrary,
560 the small unconformities recognized in the ice body in room D suggest that
561 several cycles of damming and subsequent ice formation cannot be discarded in
562 the formation of this ice deposit.

563

564 These observations indicate that under the current climate (both in the cave and
565 outside) only part of the water dammed in rooms F and E freezes during winter
566 and spring. This strongly suggests that the ice bodies in Devaux cave must have
567 been associated with colder and/or longer events of ponding and freezing than
568 today, when the cave was effectively sealed from the outside for prolonged times.
569 We hypothesize that the advance of a glacier on the steep slopes of Devaux's
570 surroundings could have contributed to the blockage of the spring, leading to
571 backflooding and the formation of large ice bodies in the cave. In the study area,
572 such periods of glacier growth occurred during the Little Ice Age and/or the
573 Neoglacial (González Trueba et al., 2008; García-Ruiz et al., 2014, 2020).

574

575 The freezing of a flooded cave passage cannot be explained by the advection of
576 cold air alone. It is thus surmised that heat transfer through the host rock is a
577 more plausible mechanism for the complete freezing of ponded water. The cave
578 ice bodies as well as the presence of cryogenic minerals therefore record a long
579 cold period or several shorter episodes. Although cryogenic minerals and in
580 particular CCC_{coarse} are typically associated with permafrost thawing during warm
581 spells (Žák et al., 2004; Richter et al., 2010; Žák et al., 2012; Luetscher et al.,
582 2013), permafrost conditions prevailed during ice formation in Devaux cave. The
583 water that feeds Devaux's springs infiltrated during late spring and summer from
584 ponors at Lago helado and/or surrounding poljes. However, the heat supplied by
585 this water may have probably not been enough to thaw the frozen host rock. It is
586 thus very likely that the hostrock temperature was lower and/or the outlets
587 remained closed for longer periods than today to allow for the complete slow
588 freezing of the ponded water.

589

590 **5.2.1 Ice volume changes**

591 The colour changes in the walls close to the river (room E), the historical
592 photograph as well as speleological reports point to large changes (several
593 meters) in the height of the seasonal ice in the flood-prone sector of the cave
594 (Figs. 8a, b). This ice is influenced by the heat exchanged between the water and
595 the cave.

596 In contrast, changes in the ice volume are almost negligible in rooms D and G
597 where the temperature is more constant and below 0°C (Figs. 7a, b). The ice
598 body in room G has been retreating by only ~0.6 to ~2.2 mm a⁻¹. A similar value
599 (3 mm a⁻¹) was observed in Coulthard cave (Alberta, British Columbia, Marshall
600 and Brown, 1974), a cave located in permafrost (Yonge et al., 2018). Changes in
601 the ice body in this cave were related to slow sublimation due to convective air
602 flow inside the cave (Marshall and Brown, 1974). On the other hand, the ice in
603 SPD room shows higher ice retreat rates (~ 20 mm a⁻¹). Similar sublimation rates
604 have been reported in 'ice caves in the Pamir Mountains and the northern part of
605 the Russian Platform (Mavlyudov, 2008; Žák et al., 2018). Overall, Devaux's cave
606 ice deposits show a remarkable stability which contrasts with the rapid changes

607 observed in ice caves outside permafrost areas (Kern and Perşoiu, 2013; Perşoiu
608 et al., 2021; Wind et al., 2022), including other ice caves in the Pyrenees and
609 Picos de Europa (Belmonte-Ribas et al., 2014; Gomez-Lende et al., 2014, 2016).

610

611 **5.3. Cryogenic cave minerals**

612 In Devaux cave, CCC and CCG are still present within the ice (Figs. 6, a, b, c, d).
613 Worldwide, only very few *in situ* observations of coarse-grained cryogenic cave
614 minerals are known (e.g., Bartolomé et al., 2015; Colucci et al., 2017). du Cailar
615 and Dubois (1953) reported the presence of gypsum crystals at ~50 cm depth
616 within the ice in Devaux cave. The first evidence of *in situ* CCC_{coarse} in cave ice
617 was reported from Sarrios 6, an ice cave at 2780 m a.s.l. on the southern slope
618 of the MPm (Bartolomé et al., 2015). Colucci et al., (2017) documented the
619 presence of CCC_{coarse} in a small ice cave in the Italian Alps. Recently, Munroe et
620 al., (2021) found CCC_{coarse} in ice of Winter Wonderland cave (Utah, USA).
621 Because of the abundance of cryogenic cave minerals, the size of individual
622 crystals and aggregates thereof, and their different mineralogy, Devaux cave
623 provides an additional opportunity for studying the origin of such cryogenic cave
624 minerals.

625

626 CCG in Devaux cave represents, to our knowledge, the first occurrence of its kind
627 in a carbonate karst terrain. So far, CCG have only been reported from gypsum
628 karst areas in Russia and Ukraine (Korshunov and Shavrina, 1998; Žák et al.,
629 2018 and references therein). In those caves, tiny gypsum crystals form during
630 rapid freezing of water. When ice sublimates in winter, these particles are
631 released and accumulate as powdery deposits on the ice surface. Eventually,
632 they partly dissolve during spring and summer due to the increase in cave air
633 humidity, and later recrystallize forming a wide variety of crystal morphologies.
634 CCG from Devaux cave shows features that do not correspond to those
635 previously published from gypsum karst caves. In particular, the Devaux cave
636 CCG i) appears together with CCC_{coarse} crystals (≥ 5 mm in some cases, in rooms
637 D and G), ii) the (raft-like) gypsum crystals are large (Fig. 9b) and, in some cases,
638 are still found within the ice (Fig. 9a) and surrounded by milky ice rich in air

639 inclusions (Fig. 9a, e), and iii) boulders are locally overgrown by gypsum (Fig.
640 9c).

641 Coarse-grained cryogenic cave minerals form in a semi-closed system, when
642 water freezes very slowly (Žák et al., 2004). Once supersaturation is reached,
643 CCM start to crystallize. The formation of gypsum crystals requires the presence
644 of elevated concentrations of dissolved sulfate which may relate to i) sedimentary
645 gypsum deposits intercalated within carbonates (e.g., Sancho et al., 2004), ii) the
646 presence of hydrothermal water containing H₂S related to hydrocarbons (e.g.,
647 Hill, 1987), or iii) the oxidation of sulfides (e.g., pyrite) disseminated in carbonate
648 rocks (e.g., Bottrell, 1991). In the case of Devaux cave marine evaporite rocks
649 (e.g., of the Upper Triassic Keuper facies) and hydrocarbons are absent in the
650 catchment of the cave. The most plausible explanation for the presence of
651 dissolved sulfate in Devaux's water is the oxidation of pyrite present in the
652 limestone (du Cailar and Dubois, 1953; Requirand, 2014).

