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### ► To cite this version:

Daniel Ballesteros, Santiago Giralt, Joaquín García-Sansegundo, Montserrat Jiménez-Sánchez. Quaternary regional evolution based on karst cave geomorphology in Picos de Europa (Atlantic Margin of the Iberian Peninsula). *Geomorphology*, 2019, 336, pp.133-151. 10.1016/j.geomorph.2019.04.002 . hal-02469137

**HAL Id: hal-02469137**

**<https://hal.science/hal-02469137v1>**

Submitted on 22 Oct 2021

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1 **Quaternary regional evolution based on karst cave geomorphology in Picos de**  
2 **Europa (Atlantic Margin of the Iberian Peninsula)**

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11 Abstract

12 Alpine caves have attracted considerable geomorphological, paleoenvironmental and  
13 hydrogeological interest since climate, glaciations, relief uplift, fluvial incision and karst  
14 aquifer control their evolution. In the Atlantic Margin of the Iberian Peninsula, Picos de  
15 Europa mountains is among of the most important karst areas of the World containing  
16 some of the deepest caves explored today. In addition, these mountains represent a  
17 reference site for the study of the Last Glacial Cycle in the SW of Europe. This work  
18 aims to reconstruct the Pliocene-Quaternary evolution of this region based on  
19 geomorphological and geochronological research (U/Th and Al/Be) carried out in four  
20 alpine caves. Cave geomorphological mapping evidences that 12 km of studied caves  
21 are made up of 47 % vadose canyons and shafts, 45 % phreatic/epiphreatic conduits  
22 organised in six cave levels, and 7 % breakdown-modified passages. Their deposits  
23 are characterized by speleothems, including flowstones, that represent ancient cave  
24 pavements, fluvial terrace deposits with allochthonous clasts, slackwater deposits  
25 related to cave floods, and debris deposits produced by breakdown. One  $^{26}\text{Al}/^{10}\text{Be}$   
26 burial age indicates a minimum age of  $2.1 \pm 0.5$  Ma for the caves origin, allowing



27 estimation of the mountain uplift at 0.15-0.25 mm a<sup>-1</sup> since the Late Pliocene. Twenty-  
28 eight new <sup>234</sup>U/<sup>230</sup>Th ages and another six previous speleothem ages give ages ranging  
29 from MIS 8 to 1. The speleogenetic model comprises six phases of regional evolution.  
30 Phase 1: main development of cave levels with SE-directed phreatic flow in the NW of  
31 Picos de Europa, in a karst partially or totally covered by the detrital Permian-Mesozoic  
32 cover, presently eroded. Phase 2: erosion of the Permian-Mesozoic cover and onset of  
33 vadose conditions before 260 ka, in a karst-affected by fluvial captures. Phase 3: cave  
34 infill during 220-145 ka, probably caused by the erosion of Stephanian detrital outcrops.  
35 Phase 4: erosion of cave infill during 125-45 ka. Phase 5: apparent pause in the  
36 speleothem formation during 45-25 ka related to dry and cold regional conditions.  
37 Phase 6: reactivation of the speleothem precipitation since 25 ka. Regional climate,  
38 fluvial incision and the ancient presence of detrital outcrops at the surface appear to  
39 have been the main factors that controlled the cave evolution and regional  
40 geomorphological evolution throughout Pliocene and Quaternary times.

41

42

43 Keywords: alpine karst, geomorphology, geochronology, speleogenesis.

#### 44 **1. Introduction**

45 Alpine caves are dominated by successions of vadose canyons and shafts developed  
46 in mountain karst areas (Maire, 1990), which correspond frequently to glaciokarsts  
47 (Ford, 1987). Alpine caves are of interest as they are developed close to the zero  
48 degrees isotherm. This makes them very sensitive to climatic and environmental  
49 change (Johnston et al., 2013; Luetscher et al., 2015). In these areas, low  
50 temperatures limit the vegetation productivity, reducing soil pCO<sub>2</sub>, acid organics and  
51 drip water saturation (Lauritzen and Skoglund, 2013; Zhou et al., 2015). Alpine caves  
52 support important speleothems and ice records in glaciated areas of South Europe

53 during the Quaternary, such as the Alps and Pyrenees (Miorandi et al., 2010;  
54 Wackerbarth et al., 2012; Weremeichik and Mylroie, 2014). Further, the presence of  
55 remains of troglobitic/stygobitic fauna in alpine caves indicates past climate fluctuations  
56 and glacial ice extensions (Eme et al., 2014).

57 The study of the geometry and deposits of alpine caves reveals valuable information  
58 about glaciations, fluvial evolution, relief uplift and neotectonics over the past several  
59 millions of years (Audra et al., 2006; De Waele and Pasini, 2013). Regarding cave  
60 geometry, alpine cavities usually show several cave levels formed by phreatic and  
61 epiphreatic conducts originated at the water table (Palmer, 1987). Thus, cave levels  
62 represent ancient water tables that can be currently located 1-2 km above the  
63 saturated zone of karst aquifer (e.g. Plan et al., 2009; Calvet et al., 2015). This  
64 situation evidences the lowering of the water table, triggered by fluvial incision caused  
65 by mountain uplift or the drop of the fluvial base level, which is frequently related to  
66 glacier stages (Audra et al., 2006). Regarding cave deposits, they constitute  
67 exceptional records preserved over long timescales. In lowland areas, surficial deposits  
68 are well preserved and can be useful for reconstructing the geomorphological and  
69 climatic evolution of a region. However, in upland areas where erosion has removed  
70 much of the surface evidence, cave deposits represent the most common and best-  
71 preserved archive of palaeoenvironmental and paleoclimate data. Among these  
72 deposits, fluvial deposits came from erosion of the limestone bedrock as well as detrital  
73 rocks that cropped out on the surface, thus these sediments constitute evidence of the  
74 ancient landscape that was strongly eroded by the last glaciation (Häuselmann, 2013).  
75 The dating of cave deposits provides a chronology for the aforementioned cave levels,  
76 usually based on minima ages, and the timing of palaeoenvironmental and  
77 paleoclimate changes. The  $^{234}\text{U}/^{230}\text{Th}$  method is frequently used to date cave deposits  
78 up to Middle Pleistocene in age (e.g. Fairchild et al., 2010; Wackerbarth et al., 2012),  
79 whereas cave ages obtained by cosmogenic isotopes, U/Pb or paleomagnetism

80 methods can extend to the Pliocene (e.g. Hobléa et al., 2011; Calvet et al., 2015; Rossi  
81 et al., 2016).

82 Geomorphological studies have shown that alpine karst are probably of Miocene age,  
83 and have been strongly modified by later fluvial modifications and Quaternary  
84 glaciations (Audra et al., 2002, 2006; Hobléa et al., 2011; Columbu et al., 2015).

85 Flowstone formation usually occurred during warm environmental conditions while  
86 detrital sedimentation took place during glacial periods in the Alps (Europe) and  
87 Canadian Rocky Mountains, in North America (Ford, 1993; Plan et al., 2009).

88 Therefore, these sediments constitute records of glacial timing, including glacier  
89 advances and retreats. Combining absolute dating and geomorphological studies,  
90 alpine caves allow the estimation of uplift since the Pliocene, including phases of  
91 abrupt valley over-deepening, as the abrupt glacial valley incision occurred at 0.8 Ma in  
92 the Alps (Häuselmann et al., 2007), or Quaternary fluvial incision acceleration in the  
93 Pyrenees (Calvet et al., 2015). These works also quantified fluvial incision rates, with  
94 ranges of 0.1-0.8 mm a<sup>-1</sup> for the Quaternary, based on the presence of ancient phreatic  
95 conduits perched hundreds of meters above the current watertable. Locally, the study  
96 of alpine caves reveals sea-level changes. Alpine caves also hold evidence the timing  
97 and deformation mechanism of neotectonic movements based on speleothem damage  
98 and displacements in karst conduits, as reported in caves of the Austrian Alps (Plan et  
99 al., 2010).

100 The study of alpine caves reveals data about the geometry and functioning of many  
101 karst aquifers that contain significant water resources (Goldscheider and Neukum,  
102 2010; Vigna and Banzato, 2015). These data include variations in phreatic paleoflows  
103 directions and paleoaquifer recharge that has occurred since the Miocene (Audra et al.,  
104 2002, 2006; Plan et al., 2009).

105 In spite of their great interest, few alpine caves have been studied in the European  
106 Atlantic Margin, with few examples from Scandinavian (North Europe). In SW Europe

107 (Fig. 1), studies focused on geomorphology, drip water chemistry and speleothems of  
108 alpine caves were performed in the Western Pyrenees (Quinif and Maire, 1998) and its  
109 extension to the W: the Cantabrian Mountains (Aranburu et al., 2014; Gázquez et al.,  
110 2014; Ballesteros et al., 2015a, 2017; Rossi and Lozano, 2016; Rossi et al., 2016).

111 This work aims to establish the Quaternary geomorphological evolution of Picos de  
112 Europa and the influence of the climate and surficial processes (glaciations and others)  
113 on its speleogenesis. With this purpose, we combined previous geomorphological and  
114 geochronological data of two alpine caves (Ballesteros et al., 2011b, 2015a, 2017) and  
115 geomorphological evidence collected in other two cavities, as well as 28 new numerical  
116 ages based on  $^{234}\text{U}/^{230}\text{Th}$  series dating and one  $^{26}\text{Al}/^{10}\text{Be}$  burial age. The length of  
117 studied caves reaches 12 km of conduits that represent 3% of the total conduits of  
118 Picos de Europa.

## 119 **2. Setting**

120 Picos de Europa (43.2°N, 4.8°W) is a discrete mountainous area up to 2648 m in  
121 elevation and covering 700 km<sup>2</sup>, forming part of the Cantabrian Mountain range (Fig.  
122 1c). Picos de Europe has an Atlantic maritime climate with 1000-1800 mm of  
123 precipitation distributed evenly through the year. Average air temperatures range from -  
124 3 to 17°C. Above 1500 m altitude, snow cover is present 6-9 months a year.

125 In general, Carboniferous limestone forms the bedrock although minor Ordovician and  
126 Stephanian (~Kasimovian) sandstone and shale crop out in Picos de Europe, mainly  
127 along its borders (Bahamonde et al., 2007; Sanz-López et al., 2018). Variscan thrusting  
128 affected these rocks in the upper Carboniferous, followed by the Permian-Mesozoic  
129 extension faulting, when red sand and silt and other sediments covered the karstified  
130 Carboniferous limestone (Merino-Tomé et al., 2009). During these times, Cretaceous  
131 hydrothermal activity produced local dolomitization and sulphide mineralization  
132 (Symons et al., 2015). Finally, the Alpine orogeny (Paleocene-Miocene) led to the uplift

133 of the entire Cantabrian Mountains (Fillon et al., 2016; Gallastegui et al., 2016). This  
134 uplift caused the erosion of the Permian-Mesozoic cover. A few remnant outcrops of  
135 this Permian-Mesozoic cover are preserved in some low-lying areas.

136 Carboniferous limestone forms a karst aquifer extending over 883 km<sup>2</sup> but  
137 compartmentalised by Ordovician and Stephanian sandstones and shales that  
138 represent aquitards, resulting in a dammed karst configuration (Ballesteros et al.,  
139 2015d). The saturated zones of the aquifer have less than 200-300 m thickness and  
140 unsaturated zones achieve 2.3 km in thickness in some areas. The water tables are  
141 placed at 800-1500 m altitude in the S and at 145 m elevation the N of Picos de  
142 Europa.

143 Picos de Europa is divided into three massifs - Eastern, Western and Central - by rivers  
144 that formed fluvial canyons up to 2 km deep. Three rivers (the Sella, Cares and Dobra  
145 rivers) are consequent courses and flow S to N, forming the regional base-level at 100-  
146 200 m altitude. Subsequent rivers (as the Casaño River, Fig. 1c) start in karst springs  
147 flowing to the NW or SE constrained by the regional geological structure.

148 More than 410 km of cave passage have been discovered by speleological groups,  
149 including 69 cavities with more than 500 m depth (Fig. 1b). The majority of the deep  
150 caves comprise sequences of vadose canyons and shafts, the deepest of which is  
151 1600 m depth (Erra et al., 1999). Sequences of vadose canyons and shafts constitute  
152 the majority of the deep caves, reaching 1.6 km of vertical range in the deepest cavity  
153 (Erra et al., 1999). Furthermore, ~160 km of phreatic/epiphreatic galleries form at least  
154 24 cave levels developed from 140 to 2400 m altitude, now abandoned by base level  
155 lowering and valley incision (Ballesteros et al., 2015b). Smart (1986), Senior (1987)  
156 and Fernández-Gibert et al. (2000) proposed a cave evolution which started in the  
157 Pliocene when the Permian-Mesozoic rocks still covered Carboniferous limestone.  
158 Later, the rivers fitted in the landscape, reaching the Paleozoic bedrock by eroding  
159 almost completely the Permian-Mesozoic cover. This situation triggered fluvial valley

160 deepening and the lowering of local water tables, creating a thick vadose zone with  
161 canyons and shafts (vertical conduits) up to 300 m deep, as well as the development of  
162 lower cave levels. Locally, Senior (1987) recognized paragenetic features related to  
163 alluvial sediments in the upper part of few deep caves.

