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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 ± 0.5 Ma for the caves origin, allowing

27 estimation of the mountain uplift at $0.15\text{-}0.25\text{ mm a}^{-1}$ since the Late Pliocene. Twenty-
28 eight new $^{234}\text{U}/^{230}\text{Th}$ 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_2 , 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⁻¹ 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 km², 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 km² 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 km² 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}Th (with radiogenic and
221 detrital origin) and ^{232}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}Be decontamination, and acid dissolution in HF following Granger
228 et al. (2001). We added also a carrier (303.4 μg) of ^{10}Be . Detect limits of ^9Be and ^{27}Al
229 are 10^{-15} and $5 \cdot 10^{-15}$ of the radionuclides atoms ratios, respectively. We considered
230 1.02 ± 0.04 for radioactive ^{26}Al mean life and 1.36 ± 0.07 Ma for the ^{10}Be (Chmeleff et
231 al., 2010), estimating the local production rates of the cosmogenic isotopes for 43.27°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}Be and ^{26}Al
234 and penetration length neutrons 60 cm (Granger et al., 2007). Analytical uncertainties
235 (reported as 1σ) 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 km² 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}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 ± 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 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}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 ± 59 , 287 ± 36 and
365 300 ± 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 ± 12 ka and 205 ± 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 ± 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 ± 20 ka) grew above the eroded stalagmite FR-14 (219 ± 20 ka)
399 of the second generation (Fig. 7q). Locally cave sedimentation occurred marked by the
400 growth of a pool deposit at 65 ± 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 ± 7 (TEX-21) ka and 95 ± 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 ± 2 to 1.33 ± 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 ± 2 to 63 ± 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 ± 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 mm a^{-1}) calculated for the