653

654 $\delta^{34}\text{S}$ values of gypsum (-11.9 to -15.8 ‰), pyrite (-12.7 ‰), and dissolved sulfate
655 (-14.4 ‰ in dripwater and -28.5 to -27.3 ‰ in Brulle spring water) are within the
656 range of biogenic pyrite and differ notably from values of marine evaporites (10-
657 35 ‰) (Seal, 2006). Thus, the $\delta^{34}\text{S}$ values together with the geological setting of
658 the cave support the hypothesis that disseminated pyrite in the host limestone is
659 the main source of dissolved sulfate and subsequently of CCG. Only the
660 dissolved sulfate $\delta^{34}\text{S}$ values of Brulle spring are considerably more negative (-
661 28.5‰ and -27.3‰). This may be a consequence of microbially mediated redox
662 processes in the karst that discriminate against ^{34}S (Zerkle et al., 2016; Temovski
663 et al., 2018). Further studies on the microbiology of the cave may shed light on
664 these mechanisms and how the local sulfur cycle may have changed in the recent
665 past.

666

667 In gypsum caves, dissolved sulfate dominates over the bicarbonate, and the
668 typical crystallization sequence during freezing of water with high TDS is gypsum
669 → carbonate (commonly calcite) → celestine (Žák et al., 2018). In Devaux cave,
670 however, bicarbonate dominates over sulfate, and our observations show that
671 gypsum crystals partly nucleated on CCC_{coarse}. Accordingly, the crystallization

672 sequence at Devaux cave is calcite → gypsum, taking place in a semi-closed
673 system at low freezing rates.

674

675 The second aspect that makes the CCG in Devaux cave unique is the size and
676 euhedral shapes of the crystals (Fig. 9 b), which differ notably from the much
677 smaller sizes of gypsum crystals (20-200 μm) and gypsum powders (1-30 μm)
678 found in gypsum caves in Russia and Ukraine (Žák et al., 2018 and references
679 therein). Another characteristic of CCC and CCG occurrences in Devaux cave is
680 the presence of milky ice surrounding them (Fig. 9a, e) which seems to be related
681 to the freezing process during the formation cryogenic minerals in a subaqueous
682 environment. Similar to that, CCC were found within the ice and surrounded by
683 bubbles in Sarrios 6 ice cave (Bartolomé et al., 2015). However, the scarce
684 presence of CCC within the ice today, together with the very few sites where this
685 topic is investigated, leads to a lack of studies about gas inclusions and CO_2
686 degassing during CCC formation.

687

688 Finally, the presence of gypsum aggregates overgrowing blocks (Fig. 9c)
689 supports the hypothesis of subaqueous gypsum formation. On the other hand,
690 the absence of gypsum growing on the ceiling or on the walls allows to discard
691 its formation from seepage water followed by precipitation due to evaporation in
692 the cave (e.g., Gázquez et al., 2017, 2020). In essence, all observations indicate
693 that gypsum precipitated in a semi-closed subaqueous environment and has
694 been preserved from later dissolution by the exceptionally dry environment of this
695 ice cave. Gypsum precipitating from freezing waters has been also documented
696 in the Arctic and the Antarctica (Losiak et al., 2016; Wollenburg et al., 2018) and
697 has been proposed as a mechanism for gypsum formation on Mars (Losiak et al.,
698 2016).

699

700 **6. Conclusions**

701 The investigation of Devaux ice cave, based on cave monitoring, geomorphology,
702 and geochemical analyses, provides exceptional insights into the origin of
703 modern and past mountain permafrost and associated processes and deposits.

704 - Devaux cave consists of two parts characterised by different thermal regimes:
705 1) the near-entrance parts and the main gallery showing large temperature
706 fluctuations and cave air temperatures seasonally exceeding 0°C. These
707 passages are influenced by advective air flow and heat released by the cave
708 river. 2) The inner sector and isolated chambers are characterized by muted
709 thermal oscillations and temperatures constantly below 0°C. There, the cave air
710 temperature is mainly controlled by heat conduction through the bedrock.

711

712 - Devaux cave is impacted by backflooding in late winter/early spring when the
713 main outlets freeze, damming the water inside the cave forming a lake. The
714 blocking of the outlets requires temperatures below 0°C in the Gavarnie cirque,
715 while on the southern side of the Monte Perdido massif, temperatures above
716 0°C allow water infiltration.

717

718 - The absence of dripwater in most parts of the cave together with the presence
719 of perennial/seasonal hoarfrost, and the location of massive ice bodies on the
720 ceiling and/or filling cupulas and galleries are indicative of frozen bedrock
721 surrounding the cave. Permafrost at Devaux cave is attributed to a combination
722 of rock undercooling by cave air ventilation and the local climate setting giving
723 rise to the development and/or preservation of permafrost inherited from past
724 colder periods. Currently, permafrost seems to be present above the cave
725 reaching a maximum thickness of ~200 m and a lateral extension of ~350 m
726 towards the southern face of the Monte Perdido massif.

727

728 - We report the first deposits of cryogenic gypsum in a limestone-hosted ice cave.
729 Most of the cryogenic minerals are still within the ice and surrounded by milky
730 ice rich in air inclusions. Gypsum precipitation occurred subaqueously as a
731 result of slow freezing, following CCC formation. $\delta^{34}\text{S}$ values show that the
732 sulfate originated from the oxidation of pyrite present in the limestone.

733

734 - Current climate conditions seem to be still favourable for the preservation of ice
735 within this cave. This situation contrasts to the large ice mass loss in other ice
736 caves elsewhere. The ice deposits in Devaux cave allow unique insights into
737 processes leading to the formation of cryogenic carbonates and sulfates, and

738 represents a unique site to better understand the mountain permafrost evolution
739 in the Monte Perdido massif and the Pyrenees in general.