164 Glacial ice covered up to 180-195 km<sup>2</sup> of the extension of Picos de Europa during  
165 periods of the Middle and Upper Pleistocene (Villa et al., 2013; Serrano et al., 2016).  
166 The glaciers descended up to 600-800 m altitude during the local maximum extension  
167 that took place before 46-35 ka (Serrano et al., 2012; Jiménez-Sánchez et al., 2013;  
168 Ruiz-Fernández et al., 2016a). During the Upper Pleistocene, glacial advances  
169 occurred at 48-35 ka (Serrano et al., 2016), followed by a general retreat under dry and  
170 cold conditions. An equilibrium or advance glacial stage took place at ca 23-19 ka,  
171 during a wetter period coeval with the Last Glacial Maximum (LGM) (Rodríguez-  
172 Rodríguez et al., 2014; Ruiz-Fernández et al., 2016a). The timing of the Last  
173 Deglaciation in Picos de Europa would have occurred coevally with the nearby  
174 Monasterio Valley (Fig. 1), where glaciers retreated at 18.1-16.7 ka (Rodríguez-  
175 Rodríguez et al., 2017). Later, temperature and precipitation increases led to the  
176 development of glacial cirques at the end of MIS 2 (Ruiz-Fernández et al., 2016b) and  
177 deciduous forest up to 1500 m altitude in the Holocene, although minor glacial  
178 advances happened during the Little Ice Age (LIA) (González-Trueba et al., 2008;  
179 Moreno et al., 2011). Periglacial conditions affected areas above the 1000 m in  
180 elevation, at least between 37 and 29 ka (Nieuwendam et al., 2015). Nowadays,  
181 periglacial and snow processes affect the highest areas (Ruiz-Fernández et al.,  
182 2016b), with permafrost restricted to ice caves (Berenguer-Sempere et al., 2014).

### 183 **3. Methodology**

184 The methodology comprises the characterization of the pilot caves' geomorphology  
185 and geochronology as well as the geomorphology of the surrounding area (Ballesteros

186 et al., 2011b, 2015a). All data have been integrated and handled using a Geographic  
187 Information System (GIS).

188 We selected four study pilot caves named Torca Teyera, Torca La Texa, El Frailín de  
189 Camplengu, and Pozu Lluçia, which are located at the N of the Western Massif, with  
190 entrances placed from 1266 to 1356 m altitude (Fig. 1c). We chose these cavities  
191 based on their accessibility and presence of phreatic/epiphreatic galleries between 800  
192 and 1500 m a.s.l., at the same altitudes of the main cave levels of Picos de Europa  
193 (Ballesteros et al., 2015b).

194 We undertook speleological, geomorphological and geochronological analyses for each  
195 pilot cave. We constructed geomorphological maps for these caves at a 1:200 scale,  
196 representing the cave features and deposits on the speleological cave survey,  
197 elaborated previously according to the UISv1 5-2-BCEF grade defined by Häuselmann  
198 (2011). These geomorphological maps depicted the spatial and relative-temporal  
199 distribution of the cave forms, and allowed us to identify the type of conduit according  
200 to its origin. The addition of the length of each type of conduit provides the percentage  
201 of the caves formed by each conduit. Finally, we defined the cave levels combining the  
202 mapped phreatic evidences and vertical distribution of cave conduits following  
203 Ballesteros et al. (2015a).

204 The construction of a robust chronological framework for these five studied caves  
205 required 28 new  $^{234}\text{U}/^{230}\text{Th}$  speleothem dates and one new  $^{26}\text{Al}/^{10}\text{Be}$  burial age in a  
206 fluvial deposit. Prior to the radiometric dating, we analysed the petrographic texture the  
207 speleothems using optical microscopy in order to exclude speleothems that presented  
208 corrosion or crystals with irregular limits between minerals. We applied the U/Th  
209 disequilibria method by alpha-spectrometry from the Institute of Earth Sciences Jaume  
210 Almera (ICTJA-CSIC, Barcelona, Spain). We undertook chemical separation of the  
211 radioisotopes and purification from a speleothem sample (~20 g) following the  
212 procedure described by Bischoff et al. (1988), and isotope electrodeposition was done

213 according to the method of Talvitie (1972), modified by Hallstadius (1984). We counted  
214 isotope concentrations using an ORTEC OCTETE PLUS spectrometer equipped with  
215 eight BR-024-450-100 detectors of Ivanovich and Harmon (1992) and calculated the  
216 absolute ages employing the software designed by Rosenbauer (1991). We applied the  
217 isochron method (Bischoff and Fitzpatrick, 1991) to date five samples with ~2-5% wt of  
218 detrital residue. In all cases, we evaluated the possible detrital contamination of the  
219 dated speleothems based on the  $^{230}\text{Th}/^{232}\text{Th}$  ratio (Bischoff and Fitzpatrick, 1991),  
220 which evaluates the relation between the concentration of  $^{230}\text{Th}$  (with radiogenic and  
221 detrital origin) and  $^{232}\text{Th}$  (with only detrital origin). A  $^{230}\text{Th}/^{232}\text{Th}$  ratio (see later, Table 2)  
222 higher than one or two indicates that detrital contamination is not significant.

223 We obtained a single cosmogenic burial age for a fluvial sediment from Torca Teyera  
224 cave based on the determination of  $^{10}\text{Be}/^9\text{Be}$  and  $^{26}\text{Al}/^{27}\text{Al}$  ratios by the Purdue Rare  
225 Isotope Measurement Laboratory (Indiana, USA) using an accelerator mass  
226 spectrometry. Laboratory procedures include purification of quartz grain from a sand  
227 sample (17.379 g),  $^{10}\text{Be}$  decontamination, and acid dissolution in HF following Granger  
228 et al. (2001). We added also a carrier (303.4  $\mu\text{g}$ ) of  $^{10}\text{Be}$ . Detect limits of  $^9\text{Be}$  and  $^{27}\text{Al}$   
229 are  $10^{-15}$  and  $5 \cdot 10^{-15}$  of the radionuclides atoms ratios, respectively. We considered  
230  $1.02 \pm 0.04$  for radioactive  $^{26}\text{Al}$  mean life and  $1.36 \pm 0.07$  Ma for the  $^{10}\text{Be}$  (Chmeleff et  
231 al., 2010), estimating the local production rates of the cosmogenic isotopes for  $43.27^\circ\text{N}$   
232 latitude and an elevation of 2 km following Stone (2000):  $P_{^{10}\text{Be}}=21.50 \text{ at}\cdot\text{g}^{-1}\cdot\text{a}^{-1}$ ;  
233  $P_{^{26}\text{Al}}=145.96 \text{ at}\cdot\text{g}^{-1}\cdot\text{a}^{-1}$ . Fraction spallation production is 0.97 and 0.98 for  $^{10}\text{Be}$  and  $^{26}\text{Al}$   
234 and penetration length neutrons 60 cm (Granger et al., 2007). Analytical uncertainties  
235 (reported as  $1\sigma$ ) are based on Arnold et al. (2010).

236 Finally, we determined the detailed geomorphological context of the selected caves to  
237 establish the relationship between cave development and surface evolution. For this,  
238 we projected the pilot caves and 144 km of cave conduits on a geomorphological map



239 of the study area (117 km<sup>2</sup> in extension), derived from fieldwork, photointerpretation  
240 and a GIS analyses.

## 241 **4. Results**

### 242 *4.1 Cave conduits*

243 Fig. 2 shows the geomorphological maps of the El Frailín de Camplengu and Pozu  
244 Lluçia caves, complemented by the published geomorphological maps of the Torca  
245 Teyera and Torca La Texa caves (Ballesteros et al., 2011b, 2015a). Table 1 indicates  
246 the percentage of conduit type for each of the pilot caves, as well as the altitude of the  
247 defined cave levels. The longitude and vertical range of the pilot caves ranges from 2.3  
248 to 4.4 km and 215 to 738 m, respectively. From a genetic point of view, the set of cave  
249 conduits includes vadose canyons and shafts, relict phreatic/epiphreatic conduits and  
250 breakdown-modified passages.

251 Vadose canyons and shafts represent 47% of the entire studied caves, varying from 49  
252 to 55% in each cavity. Canyons are usually associated with stepped shafts, although  
253 independent shafts up to 80 m high are also recognized in the pilot caves. The incision  
254 and the horizontal migration of cave streams (Fig. 4a) developed vadose canyons,  
255 invasion canyons and independent shafts, which intercepted previous  
256 phreatic/epiphreatic conduits or fed into them. The canyons show pendants and  
257 corrosion notches that appear associated with alluvial deposits, thus the origin of these  
258 erosive features is paragenetic according to Farrant et al. (2011).

259 45% of the pilot caves display phreatic/epiphreatic conduits that represent between 38  
260 and 49% of each cavity. The phreatic/epiphreatic conduits show loops (2-15 m in  
261 amplitude) and orientations toward the N in the Torca Teyera cave, and toward the SW  
262 in the remaining cavities (Fig. 2). These orientations agree with the scallops and the  
263 convergence between different phreatic conduits. Consequently, the phreatic  
264 groundwater flowed to the SW, locally to the N in Torca Teyera, during the formation of

265 these phreatic/epiphreatic conduits. Dissolution cupolas, phreatic/epiphreatic tubes and  
266 other phreatic features (Figs. 3, 4a) provide evidence the presence of six cave levels at  
267 1300, 1240-1270, 1150-1190, 1080, 700-800 and 615 m a.s.l. (Fig. 3; Table 1). Cave  
268 level 1 only appears in the Torca Teyera cave, whereas levels 2 and 3 form part of the  
269 remaining caves. Level 4 can be identified in the El Frailín de Camplengu and Pozu  
270 Llucia caves while levels 5 and 6 are only seen in the Torca Teyera cave.

271 The studied caves include 7% of breakdown-modified passages, ranging from 5 to 9%  
272 depending on the cavity. These passages are previous vadose and phreatic passages  
273 modified by breakdown processes that produced the accumulation debris, involving  
274 boulders up to 15 m diameter (Fig. 4c).

#### 275 *4.2 Cave deposits*

276 The geomorphological maps of the pilot caves show that speleothems, fluvial,  
277 slackwater and debris deposits occupy 68% of the studied cavities (Fig. 2). Fluvial  
278 sediments include current thalweg and terrace deposits mainly formed by rounded  
279 limestone cobbles and pebbles, with a matrix dominated by quartz and carbonate sand  
280 (Fig. 5). Locally, these deposits contain clasts of sandstone, igneous rocks, bauxite,  
281 nodules of siderite/limonite and fragments of speleothem. The present stream channels  
282 contain thalweg deposits often capped by flowstones that are now being eroded by  
283 stream action (Fig. 4a). Fluvial terrace deposits are perched up to 25 m above the  
284 bottom of the canyons and phreatic/epiphreatic conduits. Frequently, these deposits  
285 are associated with pendants and involve interlayered flowstones very rich in detrital  
286 minerals.

287 Speleothems are frequently flowstones and stalactites precipitated at the walls or  
288 above fluvial, slackwater and debris deposits (Figs. 3, 4), and comprise up to 60% of  
289 insoluble residue, frequently quartz and clays according to microscope observations.  
290 Flowstones show erosive features and form ledges perched up to 10 m above the cave

291 floor (Fig. 5a). The base of these ledges englobes rounded pebbles, thus these  
292 flowstones precipitated above alluvial sediments (Fig. 5b). Later, groundwater eroded  
293 the underlying fluvial sediments leaving the flowstone hanging on the wall. This  
294 situation results in the unstable gravitational position of these flowstones, favouring  
295 their breakdown and collapse (Fig. 4C). Furthermore, speleothems show erosive scars  
296 frequently related to the fluvial incision occurred after their precipitation.

297 All this information about the alluvial sediments and speleothems evidences that these  
298 deposits filled the vadose canyons and phreatic/epiphreatic conduits in the past.  
299 Therefore, at least, a phase of cave filling and another one of cave erosion occurred  
300 during cave evolution.

301 Slackwater deposits comprising up to 4 m-thick deposits of carbonate silts and clays  
302 are often preserved along the walls or at the bottom of phreatic/epiphreatic conduits  
303 (Fig. 2). Quartz grains are also frequent in these sediments. These deposits are either  
304 massive or show a fine-lamination marked by millimeter-scale fining-upward  
305 sequences. In few cases, these sediments cover fluvial and breakdown deposits. In the  
306 Torca La Texa cave, Ballesteros et al. (2017) interpreted two of these deposits as  
307 rhythmites formed during floods caused by glacial melting in the MIS 5c-b; thus these  
308 sediments come from glacial erosion of the limestone.

309 Lastly, fluvial deposits, slackwater sediments, or flowstones and dripstones usually  
310 cover debris deposits by cave breakdown (Fig. 2). This process is very common in the  
311 studied cavities, especially in the breakdown-modified passages, where accumulations  
312 of up to 7 m of fallen debris were recognized. Nowadays, breakdown processes  
313 continue to actively modify the cave morphologies and their deposits, especially  
314 perched speleothems mentioned above.

315 *4.3 Cave geochronology*

316 Table 2 displays 28 new  $^{234}\text{U}/^{230}\text{Th}$  dates. The majority of speleothem samples contain  
317 siliciclastic material (clays), increasing detrital  $^{230}\text{Th}$ . However, terrigenous  
318 contamination by detrital Th is negligible as the  $^{230}\text{Th}/^{232}\text{Th}$  ratio in almost all samples is  
319 greater than one or two.

320 Fig. 7 displays the geomorphological setting of the dated speleothems and alluvial  
321 deposits in the pilot caves, providing the spatial and temporal relationships between the  
322 speleothems, fluvial, slackwater and breakdown deposits. Table 3 shows a single burial  
323  $^{26}\text{Al}/^{10}\text{Be}$  age for a sample collected from a fluvial deposit located in the Torca Teyera  
324 cave. This date provides a reference age of  $2.1 \pm 0.5$  Ma for the alluvial deposition at  
325 the 700-800 m cave level. Despite the fact, we only have one burial age, the obtained  
326 age allowed us to estimate an erosion rate of  $0.01 \text{ mm a}^{-1}$  for the study area since the  
327 Pliocene. This value only allows us to assess the order of magnitude of regional  
328 erosion.