436 same period using ^{26}Al and ^{10}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⁻¹ 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 ± 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 ± 2 ka) and LL-21 (63 ± 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.

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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.

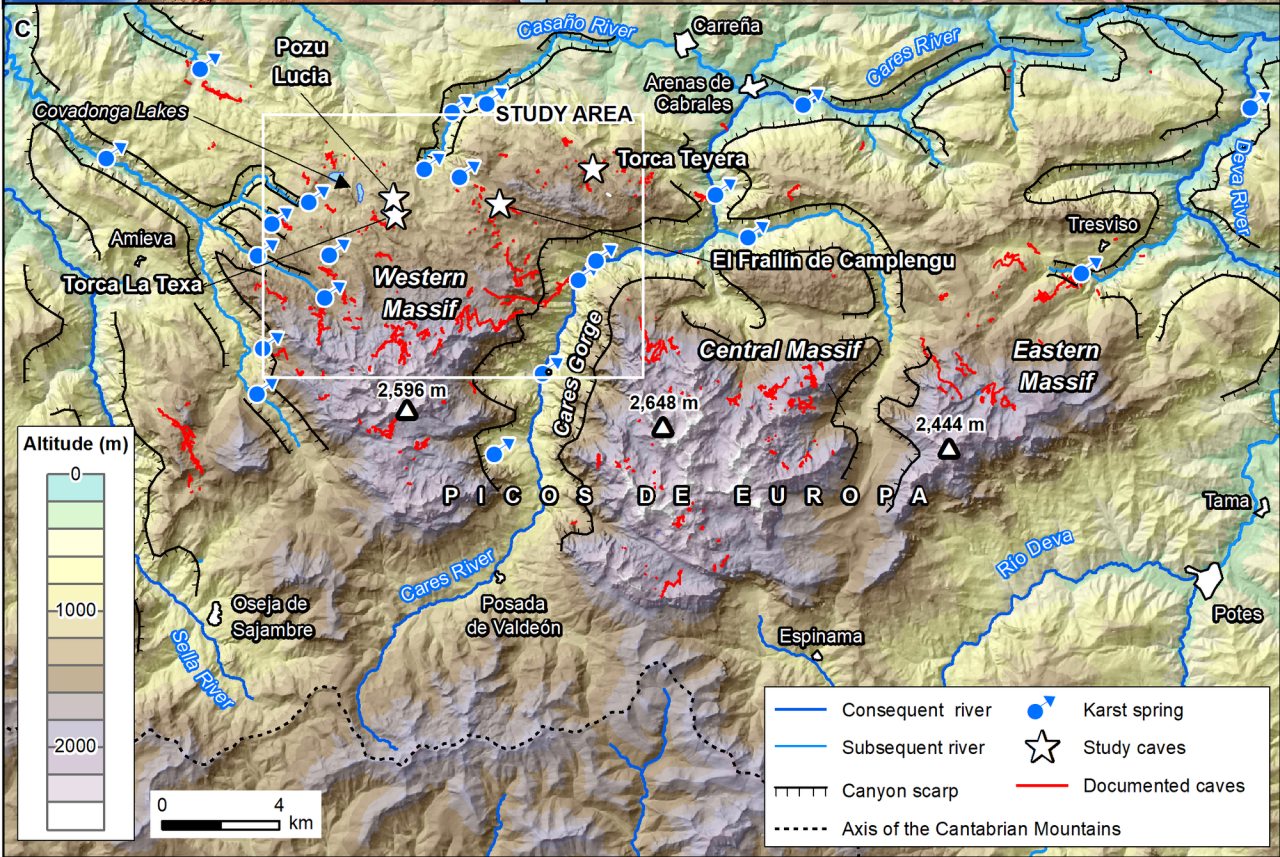
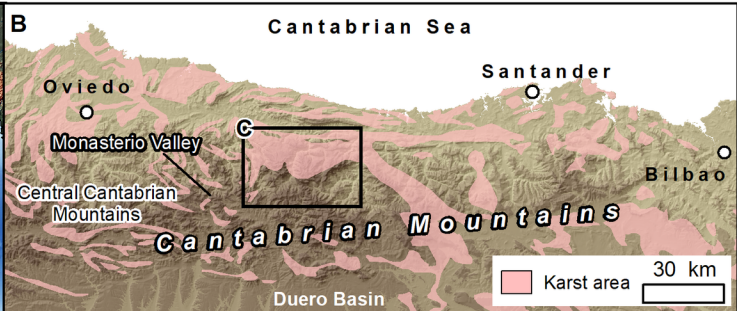
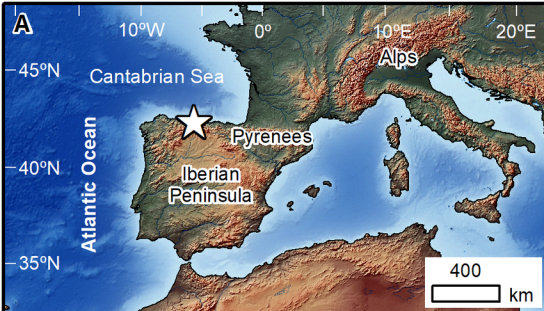
957 Fig. 9. Geomorphological map of the study area defined in Fig. 1c. Speleological