740 **Data availability**

741 Data are available from the authors upon request.

742 **Authors contribution**

743 MB conceived the project, planned fieldwork and the sampling strategy. AM
744 obtained funding for this work. MB and GC installed and maintained the sensors
745 and performed the fieldwork. GC contributed with cave monitoring data from 2011
746 to 2015. MB analysed monitoring, geomorphological, and geochemical data. FG
747 performed $\delta^{34}\text{S}$ analyses using the facilities provided by AVT. JILM created the
748 radiation map. MB designed the figures and wrote a first draft of the manuscript.
749 ML and CS contributed to the discussion of the data. ML and AM reviewed all
750 versions of the manuscript. All authors reviewed the manuscript and contributed
751 to the results, discussion, and final interpretation. All authors approved its
752 submission.

753 **Competing interests**

754 No competing of interest

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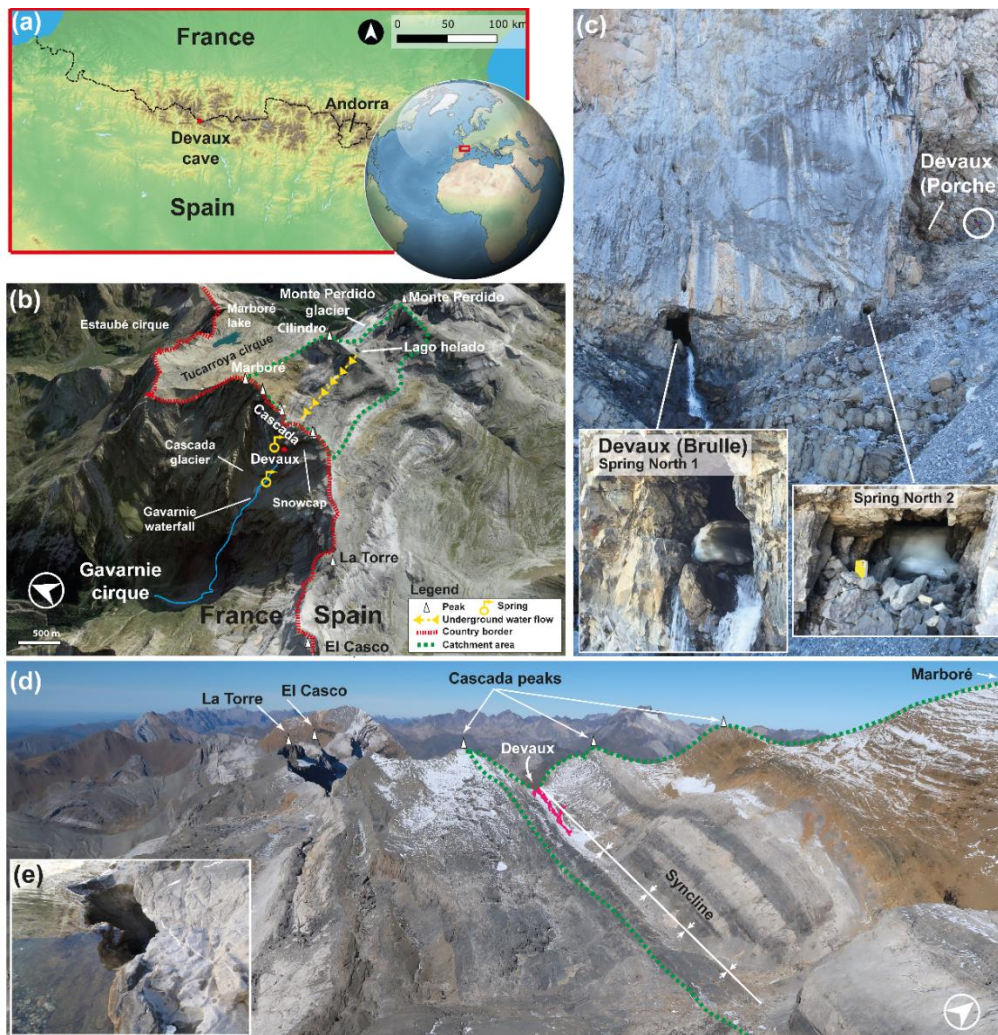


Figure 1. (a) Location of Devaux cave in the Central Pyrenees (ASTER GDEM, NASA v3, 2019). (b) Satellite image and location of Devaux cave, main peaks, lakes, glaciers and cirques in the study area (3D ©Google Earth). The yellow arrows indicate the underground flow path from Lago helado to the Gavarnie waterfall according to the dye-tracing experiment of du Cailar et al., (1953). (c) View towards the entrances of Devaux cave. The lower entrance (~2821 m a.s.l.) corresponds to the Brulle spring (Spring North 1), while the upper one corresponds to the main entrance (Porche (South), ~2836 m a.s.l.). Spring North 2 is located between both entrances. Note person for scale (within the white circle). Remnants of ice partially blocking Brulle and Spring North 2 (July 2021). (d) Landscape view of the catchment area and approximate location of Devaux cave (in dark pink; photo: Paul Cluzon). (e) Ponor located on the southern shore of Lago Helado.