#### 329 *4.4 Karst massif and field relationship between caves and surficial landforms*

330 The caves are located on a karstic plateau dipping  $6\text{-}10^\circ$  to the north, dominated by  
331 glacial valleys, glaciokarst depressions and dolines. This plateau shows glacial till  
332 mainly between 900-1300 m asl, (Fig. 9) containing clasts of limestone, sandstone,  
333 igneous rocks, bauxites and nodules of siderite (altered to limonite by weathering).  
334 These non-carbonate clasts are similar to the allochthonous fluvial deposits found in  
335 the pilot caves (section 4.2). As shown by the glacier reconstructions for the maximum  
336 local extent (e.g. Rodríguez-Rodríguez et al., 2014; Ruiz-Fernández et al., 2016b), the  
337 karst plateau containing most of the pilot caves was covered by glaciers, except for the  
338 Pozu Lluçia cave located in a smaller hillside without glacial evidence (Fig. 9).

339 Fluvial, slope and nival processes also modelled the narrow fluvial canyons  
340 surrounding the karst plateau (Fig. 9). The largest karst springs (up to  $\sim 10 \text{ m}^3\cdot\text{s}^{-1}$   
341 discharge) are located in the consequent Cares River, while karst springs with 0.01-0.2

342  $\text{m}^3\cdot\text{s}^{-1}$  discharge correspond to the source of the subsequent Casaño, La Beyera,  
343 Pomperi and Hunhumia rivers. In all these cases, the springs are perched from 3 to 10  
344 m above the river channels; nevertheless, the springs include minor discharge conduits  
345 located at the same altitude of the river. This suggests that conduit development is  
346 keeping pace with valley incision.

347 Fig. 9 shows the location of the known caves in relation to surface geomorphology.  
348 Many cave entrances are located in glacial valleys or cirques, or in the Cares river  
349 canyon, where surface erosion has truncated existing phreatic/epiphreatic conduits and  
350 vadose cave systems, leaving decapitated shafts (Klimchouk et al. 2006) (Fig. 10). This  
351 suggests that most surface landforms are generally younger than the truncated karst  
352 landforms. Locally, glacial valleys include karst springs that were mostly blocked in the  
353 past by glaciers and till (Fig. 10c), at least during the local maximum extension  
354 (Ballesteros et al., 2017).

## 355 **5. Discussion**

### 356 **5.1 Generations of speleothems**

357 The  $^{34}\text{U}$ -Th speleothem dates and the  $^{26}\text{Al}/^{10}\text{Be}$  burial age (including previous 6 ages  
358 obtained by Ballesteros et al., 2015d, 2017), and their relationship with fluvial and  
359 breakdown deposits help constrain the regional evolutionary model of cave and  
360 landscape development.

#### 361 *5.1.1 First generation of speleothems (>260 ka)*

362 The oldest recognized generation of speleothems comprise seven flowstones  
363 precipitated along cave walls or over fluvial, slackwater and breakdown deposits,  
364 including large fallen blocks. These speleothems precipitated at  $259 \pm 59$ ,  $287 \pm 36$  and  
365  $300 \pm 46$  ka (samples LL-20, FR-16 and FR-13) coevally with end of MIS 8 transition to  
366 MIS 7, and another five were deposited before 350 ka, whose  $^{230}\text{Th}/^{234}\text{U}$  ratios are  
367 larger than one (samples TEY-03, TEY-04, TEX-04, FR-03, FR-10 and FR-17) (Table

368 2). Therefore, fluvial and slackwater deposits were covered by the first generation of  
369 speleothems that took place before the end of MIS 7 (Fig. 8). Locally, the samples FR-  
370 03, FR-10 and FR-13 precipitated mainly above fallen boulders, thus they post-dated  
371 collapse events that occurred prior to 254/350 ka.

#### 372 *5.1.2 Second generation of speleothems (220-145 ka)*

373 The second generation of speleothems involves seven flowstones related to cave  
374 deposits. The samples TEX-01 and TEX-03 are located on top of fluvial deposits, while  
375 the sample TEY-02 belongs to a flowstone interlayered into a fluvial terrace deposit,  
376 and the sample FR-15 is a flowstone ledge interbedded within a fluvial deposit (Fig.  
377 7s). The sample FR-14 covered a fallen boulder post-dating the rock-fall process (Fig.  
378 7r) while the sample FR-11 is located above a previous slackwater deposit (Fig. 7q).  
379 The ages of these samples are between  $156 \pm 12$  ka and  $205 \pm 19$  ka, suggesting that  
380 this second generation is associated with the fluvial sedimentation that took place  
381 during the MIS 7-6. These fluvial sediments almost filled the pilot caves (Fig. 7; section  
382 4.2) owing to the presence of an ancient pavement of the cave higher than the current  
383 cave floor. Later, the cave water eroded most of the fluvial sediments causing the  
384 collapse of the flowstone that were precipitated above them. The remains of these  
385 flowstones are preserved as ledges in the cave walls at the present day. The samples  
386 TEY-02, TEX-01, FR-11 and FR-15 show evidence of water erosion that likely occur  
387 after 145 ka (Fig. 8).

#### 388 *5.1.3 Third generation of speleothems (125-45 ka)*

389 The third generation of speleothems comprises flowstones (samples FR-09, FR-12, LL-  
390 15, LL-17, LL-21 and LL-24), and one stalagmite (sample LL-13) precipitated in vadose  
391 canyons and on top of cave deposits that display erosive scars created by cave  
392 streams. This speleothem generation also involves one pool deposit (sample TEX-02)  
393 and two flowstones interbedded in slackwater deposits (samples TEX-21 and TEX-

394 24B). In general, these speleothems precipitated on erosive surfaces between  $126 \pm$   
395  $11$  and  $45 \pm 3$  ka (Table 2), and also show frequently erosive scars. This suggests the  
396 development of a general erosive period coeval to the precipitation of the third  
397 speleothem generation, from 125 to 45 ka (~MIS 5-4). In El Frailín de Camplengu, the  
398 stalagmite FR-12 ( $124 \pm 20$  ka) grew above the eroded stalagmite FR-14 ( $219 \pm 20$  ka)  
399 of the second generation (Fig. 7q). Locally cave sedimentation occurred marked by the  
400 growth of a pool deposit at  $65 \pm 6$  ka (sample TEX-02) associated with a small  
401 paleolake (Fig. 7g) (Ballesteros et al., 2015a), and by the deposition of slackwater  
402 deposits at  $109 \pm 7$  (TEX-21) ka and  $95 \pm 6$  ka (TEX-24B), (Fig. 7j, k) (Ballesteros et  
403 al., 2017).

#### 404 *5.1.4 Fourth generation of speleothems (<25 ka)*

405 The fourth generation of speleothems comprises the four flowstone precipitated on  
406 cave deposits, two stalagmites located on top of previous slackwater deposits and  
407 flowstones, and one small stalactite formed on a cave wall. The ages of these  
408 speleothems range from  $22 \pm 2$  to  $1.33 \pm 0.09$  ka and define the timing of the fourth  
409 generation since 25 ka (~MIS 2-1). The flowstone LL-22 precipitated over the flowstone  
410 LL-21 of the third generation evidencing the presence of a sedimentary hiatus from  $22$   
411  $\pm 2$  to  $63 \pm 3$  ka (~MIS 3) (Fig. 7ab).

#### 412 *5.2 Regional evolution model*

413 We propose a speleogenetic model of Picos de Europa based on geomorphological  
414 and geochronological evidence previously described, and includes six phases (Fig. 11).  
415 Phases 1 and 2 correspond to the origin and main development of the cave conduits,  
416 while phases 3-6 represent the evolution of the caves since the Upper Middle  
417 Pleistocene. The presence of cave levels up to 2400 m altitude points out that  
418 karstification in Picos de Europa started before phase 1 because the studied cave  
419 levels are located up to 1300 m a.s.l. (Ballesteros et al., 2015b).

420 *5.2.1 Phase 1: main cave levels development during Pliocene*

421 The development of the main cave levels between 700 and 1300 m altitude most  
422 probably took place during phase 1 (Fig. 11). The phreatic flow was orientated to the  
423 SE, supplying the Cares River, except for Torca Teyera that drained to the N. During  
424 this first phase, Picos de Europa would have been an uplifting mountain area already  
425 divided in the current three massifs by the developing gorges of the consequent Cares,  
426 Sella and Deva rivers (Fig. 12a). The main surface of the landscape probably dipped to  
427 the N and the Permian-Mesozoic rocks covered (partially to completely) the karstified  
428 limestone (Smart, 1984, 1986; Fernández-Gibert et al., 2000).

429 The cosmogenic age ( $2.1 \pm 0.5$  Ma) obtained from fluvial deposits from the 700-800 m  
430 cave level is consistent with a Pliocene age suggested by Smart (1986) and  
431 Fernández-Gibert et al. (2000). The vertical elevation range between dated fluvial  
432 sediment (930 m a.s.l.) and the elevation of the water table currently located below the  
433 Torca Teyera cave (400 m a.s.l.) is 530 m; therefore, the rate of base-level lowering  
434 over the last 1.6-2.6 Ma can be estimated as  $0.15\text{-}0.25\text{ mm}\cdot\text{a}^{-1}$ . This value is one order  
435 of magnitude higher than the inferred erosive rate ( $0.01\text{ mm a}^{-1}$ ) calculated for the  
436 same period using  $^{26}\text{Al}$  and  $^{10}\text{Be}$  radioisotopes (section 4.3), thus the age of the cave  
437 would be older than 2.1 Ma.

438 The highest cave level of Picos de Europa is located at 2400 m in the Central Massif,  
439 with its current water table located at 315 m a.s.l. (Ballesteros et al., 2015b, 2015d).  
440 Assuming a constant rate of base-level lowering of  $0.15\text{-}0.25\text{ mm}\cdot\text{a}^{-1}$  for the drop of the  
441 water table (2085 m), we infer in 8.8-13.5 Ma the hypothetical age for the oldest cave  
442 level of Picos de Europa. This suggests that initial karstification occurred during the  
443 Miocene.

444 Following previous studies (Strasser et al., 2009; Wagner et al., 2010), we consider  
445 that the rate of tectonic uplift is similar to the rate of base-level lowering, resulting in a



446 rate of around 0.15-0.25 mm·a<sup>-1</sup> since the Pliocene. This value is consistent with the  
447 rates deduced by geomorphological and thermochronological studies in the Cantabrian  
448 Mountains (Table 4). The obtained rate is similar to the rates proposed for the  
449 Pliocene-Quaternary and is one order of magnitude larger than the rates proposed for  
450 the Neogene-Paleogene in the Cantabrian Mountains. A rejuvenation of the relief  
451 during the Pliocene can explain these differences, as it was suggested by apatite  
452 fission track dating in the Pyrenees (Babault et al., 2005; Jolivet et al., 2007).

453 *5.2.2 Phase 2: main development of vadose conduits during the Calabrian-Middle*  
454 *Pleistocene*

455 Valley incision and the erosion of the Alpine sedimentary cover after the Pliocene  
456 triggered the descent of the regional water tables and the subsequent extension of the  
457 vadose zone. Fluvial incision and lateral migration of cave streams modified the  
458 geometry of phreatic/epiphreatic conduits (Fig. 11b, d) and developed vadose canyons  
459 and shafts that intercepted previous conduits. Paragenetic features (pendants,  
460 corrosion notches) likely occurred during this phase. New vadose canyons also formed  
461 as well as the formation of the second generation of speleothems before and during the  
462 MIS 8 (Fig. 11d). Major breakdown and collapse events occurred during this phase  
463 because flowstones with more than ~220 ka cover the largest fallen boulders (samples  
464 FR-03, FR-13 and FR-14; section 4.3). All these processes generated the current  
465 general configuration of caves geometry, producing later variations in their infill. The  
466 change from phreatic to vadose conditions allowed the precipitation of first generation  
467 of speleothems before 260 ka.

468 The landscape of the second phase would be similar to the first one, although the  
469 extent of the Alpine sedimentary cover was smaller and the river canyons were deeper  
470 than in Phase 1 (Fig. 12b). This situation would allow the development of dolines and  
471 the border polje of Vega de Comeya. Glaciers occupied at least the highest areas  
472 before 394-276 ka (Villa et al., 2013). In the NW of Picos de Europa, the development

473 of the subsequent Casaño River flowing to the N began during this phase, developing  
474 its canyon and capturing the groundwater of the surroundings of Torca La Texa and  
475 Pozu Lluçia (Fig. 12b). Therefore, the groundwater of these caves changed their  
476 drainage directions from the SE in Phase 1 to the N in Phase 2. Nowadays, the  
477 groundwater continues to flow to the N and emerges in the spring of the Casaño River  
478 (Ballesteros et al., 2015a, 2015d).

#### 479 *5.2.3 Phase 3: cave sedimentary infill at 220-145 ka (~MIS 7-6)*

480 The third phase of the speleogenetic model is based on the reconstruction of caves  
481 fluvial infill (section 4.2) and the second generation of speleothems, whose age is  
482 considered as a reference timing for the cave filling (section 4.3). These sediments  
483 filled the cavities almost completely, thus the ancient pavement of the caves was  
484 located higher than nowadays. The infill favoured the development of pendants under  
485 paragenetic conditions (Fig. 11). Considering U/Th ages, Phase 3 took place during  
486 MIS 7-6.