958 groups detailed in the acknowledgements provided the cave conduits information
959 displayed in the map.

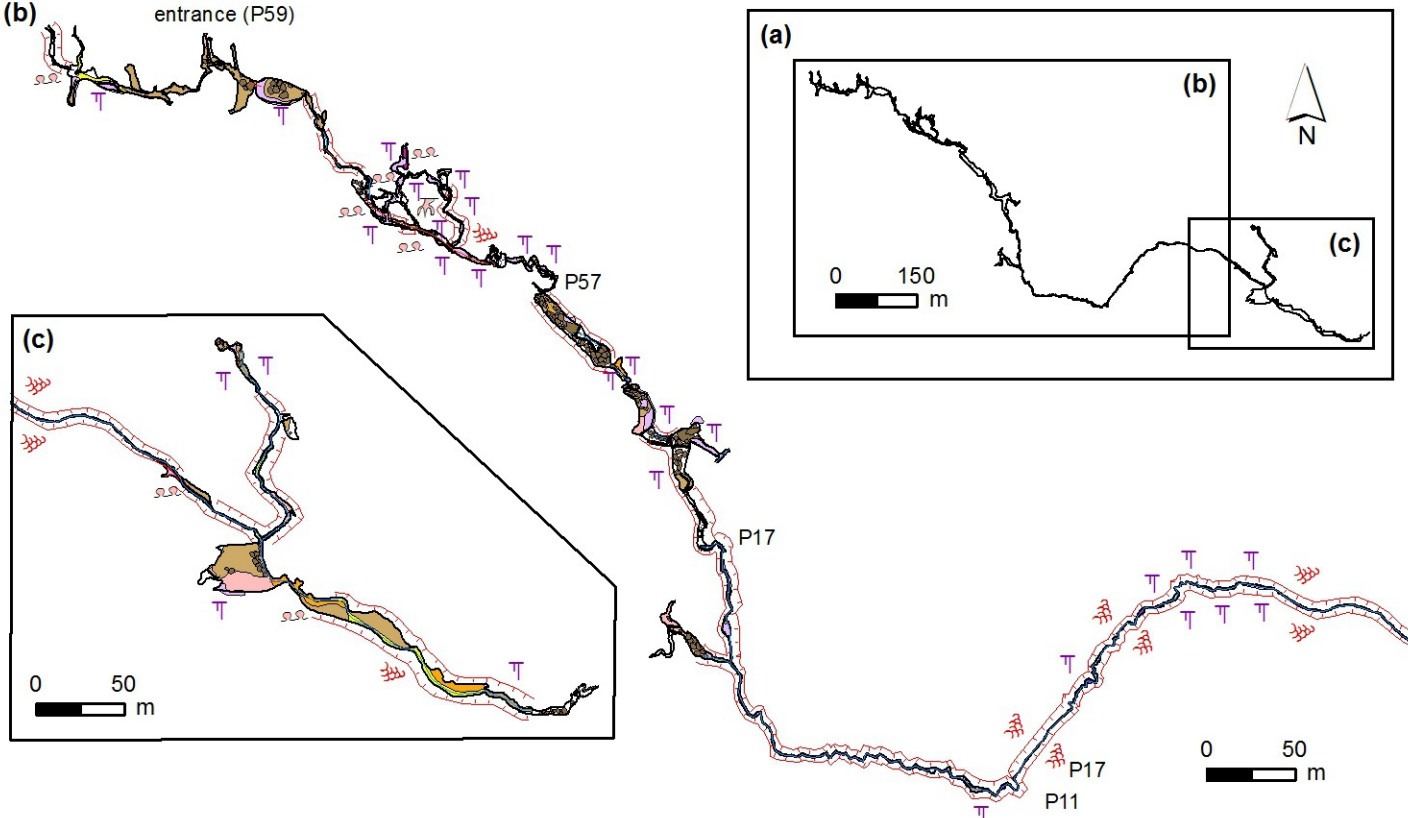
960 Fig. 10. Field evidence of relationship between caves and younger erosive landforms:
961 (a) Border polje of Vega de Comeya (N of the study area; Fig. 9) cutting the Infiernu
962 Cave (~4 km length) and other phreatic/epiphreatic conduits. (b) The vadose shaft of
963 Pozu Los Texas (240 m depth) 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

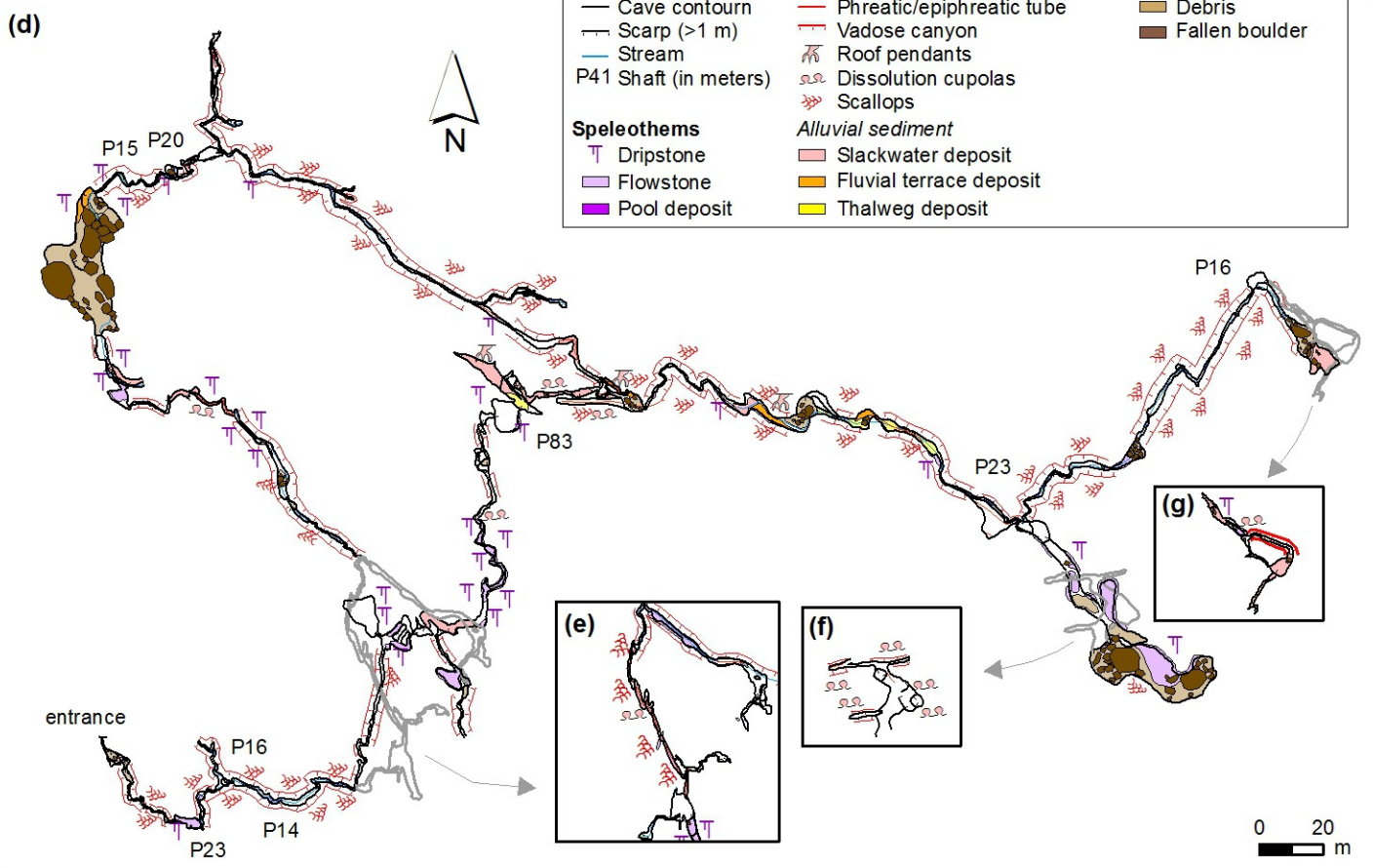
980 melting water during the MIS 2 (Moreno et al., 2010). (f) Phase 6 with glaciers