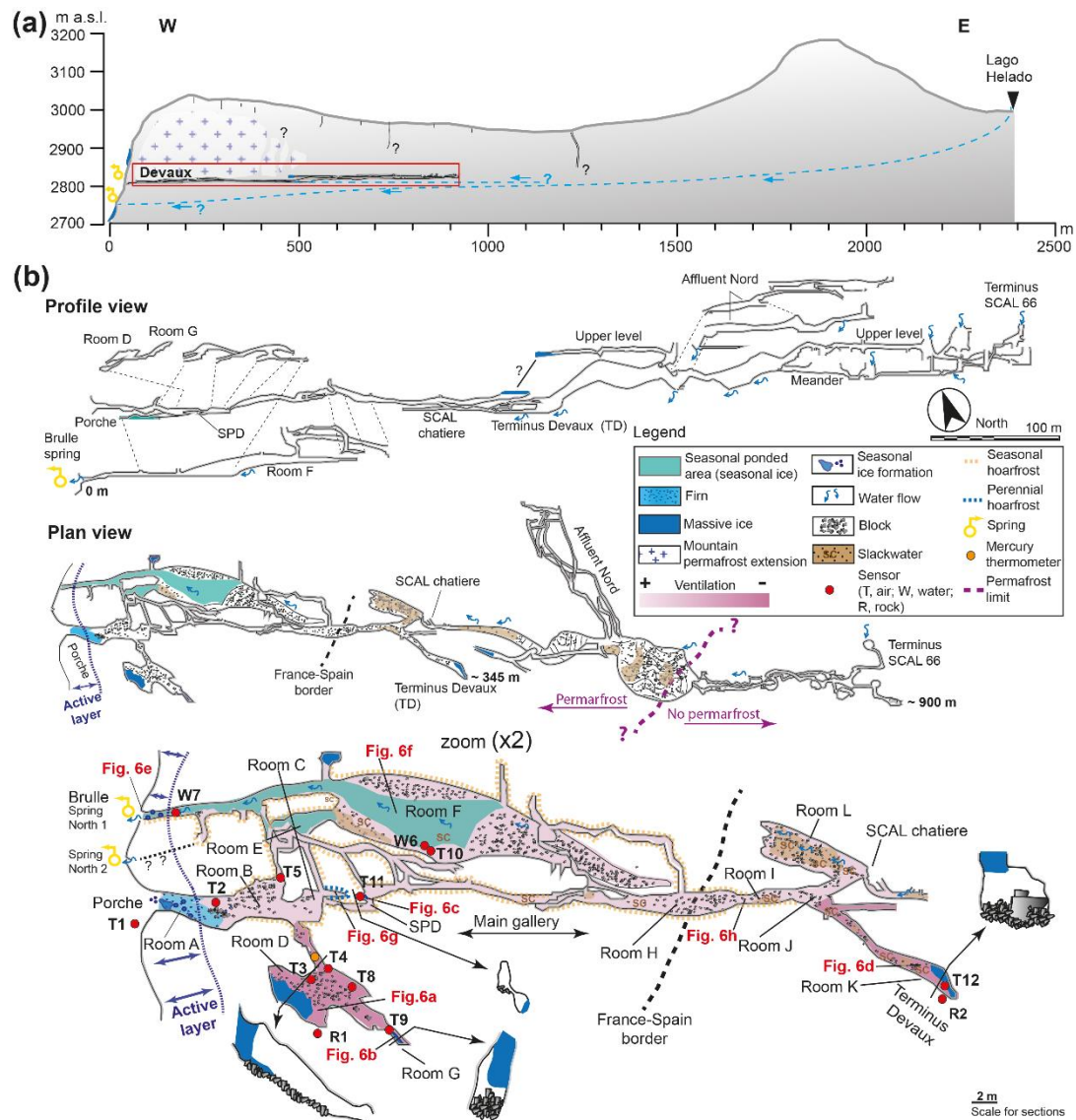


Figure 2. (a) Schematic W-E cross section from Lago Helado to Devaux cave, the assumed extent of mountain permafrost, and the interpreted underground flow path according to du Cailar et al., (1953). (b) Longitudinal section and plan view of Devaux cave showing the locations of sensors and cave deposits. Labels R, W and T refer to rock, water and air temperature sensors, respectively. The enlarged area corresponds to the first ~345 m of the studied sector. Red labels correspond to the approximate location of the photographs in Fig. 6. Cave survey by Marc Galy, Groupe Spéléologique des Pyrénées (GSPY 86).

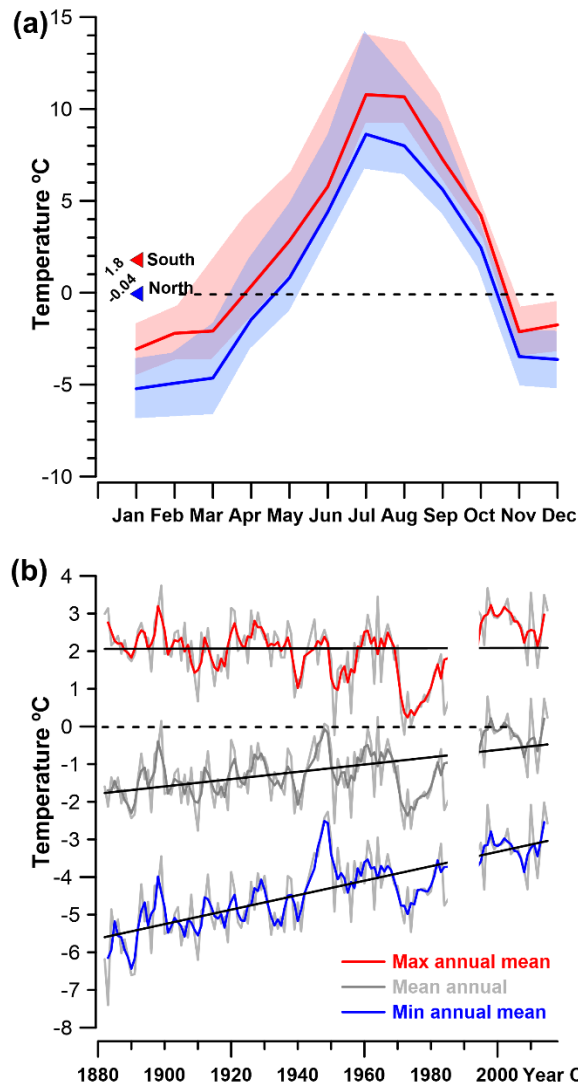


Figure 3. (a) Monthly temperature variation on the northern and southern side of the Monte Perdido massif. Red and blue triangles correspond to the 4-year means. The dashed black line indicates 0°C. Light red and blue shaded envelopes represent the maximum and minimum mean monthly temperatures, respectively. (b) Maximum, mean and minimum annual temperatures recorded at the Pic du Midi de Bigorre station since 1882. Black line indicates the general trend and dashed black line corresponds to 0°C.