487 The landscape reached the current configuration at a regional scale during Phase 3  
488 (Fig. 12c). The Alpine sedimentary cover was almost completely eroded, at least in the  
489 surroundings of the pilot caves. Fluvial sediments contain allochthonous clasts derived  
490 from the erosion of Stephanian (~Kasimovian) sandstone (with siderite nodules) and  
491 igneous rocks that cropped out to the S of the study area. The igneous rocks  
492 correspond to the andesite and basaltic dykes described by Ballesteros et al. (2011a)  
493 and located toward the SW of the pilot caves. Considering all this information, the  
494 landscape of phase 3 presented a developing karst plateau with outcrops of  
495 Stephanian sandstone and shale (Fig. 12c).

#### 496 *5.2.4 Phase 4: cave erosion at 125-45 ka (~MIS 5-3)*

497 The erosion of the sedimentary sequences formed during phase 3 defines the fourth  
498 phase of the speleogenetic model. During this phase, the small speleothems of the

499 third generation precipitated on top of the erosive surfaces developed along the walls  
500 of vadose conduits or on cave deposits (section 4.3). This generation of speleothem  
501 deposition (125-45 ka) took place between MIS 5 and 3. Simultaneously, fluvial erosion  
502 partially eroded fluvial sediments and speleothems of the first and second generations,  
503 leaving erosional remnants as terraces above the cave floor (Fig. 11). Breakdown  
504 processes affected these speleothems and, sometimes, triggered their collapse (for  
505 instance, samples FR-09, FR-17 and FR-18). This situation provoked the formation of  
506 “false floors” (hanging ancient speleothem pavements), very common in caves of Picos  
507 de Europa (Sefton, 1984; Smart, 1984) and the Cantabrian Mountains (Gázquez et al.,  
508 2014).

509 In the Cantabrian Mountains, the presence of fluvial terraces older than 47-48 ka and  
510 other terraces with inferred ages of Upper Pleistocene suggest a general fluvial incision  
511 between 120 and 50 ka (González Díez et al., 1996; Ruiz-Fernández and Poblete  
512 Piedrabuena, 2011) in accordance with the general erosion of the cave infill.

513 Furthermore, during this phase, the karst landscape involved still minor outcrops of  
514 sandstone that were eroding (Fig. 12d), as evidenced by the presence of sandstone  
515 clasts in the till (section 4.4) and minerals in the glacial cave rhythmites (Ballesteros et  
516 al., 2017). These sediments also indicated that glaciers should have occupied the  
517 areas located at least at 1300 m of altitude during the ~MIS 5d-c. The presence of  
518 glaciers in phase 4 agrees with the development of a glacial paleolake with a minimum  
519 age of 46 ka in the border polje of Vega de Comeya (Jiménez-Sánchez et al., 2013)  
520 and with the maximum glacial local extension dated at  $114 \pm 8$  ka in the neighboring  
521 Central Cantabrian Mountains (Rodríguez-Rodríguez et al., 2016). The glaciers  
522 intercepted previous vadose and phreatic/epiphreatic conduits recognized in the study  
523 area (section 4.4), blocking the karst springs located above 800 m a.s.l. (Ballesteros et  
524 al., 2017). The geomorphological map of the study area indicates that the surroundings  
525 of the Pozu Lluçia cave was ice-free, at least, during the Upper Pleistocene (Fig. 12d).

526 This situation suggests that liquid water would have been more available: This would  
527 favour a speleothem growth greater than other pilot caves located in areas covered by  
528 glaciers.

#### 529 *5.2.5 Phase 5: speleothem apparent pause at 45-25 ka (~MIS 3-2)*

530 Phase 5 represents a general apparent pause in the speleothem (Fig. 11). The  
531 combination of five arguments supports this hypothesis: (1) no speleothems deposited  
532 between 45 and 25 ka have been found so far in the pilot caves (Fig. 8); (2) the  
533 speleothem growth of Pozu Lluçia cave displays a hiatus between the precipitation of  
534 flowstones LL-22 ( $22 \pm 2$  ka) and LL-21 ( $63 \pm 3$  ka), (3) the content of carbonates of the  
535 Enol Lake (Fig. 9) decreased between 38 and 17 ka (Moreno et al., 2010), (4)  
536 cryogenic processes took place in the Belbin depression from 37 to 29 ka (Fig. 9)  
537 (Nieuwendam et al., 2015); and (5) the development of dry and cold conditions during  
538 the MIS 3-2 in the Cantabrian Mountains (Álvarez-Lao et al., 2015; Uzquiano et al.,  
539 2016).

540 The landscape present during this phase corresponds to a karst covered by glaciers,  
541 whose extension varied temporally, reaching the 1000 m of altitude, at least, at ca 40-  
542 45 ka (Fig. 12e) (Jiménez-Sánchez and Farias, 2002; Moreno et al., 2010;  
543 Nieuwendam et al., 2015). The variation of the ice extension was coeval with a general  
544 glacial retreat up to beginning of the Last Glacial Maximum (LGM), at 23-25 ka in the  
545 Cantabrian Mountains (Rodríguez-Rodríguez et al., 2014; Serrano et al., 2016). Frost  
546 weathering and solifluction processes modelled the ice-free areas (Nieuwendam et al.,  
547 2015). Locally, lacustrine environments occupied glacial and karst depressions, as with  
548 the Enol Lake (since 38 ka) and the paleolake of border polje of Vega de Comeya (Fig.  
549 12e) (Moreno et al., 2010). This paleolake was completely filled at 3-4 ka (Farias et al.,  
550 1996).

551 The dry and cold conditions, combined with glacial and periglacial activities, decreased  
552 the recharge of the karst aquifer. In carbonates, environments with less -5°C average  
553 annual temperature can limit strongly the groundwater flow in the endokarst (Ford,  
554 1993). The water scarcity agrees with the flowstone precipitation above the thalweg  
555 deposits; however, the high detrital content of these speleothems hampers their dating  
556 using the uranium-series decay method.

#### 557 *5.2.6 Phase 6: speleothem reactivation since 25 ka (~MIS 3-2)*

558 The precipitation of the fourth generation of speleothems defines the last phase of the  
559 speleogenetic model (Fig. 11). This phase represents a reactivation of the speleothem  
560 precipitation respect to the hypothetical phase 5. Fluvial sedimentation and speleothem  
561 formation increased in the pilot caves, precipitating mainly dripstone and flowstone on  
562 top of previous deposits.

563 The glacial advances related to LGM took place during phase 6, descending up to  
564 1000 m in the Vega del Brial before 11 ka (Fig. 12f) (Ruiz-Fernández et al., 2013),  
565 however, they did not supply water to the Enol Lake since 26 ka (Moreno et al., 2010).  
566 Subsequently, the glaciers retreated up to the cirques, disappearing almost completely  
567 in the Holocene (Fig. 12g). Nowadays, the incision of cave streams continues and karst  
568 springs are perched above the surface rivers (section 4.4). Consequently, the  
569 karstification continues to develop down to the base level marked by river position,  
570 evidencing that the caves and rivers are at disequilibrium and the fluvial incision still  
571 continues. This situation suggests that Picos de Europa is uplifting at least up to the  
572 present.

## 573 **6. Conclusions**

574 The geomorphologic regional history of the Picos de Europa based on the  
575 geomorphology and speleogenesis of four alpine caves has been reconstructed based  
576 on 34  $^{234}\text{U}/^{230}\text{Th}$  speleothem ages, the first  $^{26}\text{Al}/^{10}\text{Be}$  burial dating performed in Picos de

577 Europa, and the relationship between caves and surface processes of the glaciated  
578 karst massif. The 12 km of conduits in four pilot caves comprise 47 % of vadose  
579 canyons and shafts, 45 % of phreatic/epiphreatic conduits organised in six cave levels  
580 from 600 to 1300 m a.s.l., and 7 % of breakdown-modified passages.

581 Six phases constitute the speleogenetic model since the Pliocene although the cave  
582 evolution might have begun in the Miocene. We inferred the uplift rate of Picos de  
583 Europa at  $0.15\text{-}0.25\text{ mm}\cdot\text{a}^{-1}$  since  $2.1 \pm 0.5\text{ Ma}$ .

584 • Phase 1 (Pliocene): development of a karst partially or totally covered by an  
585 Alpine sedimentary cover, showing the incipient forming canyons of the  
586 consequent rivers of the region. Coevally, the main development of cave levels  
587 of 800-1300 m altitude was formed by a SE-directed flow in the Western Massif  
588 of Picos de Europa. Phreatic flow was toward the Cares River which incision  
589 favoured the descent of the water tables.

590 • Phase 2 (Calabrian to Middle Pleistocene): erosion of the Permian-Mesozoic  
591 cover and capture of the northern Western Massif by the Casaño River. Vadose  
592 canyons and shafts were developed, affected by locally important breakdown  
593 processes.

594 • Phase 3 (220-145 ka, ~MIS 7-6): cave infill by speleothems and fluvial  
595 sediments derived from the erosion of Stephanian sandstone and shale that  
596 crops out locally in the highest areas of Picos de Europa.

597 • Phase 4 (125-45 ka, ~MIS 5-3): erosion of the previous cave infill by fluvial  
598 incision.

599 • Phase 5 (45-25 ka, ~MIS 3-2): apparent pause in the speleothem deposition  
600 under a dry and cold environment dominated by glacial retreat and cryogenic  
601 processes.

602 • Phase 6 (since 25 ka; ~MIS 2-1): reactivation of the speleothem precipitation  
603 and speleothem precipitation by a general increase of temperature and

604 precipitation. This phase coincides with a slight warming at 26 ka, glacial  
605 advances during the LGM, and their retreat to the glacial cirque up to their  
606 demise in the Holocene.

607 The main factors of the evolution of Picos de Europa and its caves would be glacial  
608 activity at least since the MIS 7, the fluvial incision of consequent rivers, fluvial captures  
609 of subsequent rivers, and the erosion of the Stephanian detrital rocks in the higher  
610 areas of Picos de Europa.

611 The proposed speleogenetic model evidences the usefulness of the alpine cave  
612 studies for reconstructing the geomorphologic evolution of a region for Quaternary  
613 times, integrating information about the relief uplift, river incision, water table evolution,  
614 and glaciations.

## 615 **Acknowledgements**

616 This work is a contribution of the GeoQUO and GeoCantabrian Research Groups  
617 (University of Oviedo) funded through the GEOCAVE project (MAGRAMA-580/12-  
618 OAPN). We are grateful to P. Häuselmann (ISSKA) for help to calculate the  
619 cosmogenic date, to GE Polifemo, GES M Celtas, AD GEMA and G. Sendra for their  
620 collaboration and their help during the fieldwork, and to the Picos de Europa National  
621 Park for the provided facilities. The manuscript was improved by useful comments  
622 done by J. De Waele and another anonymous reviewer. Cave data of Fig. 1 are  
623 courtesy of GE Polifemo, OUCC, GE Diañu Burlón, AD Cuasacas, S Wroclaw, SIS-CE  
624 Terrassa, Expeditions to Castil, GE Gorfolí, GE Matallana, GEMA, CDG, CADE, SEB  
625 Escar, SIE Álga, GEG, WCC, GET, SSS, IEV, Cocktail Picos, YUCPC, AD Kami,  
626 Llabrión-Project, ERE, SCOF, GES CMT, STD-BAT, CES Alfa and AS Charentaise ,  
627 GERSOP, GS Matese, GSD, HPS, L'Esperteyu CEC, LUSS, SAR d'Ixelles, GE Llubí,  
628 ANEM, and SCS Matese. National Geographic Institute of Spain provided topographic  
629 and aerial photography data. We dedicate this work to the memory of J. Gambino,

630 brilliant speleologist, good geologist and great friend, who contributed greatly to explore  
631 and research deep caves in Picos de Europa.

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## 925 **Figure Captions**

926 Fig. 1. (a) The Iberian Peninsula showing the location of Picos de Europa. (b) Karst  
927 areas of the Cantabrian Mountains (after Ayala Carcedo et al., 1986). (c) Relief and  
928 fluvial network of Picos de Europa divided into three massifs by the deep fluvial valleys.

929 Main karst springs and more than 410 km of caves documented by speleologists are  
930 plotted.

931 Fig. 2. (a) Speleological map of El Frailín de Camplengu shaft. (b) Geomorphological  
932 maps of the NW (b) and SE (c) parts of the shaft. (d) Geomorphological map of the  
933 shaft Pozu Lluçia; (e), (f) and (g) shows the geomorphological maps of the conduits  
934 projected below the main passages of the cavity.

935 Fig. 3. Profile of the pilot caves indicating the position of the recognized cave levels: (a)  
936 Torca Teyera, (b) Torca La Texa, (c) El Frailín de Camplengu, (d) Pozu Lluçia.

937 Fig. 4. (a) Vadose canyon incised by a cave stream. The canyon shows thalweg  
938 deposits partially covered by a rich-detrital flowstone eroded by the stream. (b)  
939 Phreatic/epiphreatic conduits with dissolution pockets and pendants. (c) Breakdown-  
940 modified passages with debris from ceiling collapses and flowstone affected by  
941 collapses (picture courtesy of S. Ferreras).

942 Fig. 5. (a) Fluvial terrace deposits of the Torca Teyera cave perched 9 m above a cave  
943 stream, showing an interbedded flowstone. (b) Fluvial terrace deposit of Torca Teyera.  
944 (c) Fluvial deposit terrace covered by a flowstone preserved at a wall of the Pozu Lluçia  
945 shaft.

946 Fig. 6. (a) A ledge of flowstone of El Frailín de Camplengu. (b) Sample of the ledge of a  
947 flowstone precipitated above fluvial sediments.

948 Fig. 7. Cave sections sketches depicting the geomorphological setting of the new 28  
949 speleothems dated by U/Th, as well as the six previous dates performed in the pilot  
950 caves (sub-sections from f to k) (Ballesteros et al., 2015a, 2017). The sub-sections (b),  
951 (e), (f), (h), (s), (t) and (ab) provide the reference ages for the fluvial deposition while  
952 the sub-sections (n), (o), (r) and (u) support the reference timing for the breakdown  
953 processes.