981 occupying the El Bricial depression and without connection to the Enol Lake (MIS 1).
982 (g) Phase 6 during the cirque glacier stage. (h) Orthophotography 2007 of the Western
983 Massif projected above the Digital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

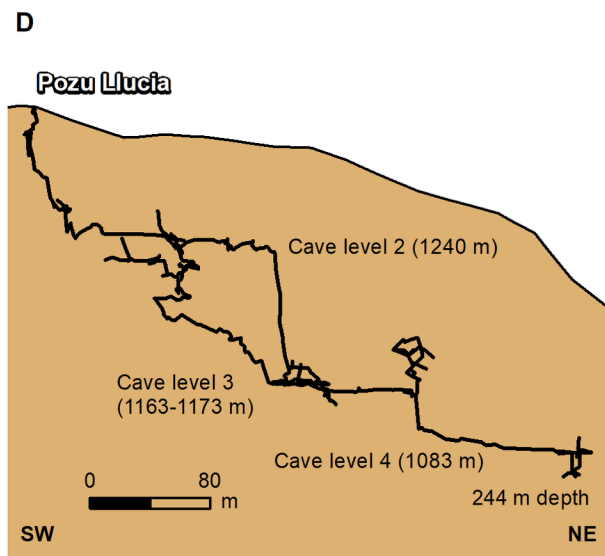
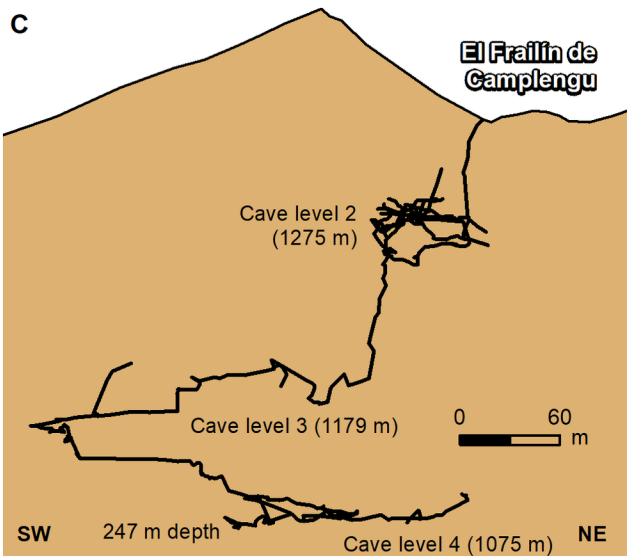
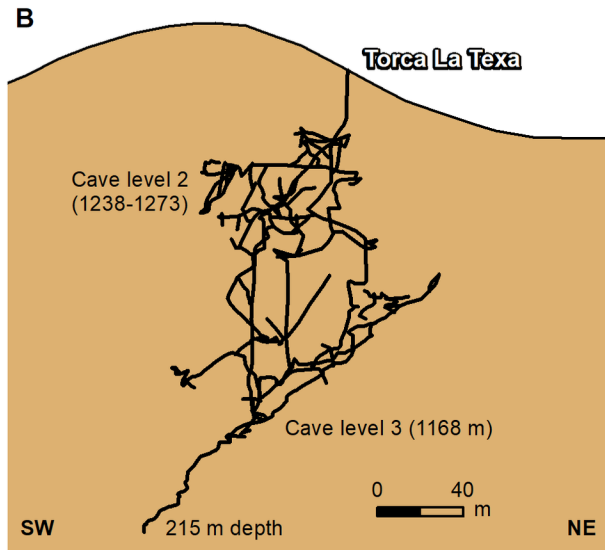
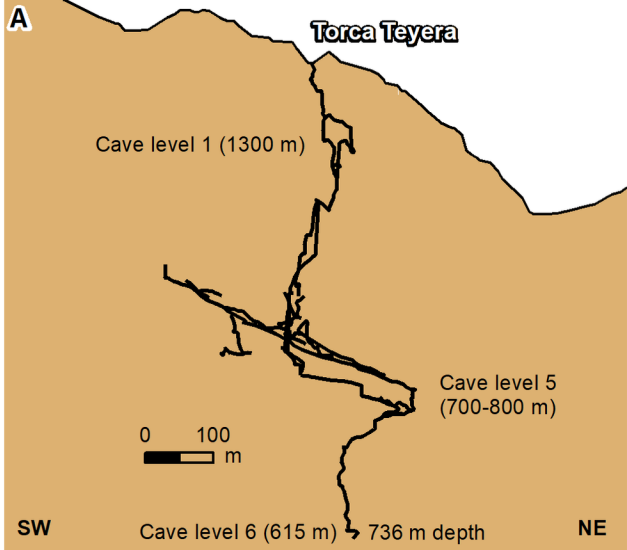


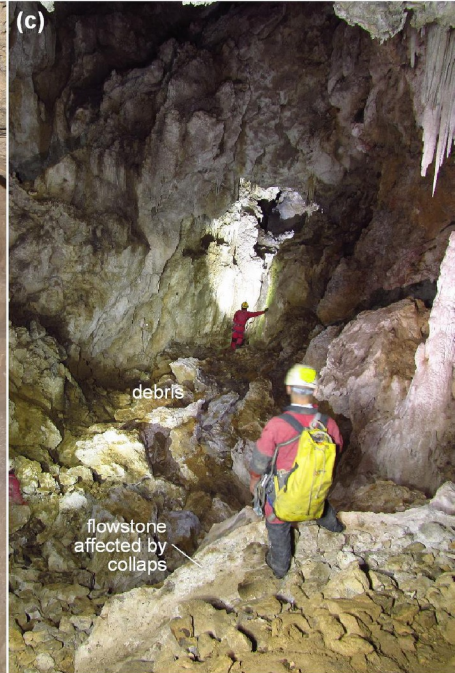


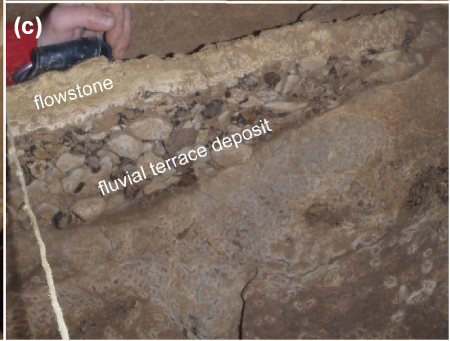
Legend

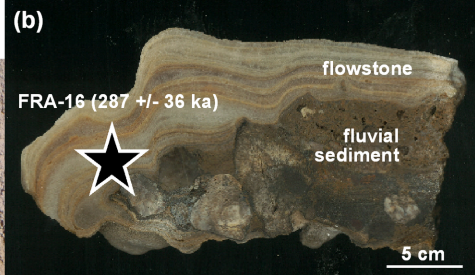
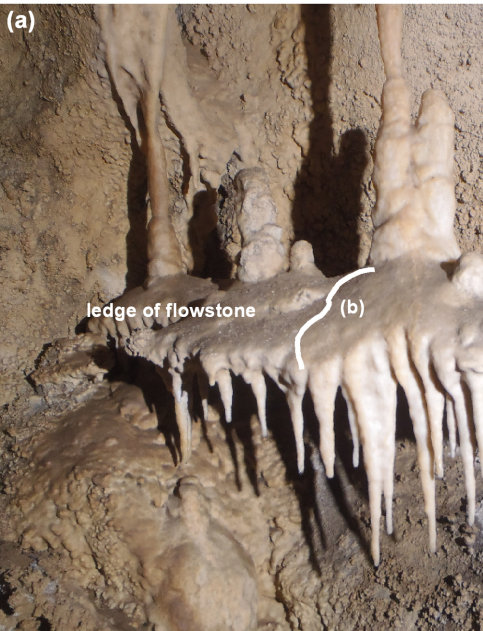