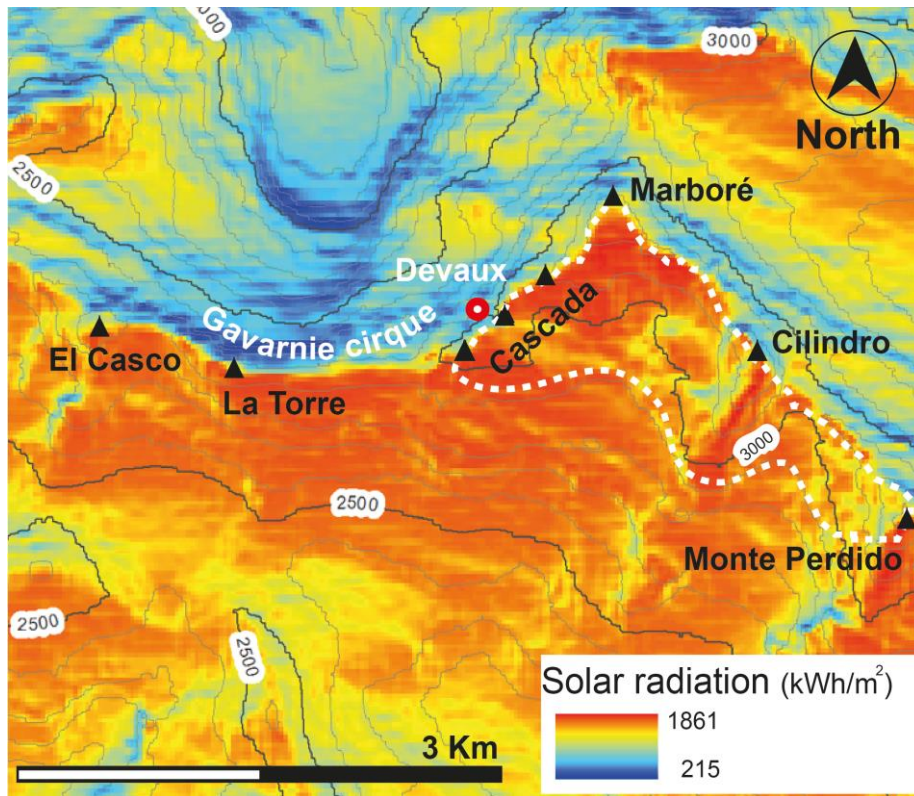


Figure 4. Solar radiation map of the study area. The solar radiation anomaly observed in the Gavarnie cirque is explained by its northerly orientation and the cirque morphology. Black triangles indicate the main peaks above 3000 m. The red-white circle marks Devaux cave, while the dashed white line delineates the approximate catchment.

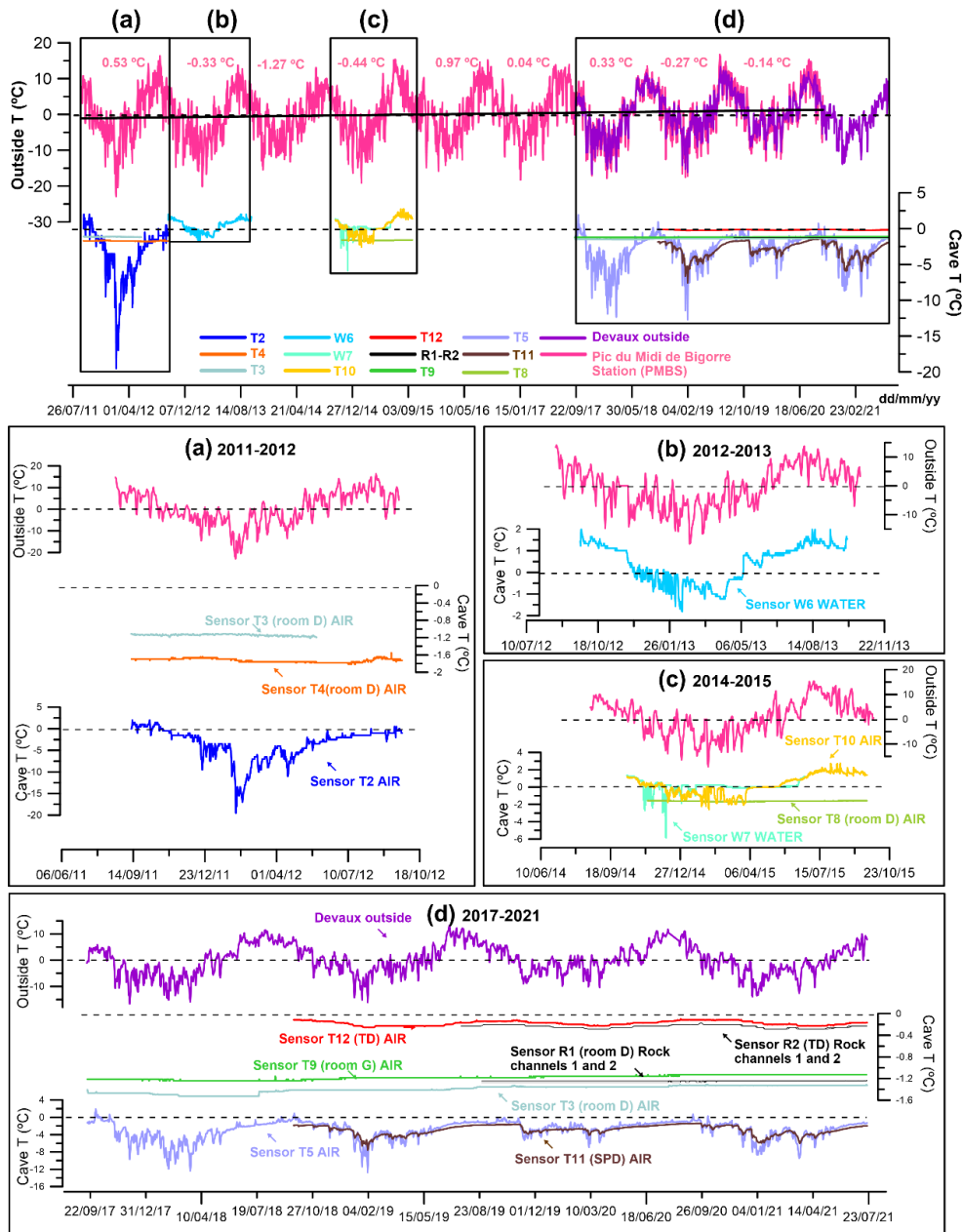


Figure 5. Mean daily air temperature variations at the Pic du Midi de Bigorre station (2860 m a.s.l., red), daily outside air temperature at Devaux cave (2836 m a.s.l., purple) and temperature variations in air, water and rock in the cave for the different time windows since 2011. Dark pink numbers are mean annual air temperatures (MAAT) at the Pic du Midi de Bigorre station (PMBS). Dashed lines indicate 0 °C. Black squares labelled a, b, c, and d correspond to the areas enlarged below. The black continuous line is the external temperature trend during the monitoring period.