954 Fig. 8. U/Th dates grouped in four generations (in grey) according to their ages.  
955 Erosive scars recognised in some dated speleothem indicate the incision of the cave  
956 streams after the speleothem precipitation.

957 Fig. 9. Geomorphological map of the study area defined in Fig. 1c. Speleological  
958 groups detailed in the acknowledgements provided the cave conduits information  
959 displayed in the map.

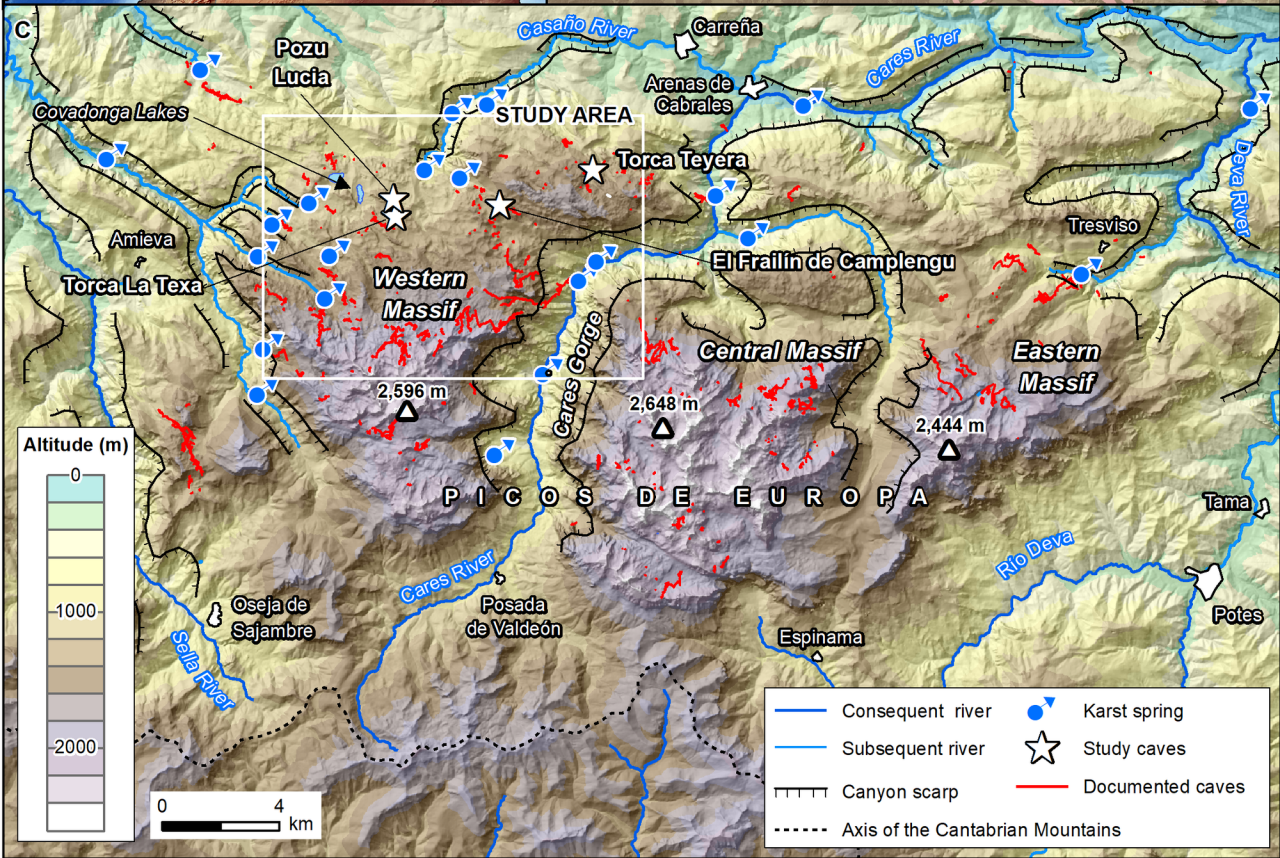
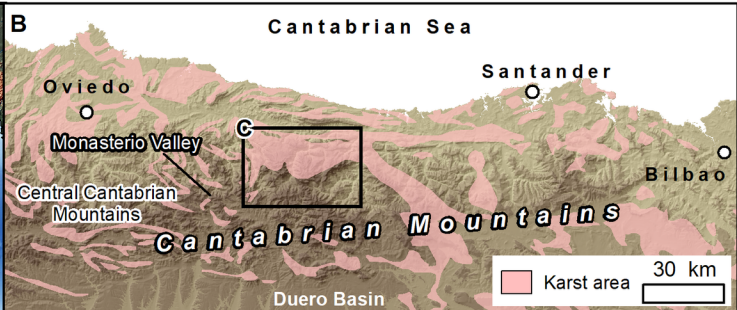
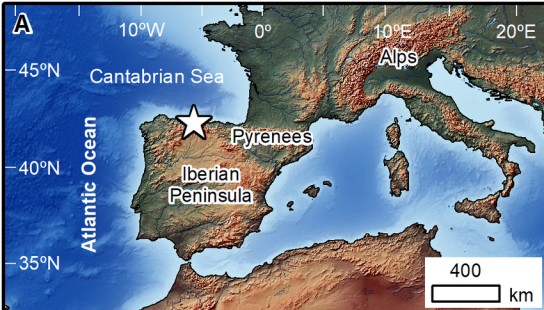
960 Fig. 10. Field evidence of relationship between caves and younger erosive landforms:  
961 (a) Border polje of Vega de Comeya (N of the study area; Fig. 9) cutting the Infiernu  
962 Cave (~4 km length) and other phreatic/epiphreatic conduits. (b) The vadose shaft of  
963 Pozu Los Texas (240 m depth) decapitated by glaciers. (c) The karst spring of the  
964 Humhumia River probably blocked by glaciers in the past. (d) Doline intercepting a  
965 phreatic/epiphreatic conduit with 169 m length.

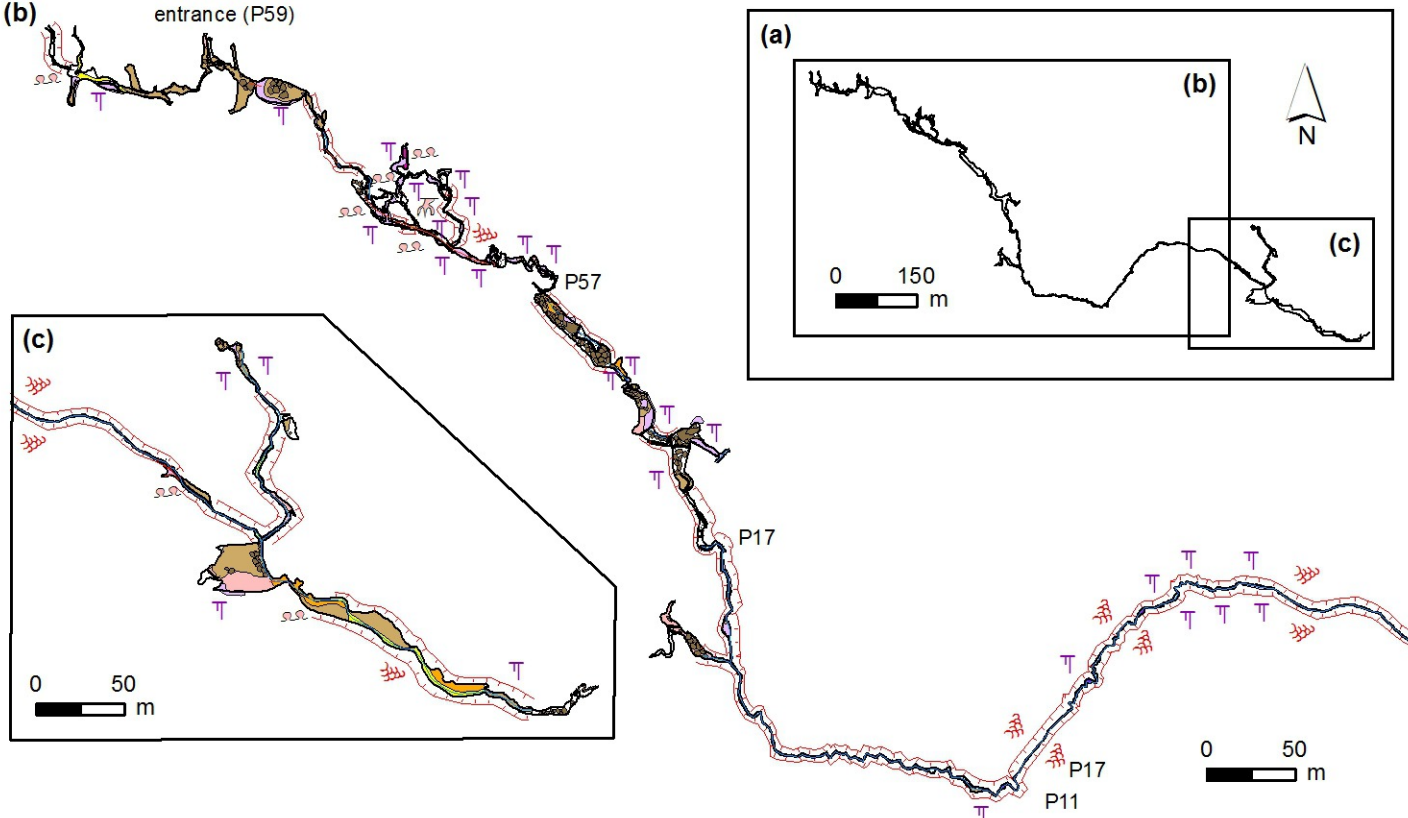
966 Fig. 11. Conceptual model based on transversal sections of the pilot caves conduits  
967 depicting their temporal evolution according to the proposed speleogenetic model. The  
968 phreatic/epiphreatic conduits originated in phase 1 evolved following three paths: (a)  
969 almost without changes; (b and c) as dominated by fluvial incision that generated  
970 narrow (b) or wide vadose canyons (c); and (d) as vadose canyons that developed  
971 independently after phase 2.

972 Fig. 12. Configuration of the relief during the six speleogenetic phases from a point  
973 view located to the NW (X: 340 Y: 4800 Z: 8 km). (a) Phase 1 showing the Permian-  
974 Mesozoic cover above the karst (Smart, 1986; Fernández-Gibert et al., 2000). (b)  
975 Phase 2 with a partially eroded Alpine sedimentary cover and Carboniferous  
976 Stephanian outcrops larger than nowadays. (c) Phase 3 under the possible influence of  
977 glaciers during the MIS6-7. (d) Phase 4 coeval with the local glacial maximum  
978 extension that took place during the MIS5-4. (e) Phase 5 showing glaciers occupying  
979 the highest areas of the Western Massif, while the Enol lake was collecting glacial

980 melting water during the MIS 2 (Moreno et al., 2010). (f) Phase 6 with glaciers  
981 occupying the El Bricial depression and without connection to the Enol Lake (MIS 1).  
982 (g) Phase 6 during the cirque glacier stage. (h) Orthophotography 2007 of the Western  
983 Massif projected above the Digital Elevation Model used to reconstruct the landscape.