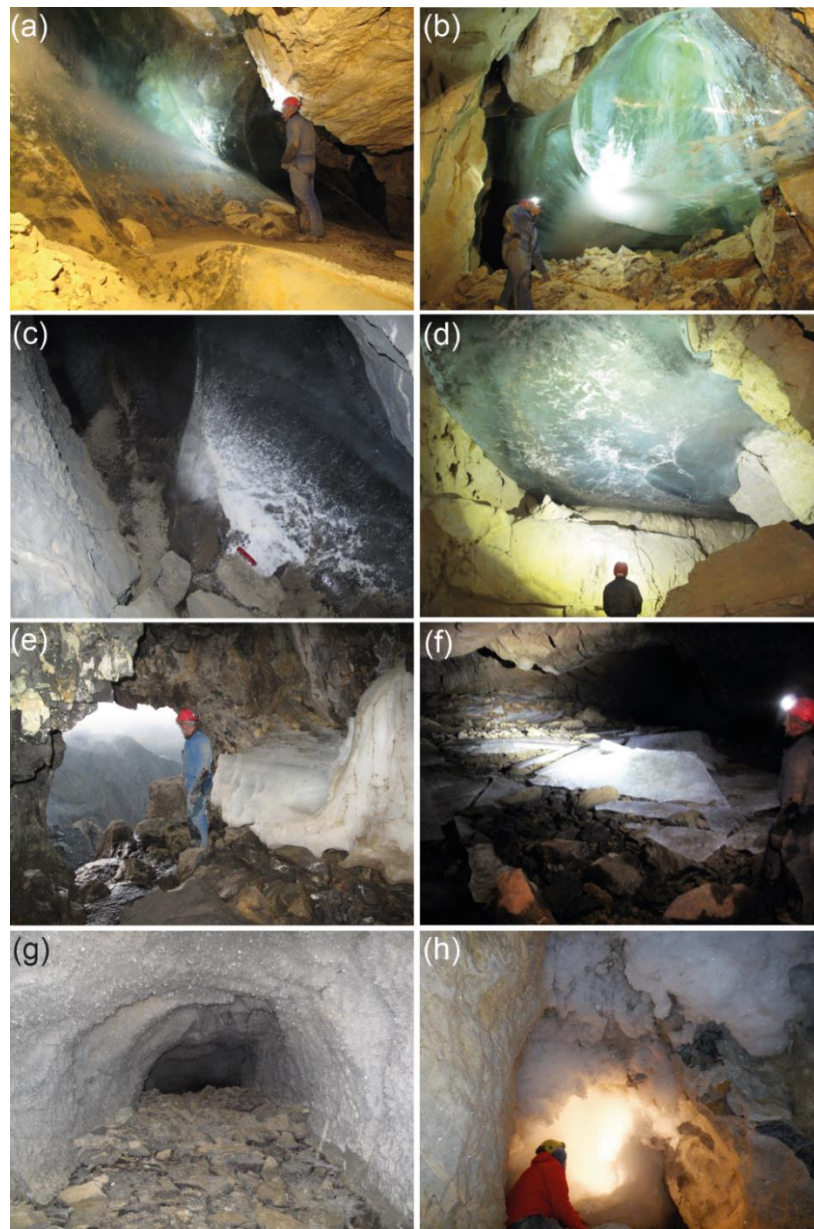


Figure 6. (a) Upper part of the ice body in room D. (b) Ice body hanging from the ceiling and the southwest wall in room G. White spots near the bottom of the deposit correspond to air inclusions as well as cryogenic carbonates and gypsum in the ice. (c) Small ice body in room SPD with CCC-CCG on and within the ice. Red knife (9 cm) for scale. (d) Ice body on the ceiling of room K (Terminus Devaux, TD). (e) Brulle spring and remains of a layered ice body (September 2018). (f) Broken ice sheets in the flooded area in room F (September 2018). (g) Millimetre to centimetre size perennial hoarfrost in a blind gallery below SPD room. (h) Seasonal hoarfrost aggregates (>30 cm long size) covering a cupola close to room J.

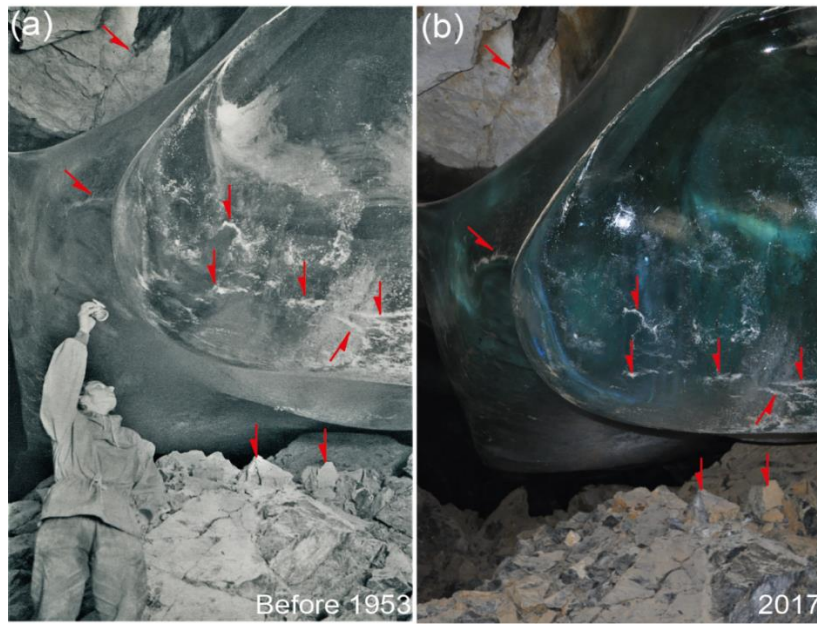


Figure 7. (a) Photo of the ice body located in room G taken shortly before 1953 (Casteret, 1953). (b) Photo taken in 2017. In both pictures, white patches on the ice surface correspond to small CCC accumulations released from the ice by sublimation. Red arrows indicate common features in both images.