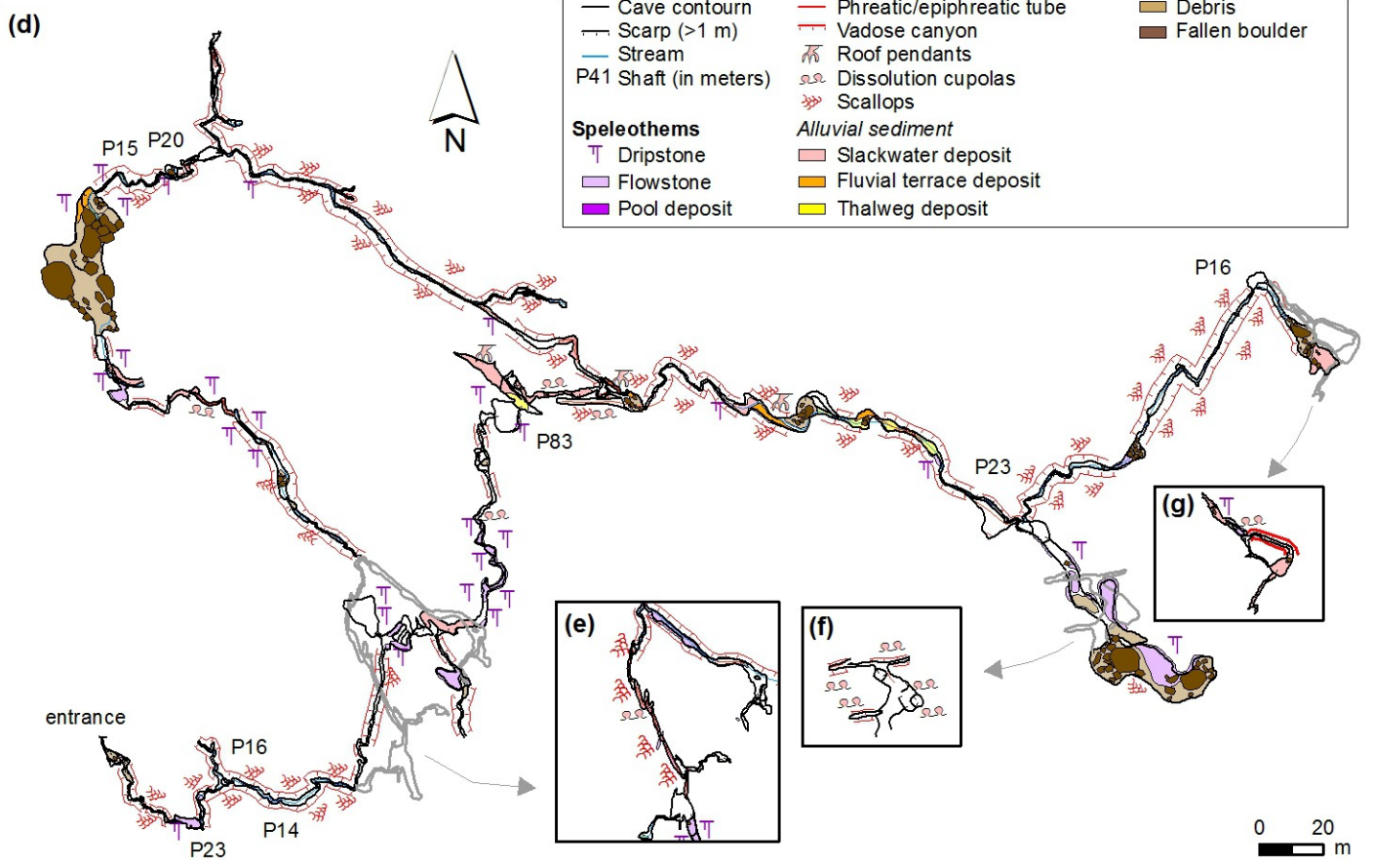




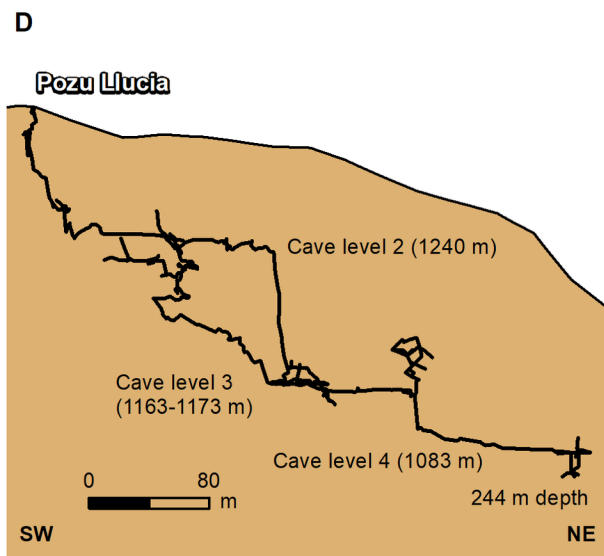
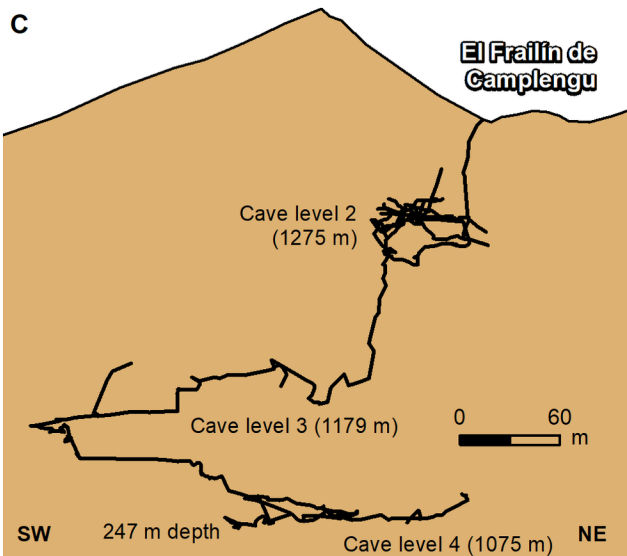
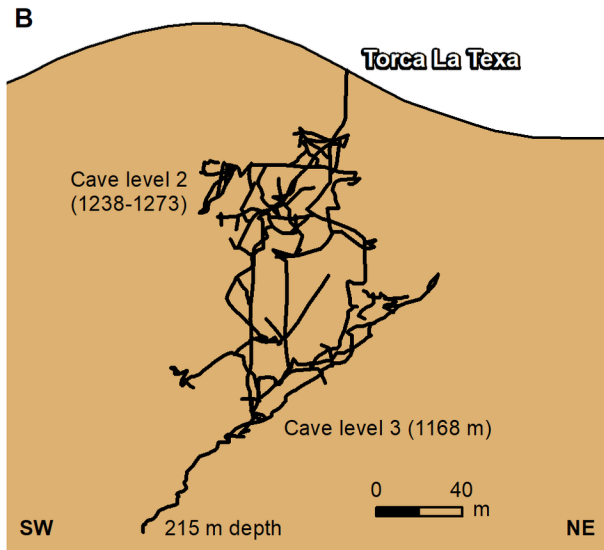
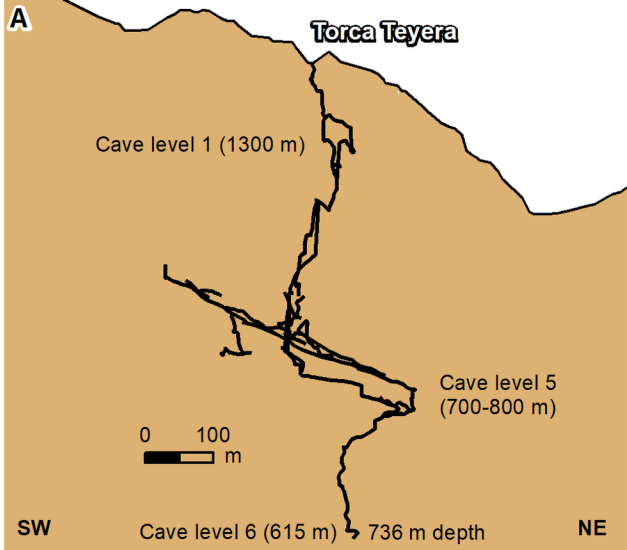


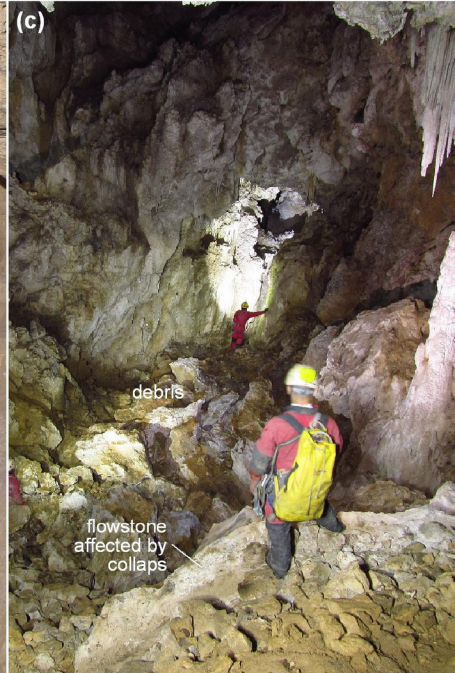
**Legend**

Survey	Fluviokarst forms	Breakdown forms
— Cave contour	— Phreatic/epiphreatic tube	■ Debris
— Scarp (>1 m)	— Vadose canyon	■ Fallen boulder
— Stream	— Roof pendants	
P41 Shaft (in meters)	— Dissolution cupolas	
	— Scallops	
<b>Speleothems</b>	<i>Alluvial sediment</i>	
⊥ Dripstone	■ Slackwater deposit	
■ Flowstone	■ Fluvial terrace deposit	
■ Pool deposit	■ Thalweg deposit	

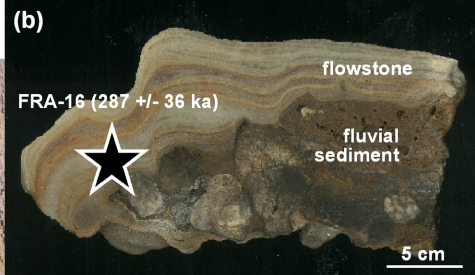
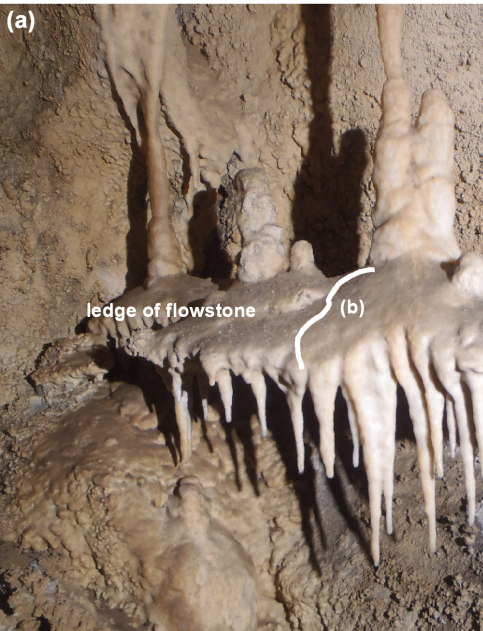




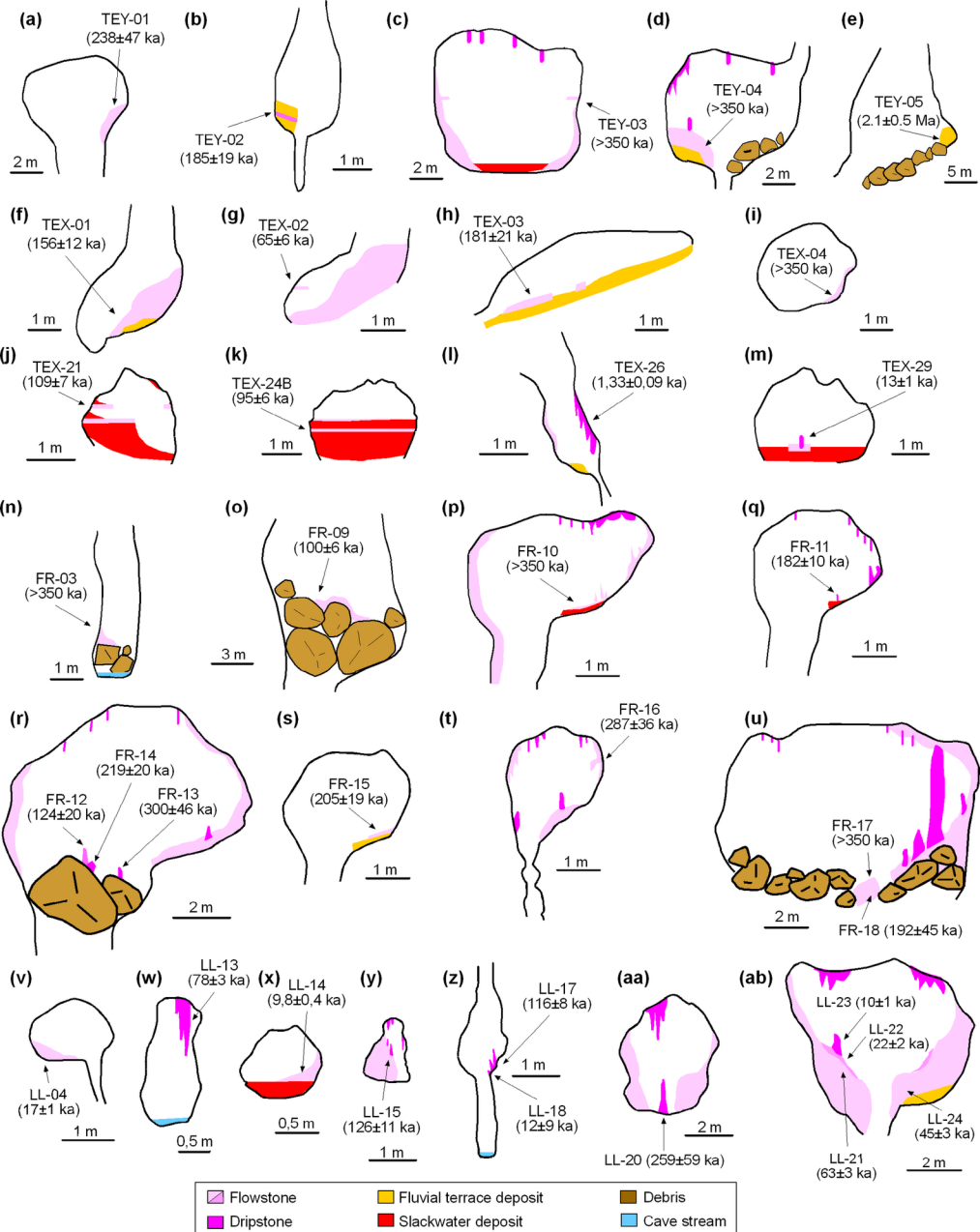


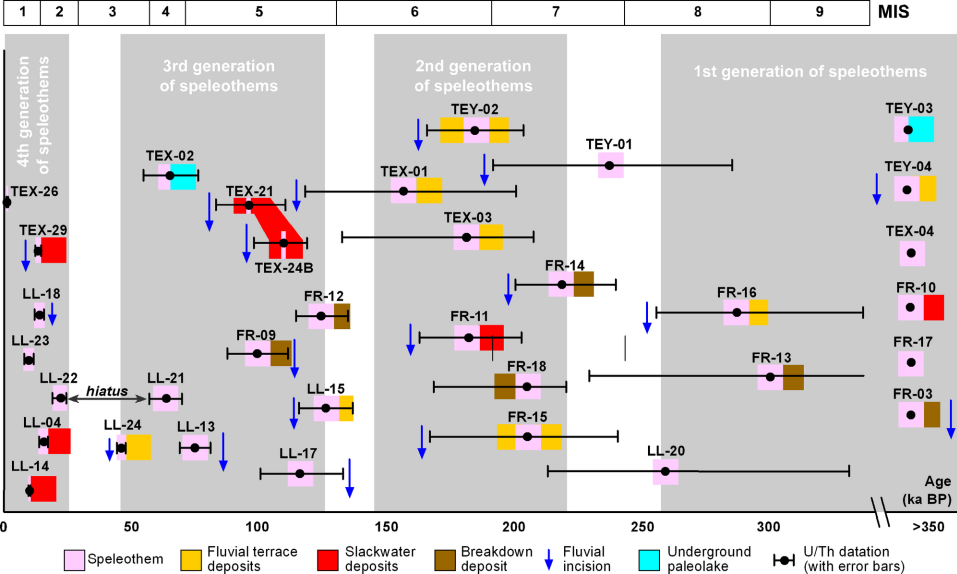


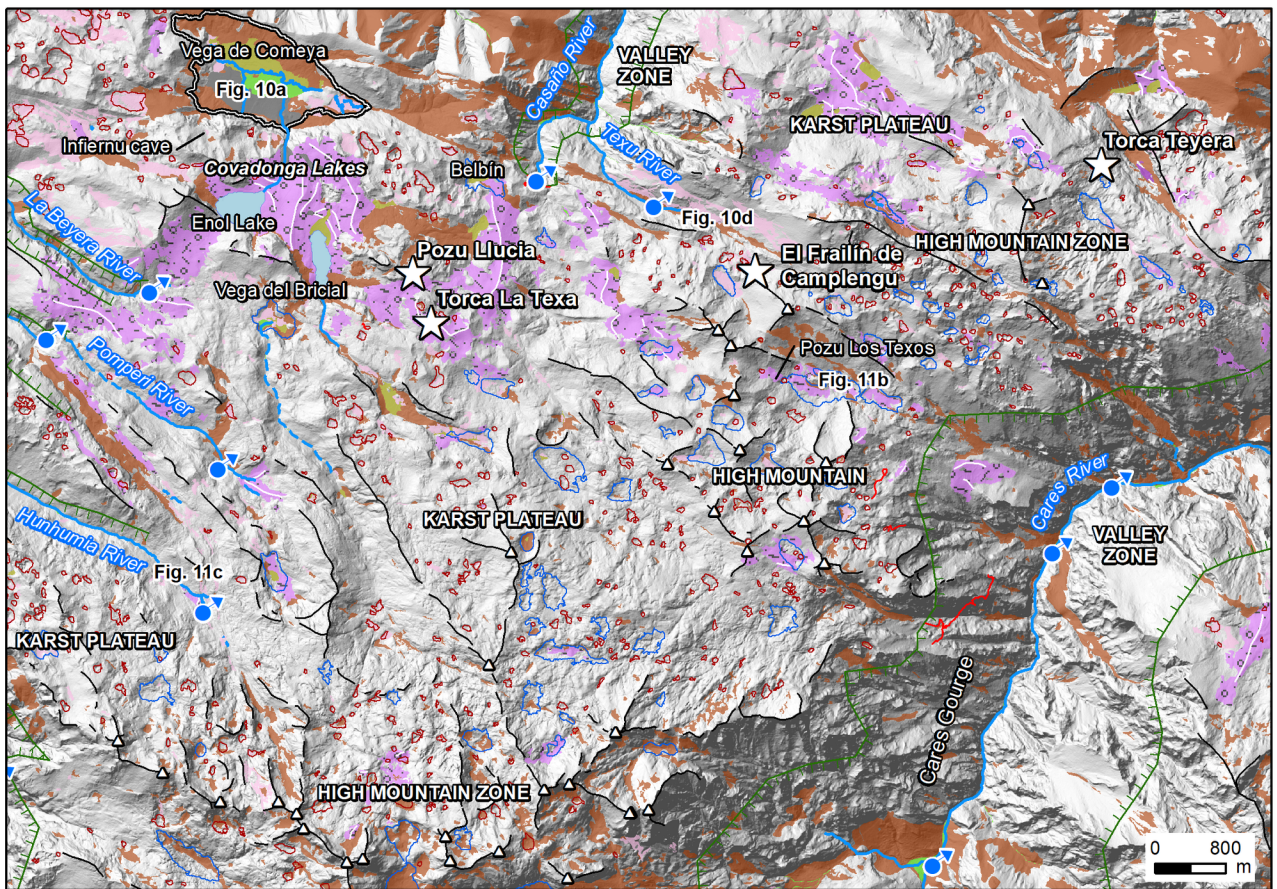












**Erosive forms**

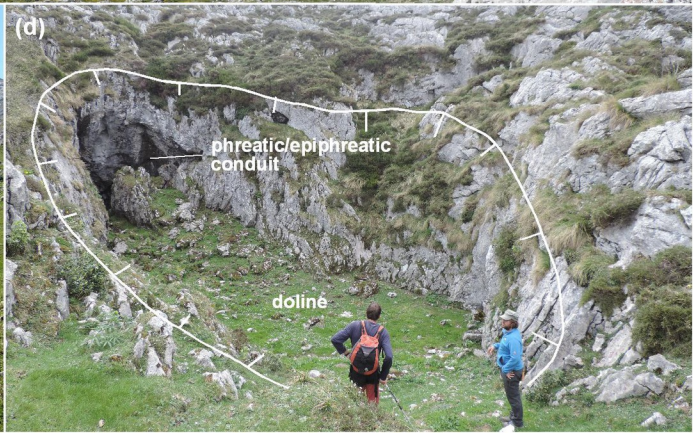
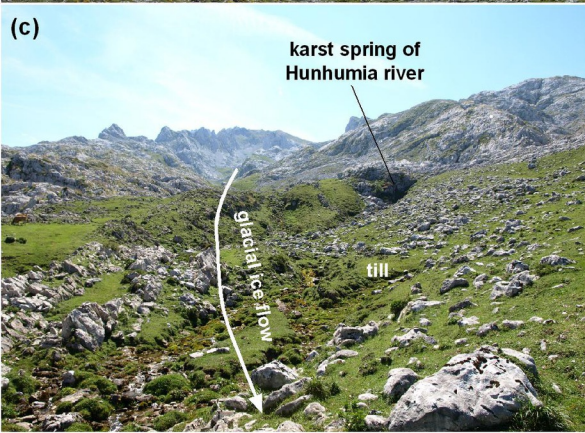
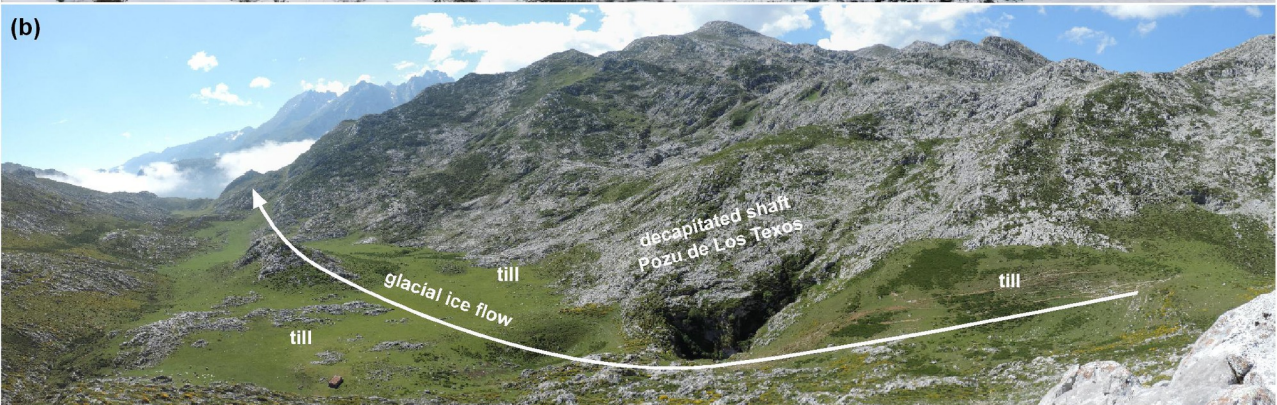
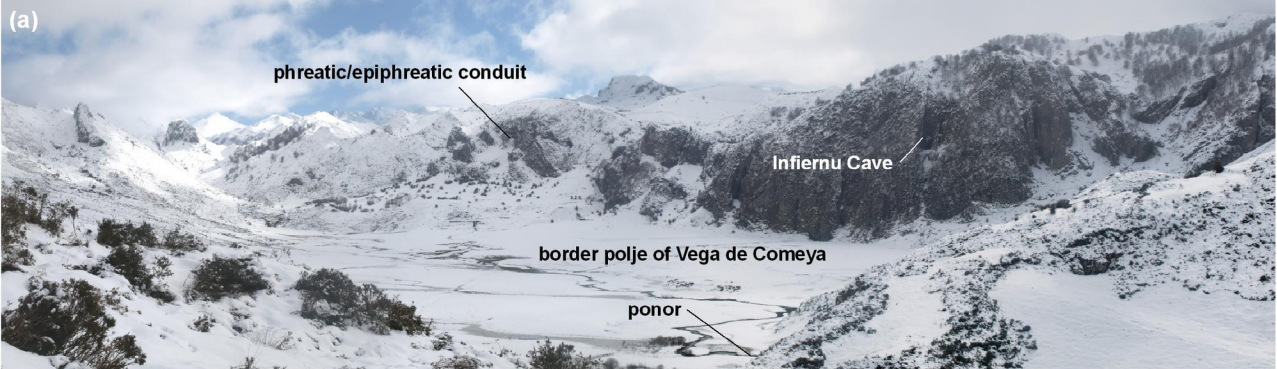
- Doline
- Glaciokarst depression
- Border polje
- Scarp of fluviokarst canyon
- Glacial cirques and arêtes
- △ Horn
- Documented cave conduits
- Karst spring

**Surface deposits**

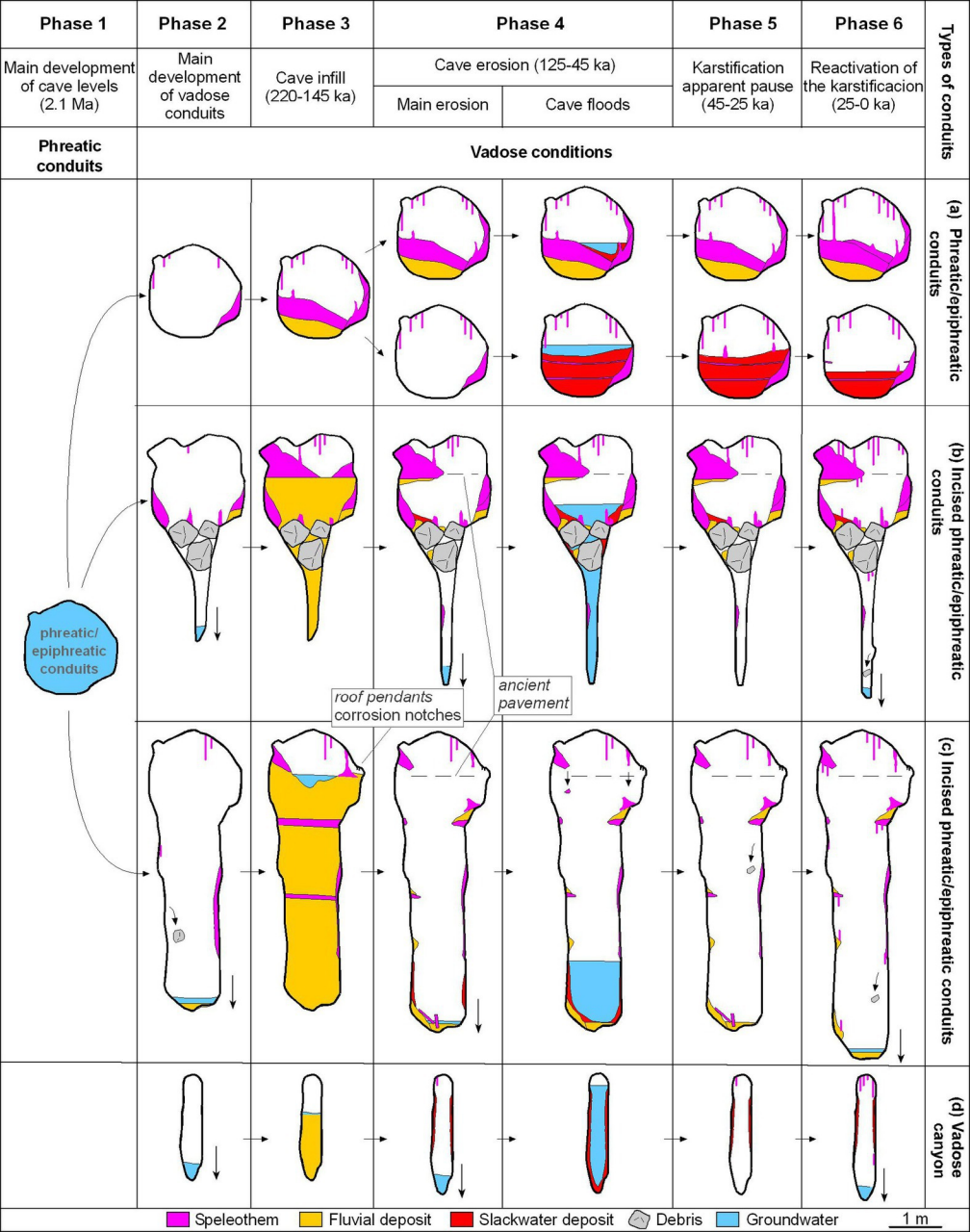
- Glacial lake
- Slope deposit
- Lacustrine and palustrine deposit
- Karst deposit and soil
- Anthropogenic deposit
- Periglacial deposit
- Fluvial deposit
- Glacial deposit
- Moraine