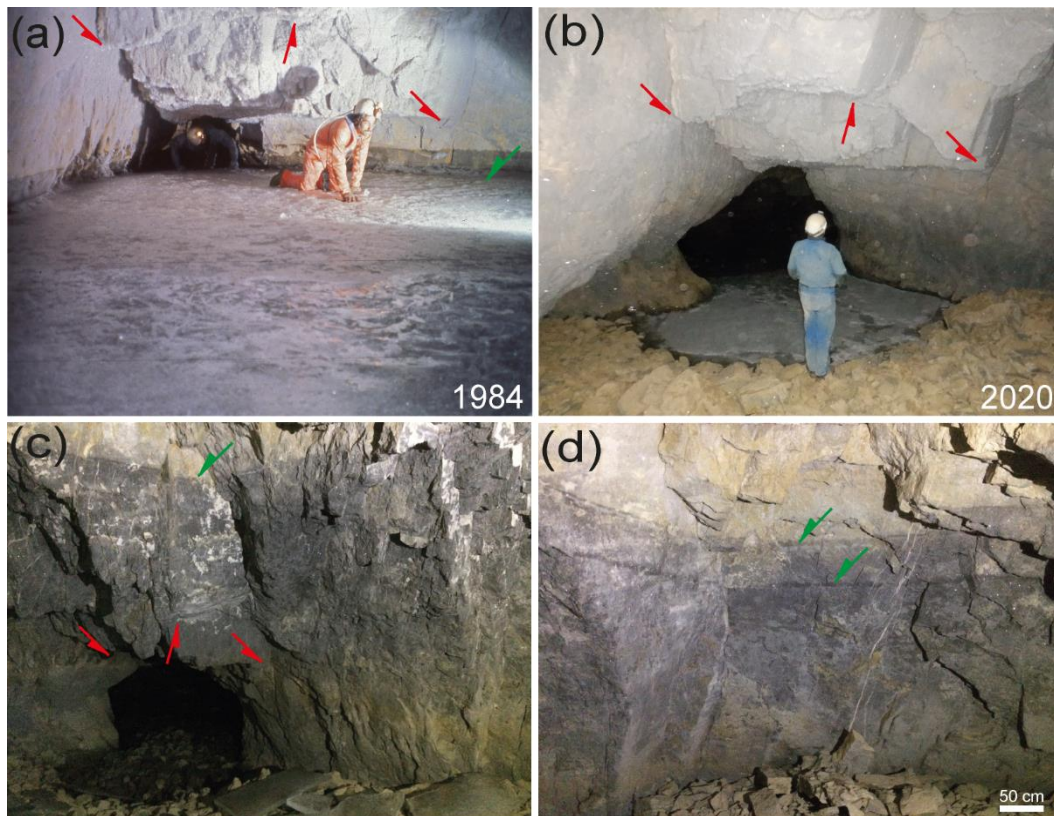


Figure 8. (a) Photo taken close to the river sector that connects the rooms F and E. The estimated ice level is 5 m higher than the Brulle spring. Photo by Jean Luc Bernardin (8th August 1984). (b) Similar area in 2020, and maximum extension of the seasonal lake ice formed during winter. (c) Higher ice mark level (c. +9.5 m with respect to the Brulle spring) and remnants of ice sheets from the frozen lake in 2018. (d) Two ice level marks (c. +9.2 m and +8.8 m with respect to the Brulle spring) located between the highest mark and the elevation of the ice in photo (a). In all images red arrows indicate the same rock edges, while green arrows show ice-level marks.

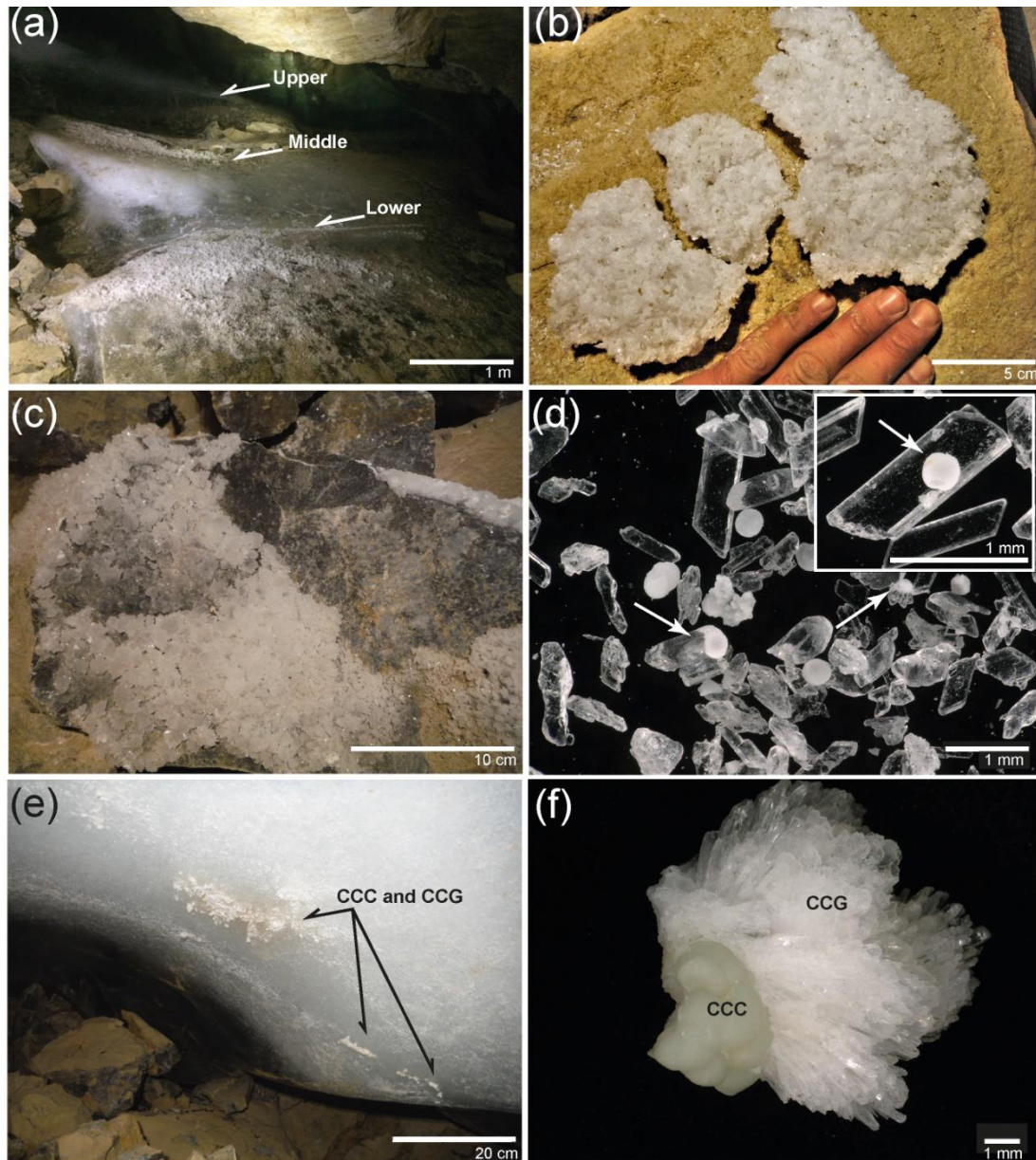


Figure 9. (a) Ice body in room G and three levels marked by cryogenic gypsum partially still in situ in the ice. The white area corresponds to milky ice with a high abundance of air inclusions. Gypsum crystals cover parts of the surface of the ice body due to ice retreat. (b) Large gypsum “raft” deposited on a block in room D. (c) Block in room D with gypsum overgrowths. (d) Microscopic image of euhedral CCG with cores of CCC (white arrows), globular CCC, and enlarged image of euhedral gypsum crystal with a nucleus of globular CCC. (e) CCC and CCG entrapped within milky ice in room G. (f) Detail of a CCC sample from room G covered by CCG.