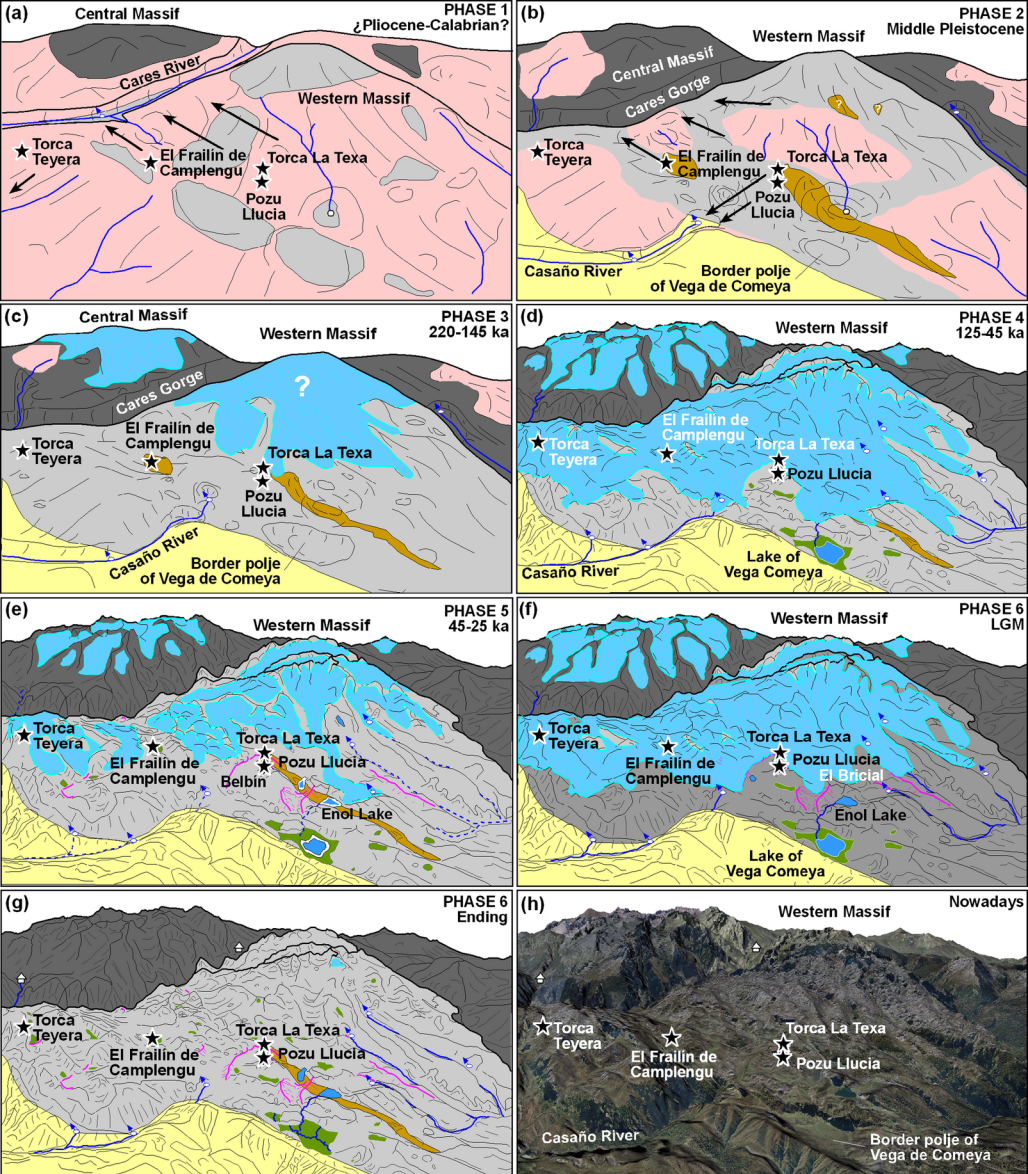












#### Geology

- Alpine cover (Permian-Mesozoic)
- Stephanian sandstone and shale
- Carboniferous limestone (karst)
- Ordovician siliciclastic rocks and others

#### Glaciology

- Glacial ice
- Glacial lake
- Glacial moraine

#### Karst

- Karst spring
- Phreatic flow

#### Other

- Depression infill
- Rivers
- Other areas

Up 1 km  
N 1 km  
E 1 km

Table 1. Dimensions, type of conduits and cave levels of the studied caves.

Cave	Torca Teyera	Torca La Texa	El Frailín de Camplengu	Pozu Lluçia	Total caves	
Altitude of the entrance (m)	1335	1305	1331	1266		
Length (km)	4.4	2.6	2.7	2.3	12.0	
Depth (m)	738	215	245	244		
Type of conduits (% of the cave length)	vadose canyons and shafts	55	51	49	51	47
	Phreatic/epiphreatic conduits	38	43	41	48	45
	Breakdown-modified passages	7	5	9	7	7
Cave levels (m a.s.l.)	1	1300				
	2		1238-1273	1275	1240	
	3		1168	1179	1163-1173	
	4			1075	1083	
	5	700-800				
	6	615				

Table 2. Results of 28 new  $^{234}\text{U}/^{230}\text{Th}$  datations by alpha-spectrometry. We applied the isochron method to calculate the age of the samples FR-03, FR-17, FR-18, LL-22 and LL-23.

Cave levels are detailed in Table 1.

Sample	Speleothem	Cave level	Lab. Ref.	$^{238}\text{U}$ (ppm)	$^{232}\text{Th}$ (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	$^{230}\text{Th}/^{234}\text{U}$	Nominal date (a BP)	Isochron date (a BP)
Torca Teyera										
TEY-01	Flowstone	5	5309	0.04	0.07	$1.16 \pm 0.07$	$2.145 \pm 0.127$	$0.92 \pm 0.05$	238083 +56456/-37939	
TEY-02	Flowstone	5	5109	0.12	0.15	$1.33 \pm 0.05$	$2.873 \pm 0.129$	$0.86 \pm 0.04$	185344 +20293/-17385	
TEY-03	Flowstone	5	5209	0.11	0.43	$1.09 \pm 0.05$	$0.875 \pm 0.030$	$1.05 \pm 0.05$	> 300000	
TEY-04	Pool deposit	1	1210 1	0.42	1.17	$1.93 \pm 0.03$	$2.506 \pm 0.062$	$1.15 \pm 0.04$	> 300000	
Torca La Texa										
TEX-26	Stalagmite	2	3413	6.68	<0.00	$4.30 \pm 0.04$	-	$0.01 \pm 0.00$	1330 +94/-94	
TEX-29	Flowstone	2	6814	0.06	0.02	$2.83 \pm 0.16$	$2.851 \pm 0.320$	$0.12 \pm 0.01$	13304 +974/-967	
El Frailín de Camplengu										
FR-03	Flowstone	2	714	0.26	0.58	$0.86 \pm 0.02$	$2.889 \pm 0.117$	$2.38 \pm 0.10$	>350000	
FR-03 (lix)	Flowstone	2	814	0.14	0.31	$1.43 \pm 0.04$	$4.306 \pm 0.145$	$2.11 \pm 0.07$	>350000	
FR-03 (res)	Flowstone	2	1314	4.07	10.39	$0.64 \pm 0.03$	$0.711 \pm 0.060$	$0.92 \pm 0.08$	>350000	>350000
FR-09	Flowstone	2	2014	0.10	<0.00	$2.58 \pm 0.10$	-	$0.65 \pm 0.03$	99603 +6386/-6103	
FR-10	Flowstone	2	1415	0.24	0.22	$1.52 \pm 0.04$	$5.390 \pm 0.159$	$1.08 \pm 0.03$	>350000	
FR-11	Stalagmite	3	515	0.16	0.03	$3.14 \pm 0.08$	$43.688 \pm 3.134$	$0.93 \pm 0.03$	181842 +10525/-9808	
FR-12	Stalagmite	2	1815	0.05	<0.00	$2.33 \pm 0.13$	-	$0.74 \pm 0.04$	124239 +10367/-9636	
FR-13	Stalagmite	2	1515	0.55	0.01	$1.00 \pm 0.02$	$139.715 \pm 15.02$	$0.94 \pm 0.03$	300027 +55541/-36665	
FR-14	Stalagmite	2	2015	0.30	0.03	$1.05 \pm 0.02$	$29.894 \pm 2.535$	$0.088 \pm 0.03$	218540 +21695/-18174	
FR-15	Flowstone	2	815	0.11	0.11	$1.91 \pm 0.06$	$5.764 \pm 0.338$	$0.95 \pm 0.04$	205453 +19991/-17410	
FR-16	Flowstone	2	2715	0.12	0.04	$1.55 \pm 0.05$	$13.985 \pm 0.768$	$1.03 \pm 0.03$	286614 +40873/-30732	
FR-17 (A)	Flowstone	1	915	0.25	0.38	$0.92 \pm 0.02$	$1.857 \pm 0.119$	$0.98 \pm 0.05$	>350000	
FR-17 (B)	Flowstone	1	2315	0.25	0.44	$0.95 \pm 0.03$	$1.610 \pm 0.040$	$0.95 \pm 0.04$	>350000	>350000
FR-18	Flowstone	1	1015	0.55	0.75	$0.88 \pm 0.01$	$1.740 \pm 0.045$	$0.87 \pm 0.03$	258021 +47355/-31960	
FR-18 (lix)	Flowstone	1	2415	0.30	0.41	$1.21 \pm 0.02$	$2.416 \pm 0.058$	$0.88 \pm 0.02$	205455 +15868/-14002	192327 +52158/-37834
Pozu Lluçia										
LL-04	Flowstone	1	1614	0.13	0.17	$2.18 \pm 0.07$	$0.818 \pm 0.052$	$0.16 \pm 0.01$	+18633 1123/-1113	
LL-13	Stalactite	2	6914	0.36	<0.00	$2.14 \pm 0.05$	-	$0.54 \pm 0.02$	77525 +3277/-3199	
LL-14	Flowstone	2	1115	0.39	0.08	$1.84 \pm 0.03$	$2.437 \pm 0.127$	$0.09 \pm 0.00$	9783 +376/-375	
LL-15	Flowstone	2	2215	0.07	0.02	$1.12 \pm 0.05$	$9.177 \pm 0.866$	$0.70 \pm 0.03$	126100 +11388/-10357	
LL-17	Stalagmite	3	715	0.05	0.03	$2.53 \pm 0.14$	$10.918 \pm 0.854$	$0.72 \pm 0.03$	116349 +8278/-7810	
LL-18	Stalagmite	3	415	0.05	<0.00	$3.08 \pm 0.14$	-	$0.10 \pm 0.01$	11723 +967/-960	

LL-20	Stalagmite	2	1615	0.03	<0.00	1.45 ± 0.10	-	0.99 ± 0.06	258666 +72647/-46125	
LL-21	Flowstone	2	615	0.04	0.02	3.59 ± 0.18	12.742 ± 1.261	0.47 ± 0.02	63194 +3403/-3324	
LL-22 (A)	Flowstone	2	1315	0.03	0.01	3.17 ± 0.18	4.123 ± 0.569	0.16 ± 0.01	18780 +1426/-1412	
LL-22 (B)	Flowstone	2	2515	0.02	0.01	3.59 ± 0.23	3.302 ± 0.435	0.16 ± 0.01	18166 +1426/-1411	21751 +2402/- 2358
LL-23 (A)	Stalagmite	2	1215	0.04	0.06	2.84 ± 0.14	1.763 ± 0.147	0.29 ± 0.02	35760 +2522/-2477	
LL-23 (B)	Stalagmite	2	2615	0.06	0.11	2.60 ± 0.11	1.571 ± 0.073	0.40 ± 0.02	53465 +2730/-2677	9710 +1014/ 1007
LL-24	Flowstone	2	1715	0.07	<0.00	1.67 ± 0.07	-	0.34 ± 0.02	44588 +2660/-2605	

Table 3.  $^{26}\text{Al}$  and  $^{10}\text{Be}$  concentrations, the burial age and erosion rate estimated for a fluvial deposit of cave level 5 in the Torca Teyera cave.

Sample	$^{26}\text{Al}$ ( $10^6$ at/g)	$^{10}\text{Be}$ ( $10^6$ at/g)	$^{26}\text{Al}/^{10}\text{Al}$	Burial age (Ma)	Erosion rate ( $\text{mm a}^{-1}$ )
TEY-05	$617897 \pm 155583$	$256538 \pm 13134$	$2.409 \pm 0.619$	$2.108 \pm 0.484$	$0.012 \pm 0.001$

Table 4. Uplifting rates estimated by geomorphology and thermochronology methods in the Cantabrian Mountains and Coast.

Indicator	Place	Uplifting rate (mm·a <sup>-1</sup> )	Temporal range	Reference
Fluvial terraces of the Cares River in Arenas de Cabrales	N of Picos de Europa	0.24	37 ka	Ruiz-Fernández and Poblete Piedrabuena (2011)
Phreatic conduits of Cueva del Agua and other cavities	Eastern Massif of Picos de Europa	0.3	350 ka	Smart (1984)
Phreatic conduits of El Pindal cave	Central Cantabrian Coast	0.19	200 ka	Jiménez-Sánchez et al. (2006)
Fluvial terraces of Miño River	Western Cantabrian Mountains	0.1	600 ka	Viveen et al. (2014)
Cave levels of El Soplao Cave	Central Cantabrian Mountains	0.125-0.213	1.5 Ma	Rossi et al. (2016)
Marine terraces	Western Cantabrian Coast	0.07-0.1	1-2 Ma	Alvarez-Marrón et al. (2008)
Apatite thermochronology	Western Cantabrian Mountains	0.06	Neogene-Quaternary	Martín-González et al. (2011)
Apatite and He thermochronology	Western Cantabrian Mountains	0.00025	Upper Jurassic-Quaternary	Grobe et al. (2014)