Date	Sample	Cations					Anions								
		Na ⁺	NH ₄ ⁺	K ⁺	Ca ²⁺	Mg ²⁺	F ⁻	Cl ⁻	NO ₂ ⁻	Br ⁻	NO ₃ ⁻	SO ₄ ²⁻	HCO ₃ ⁻	CO ₃ ²⁻	PO ₄ ³⁻
15/09/2017	Devaux river 1	1.6	0.0	0.5	36.0	8.5	0.0	0.2	0.0	0.0	1.8	21.6	61.0	11.6	0.0
	Devaux drip 1	0.9	0.1	0.5	50.5	18.2	0.1	0.5	0.0	0.0	6.8	67.4	95.2	0.0	0.0
	Devaux drip 2	1.4	1.2	1.3	53.2	19.5	0.1	1.1	0.1	0.0	7.4	70.1	101.3	0.0	0.0
22/07/2018	Devaux Ice 1 (room D)	2.3	0.0	0.3	24.8	2.7	0.1	1.3	0.0	0.0	0.7	19.0	23.9	1.0	0.0
	Devaux Ice 2 (room D)	2.2	1.3	2.5	27.8	2.0	0.0	2.1	0.0	0.0	1.5	17.0	30.7	0.0	0.0
	Devaux river 1	0.6	0.0	0.4	32.4	4.4	0.0	0.2	0.0	0.0	0.9	5.1	53.7	4.0	0.1
22/09/2018	Devaux river 2	0.6	0.0	0.4	32.2	4.4	0.0	0.2	0.0	0.0	0.9	5.1	56.1	2.6	0.0
	Devaux drip 1	1.4	0.0	3.2	61.0	20.8	0.2	2.2	0.0	0.0	14.1	76.0	84.2	5.6	0.0
	Devaux drip 2	2.3	0.1	1.7	60.8	21.0	0.2	2.2	0.0	0.0	14.1	76.9	91.5	4.4	0.0
28/07/2020	Devaux river 1*	1.3	0.0	0.4	40.5	7.9	0.0	0.3	0.0	0.0	2.0	17.0	65.9	0.0	0.0
	Devaux drip 1*	1.6	0.0	1.2	70.6	27.2	0.2	1.1	0.0	0.0	19.8	116.5	90.3	0.0	0.0
	Devaux ice (seasonal)*	0.4	0.0	0.5	28.2	1.1	0.1	0.5	0.0	0.0	0.5	2.8	36.6	0.0	0.0
26/07/2021	Devaux river 1*	0.6	0.0	0.3	31.5	4.1	0.0	0.2	0.0	0.0	0.8	5.9	58.6	0.0	0.0
	Devaux drip 1*	1.1	0.2	1.1	42.3	12.5	0.1	0.5	0.0	0.0	2.9	38.4	101.3	0.0	0.0
	Devaux drip 2*	1.1	0.1	1.0	43.6	13.5	0.1	0.4	0.0	0.0	2.7	38.2	89.1	0.0	0.0
13/08/2021	Devaux drip 3*	1.6	0.7	1.5	47.9	13.1	0.1	1.1	0.0	0.0	2.2	36.7	107.4	0.0	0.0
	Devaux drip 1	2.9	0.0	1.1	83	35.9	0.3	5.9	0.6	0.1	40.2	269.3	104.9	0.0	0.0
	Devaux drip 2	3.3	0.4	2.0	73.2	29.3	0.2	6.0	0.1	0.0	28.6	212	112.2	0.0	0.0
26/07/2021	Devaux river 1	0.4	0.0	0.1	25.7	4.3	0.1	2.6	0.1	0.0	3.2	16.3	68.3	0.0	0.0
	Devaux river 1	0.7	0.0	0.2	28.6	4.9	0.1	2.6	0.0	0.0	1.5	20.4	74.4	0.0	0.0
	Devaux drip 1	7.5	2.2	5.1	49.5	15.2	0.2	10.3	0.3	0.0	6.9	77.3	130.5	0.0	0.0
26/07/2021	Devaux drip 2	5.1	1.3	2.8	49.3	15.6	0.2	6.5	0.1	0.0	6.5	80.5	129.3	0.0	0.0

Table 1. Chemical composition of water and ice samples from Devaux cave (in mg/l). * Samples where TDS (total dissolved solids) was calculated.

Location	Sample and description	$\delta^{34}\text{S}$ (‰) VCDT
Room D	Gypsum crystal (part of large raft)	-15.8
Room D	Gypsum crystal (part of large raft)	-15.5
Room D; lower gypsum level	Gypsum crystal (individual)	-15.6
Room D; middle gypsum level	Gypsum crystal (individual)	-15.0
Room D; middle gypsum level	Gypsum crystal (individual)	-15.6
Room D; upper gypsum level	Tiny gypsum crystals (aliquot)	-15.3
Room D	Gypsum crystal (individual)	-15.1
Room G	Gypsum crystal (individual)	-12.3
Room G	Gypsum overgrowth (individual)	-12.1
Room G	Gypsum overgrowth (individual)	-11.9
Room G	Gypsum overgrowth (individual)	-12.1
Room G	Gypsum overgrowth (individual)	-12.0
Limestone above cave	Pyrite crystal (individual)	-12.7
Entrance "Porche"	Drip water (1 liter)	-14.4
Brulle spring	River water 1 (1 liter)	-28.5
Brulle spring	River water 2 (1 liter)	-27.3

Table 2. Sulfur isotope values of gypsum, water and pyrite from Devaux.