| Survey | Fluviokarst forms | Breakdown forms |
|-----------------------|-----------------------------|------------------|
| — Cave contour | — Phreatic/epiphreatic tube | ■ Debris |
| — Scarp (>1 m) | — Vadose canyon | ■ Fallen boulder |
| — Stream | — Roof pendants | |
| P41 Shaft (in meters) | —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

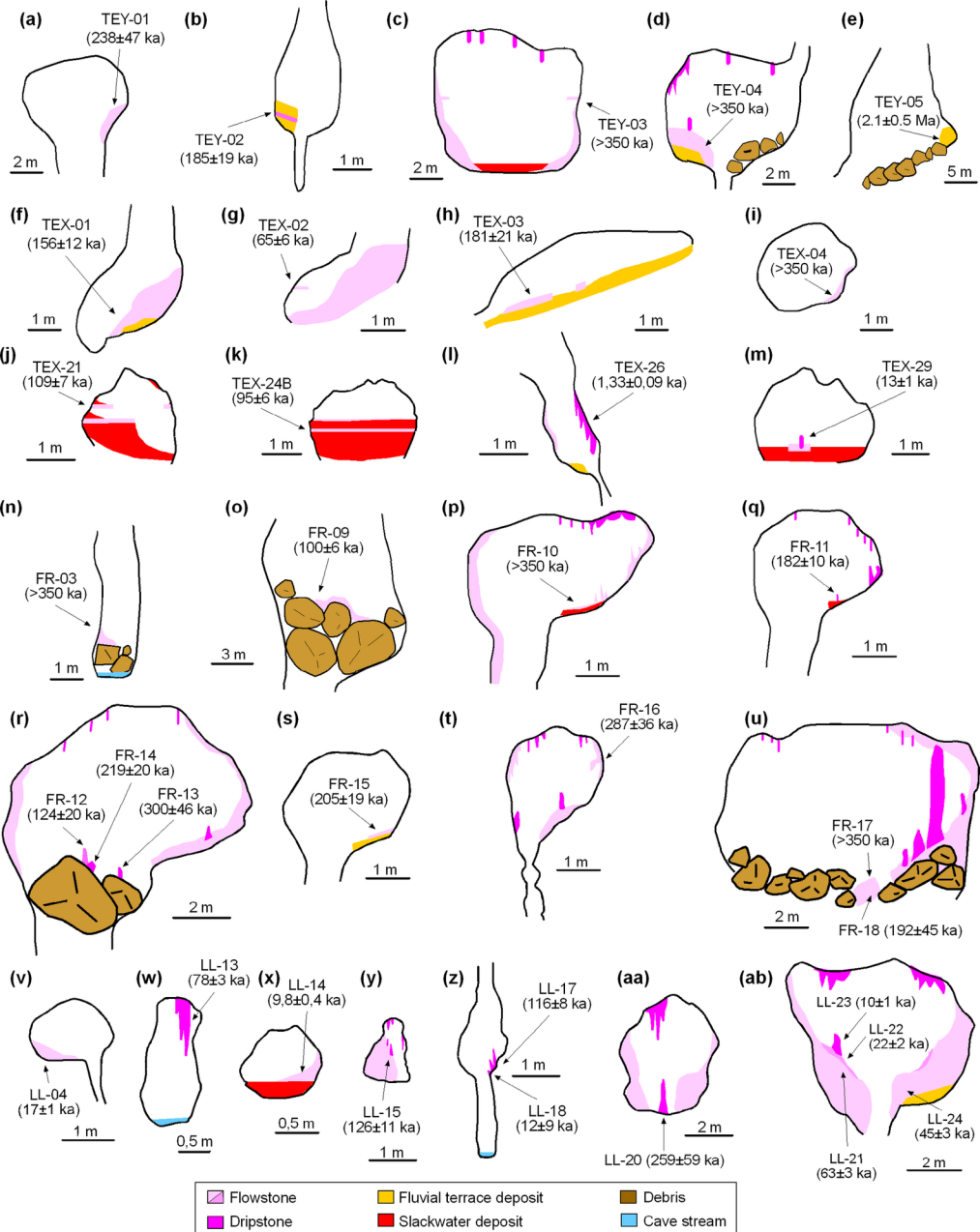


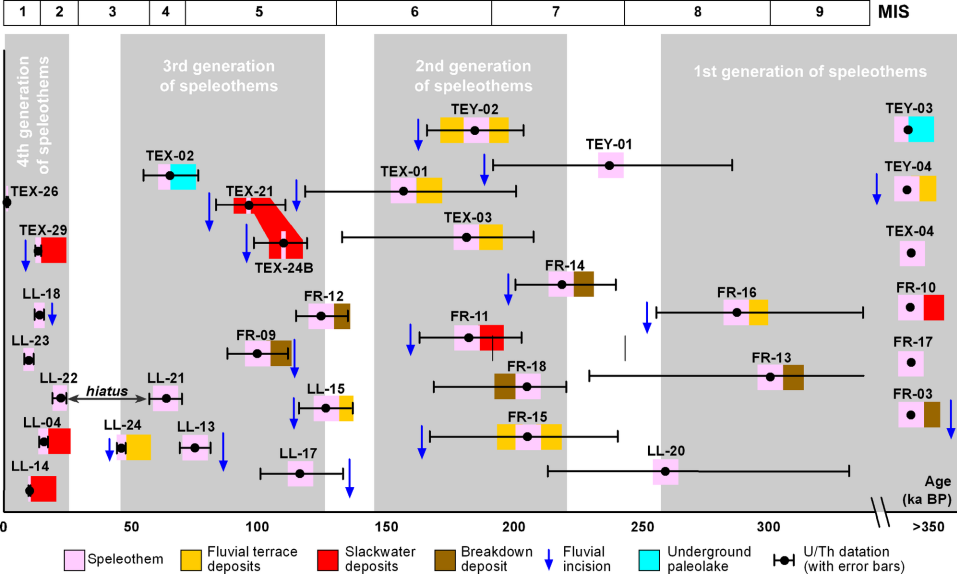


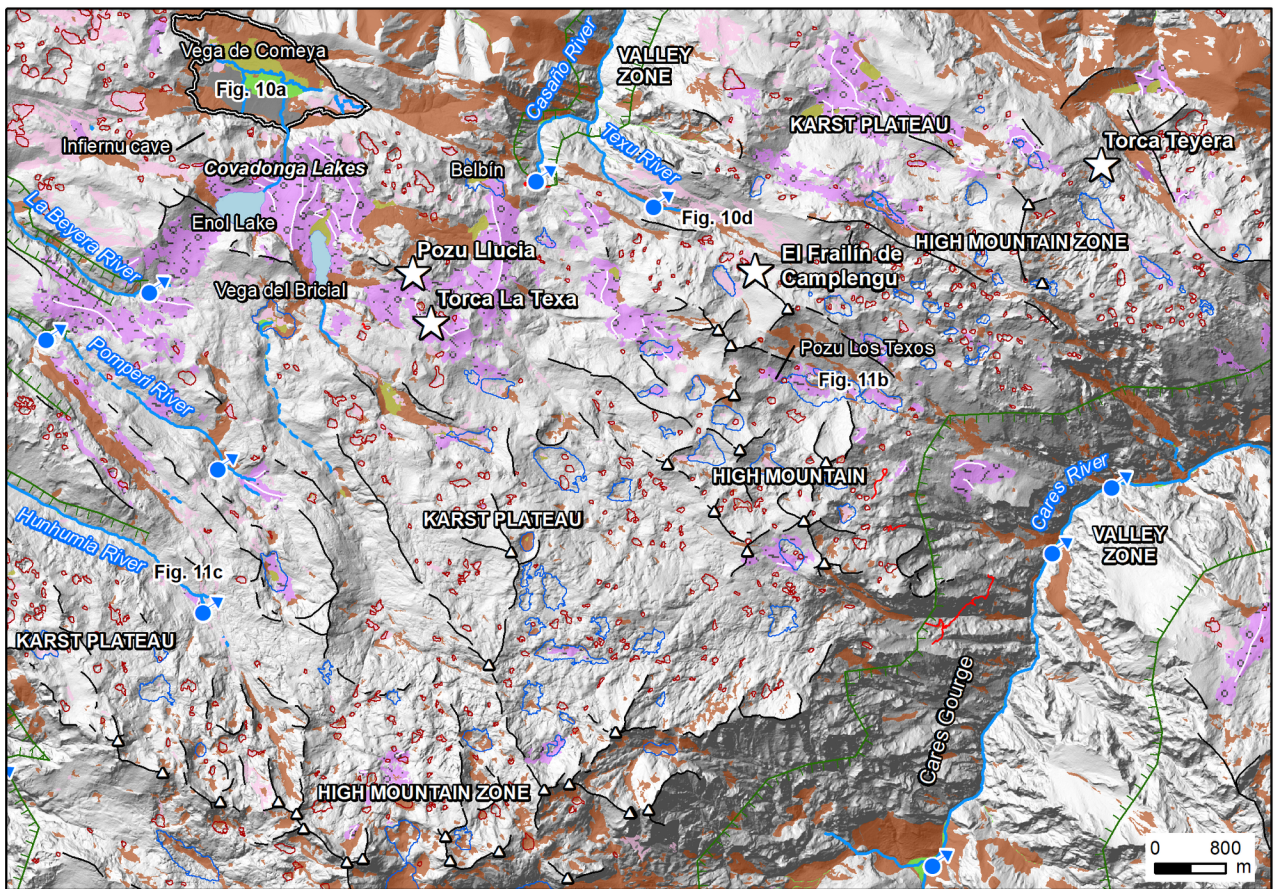












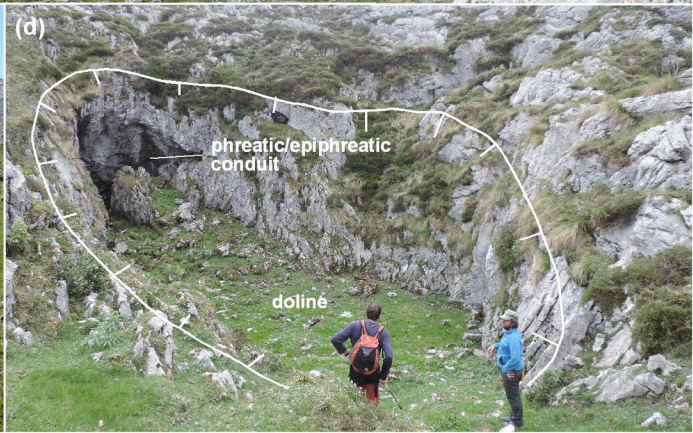
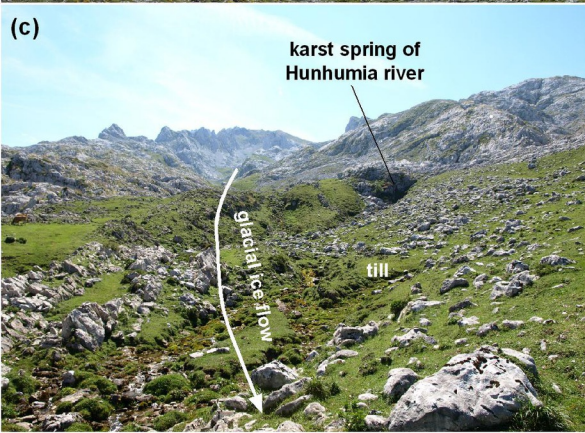
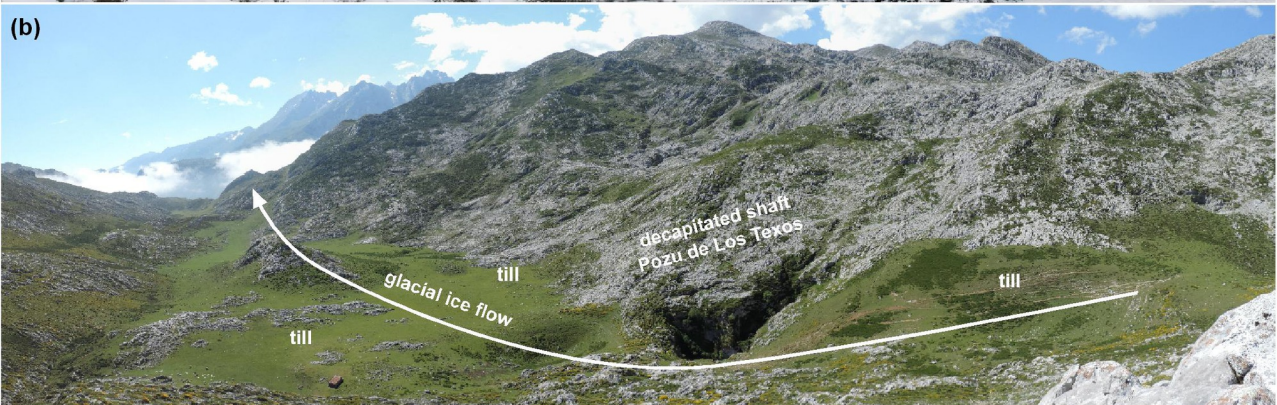
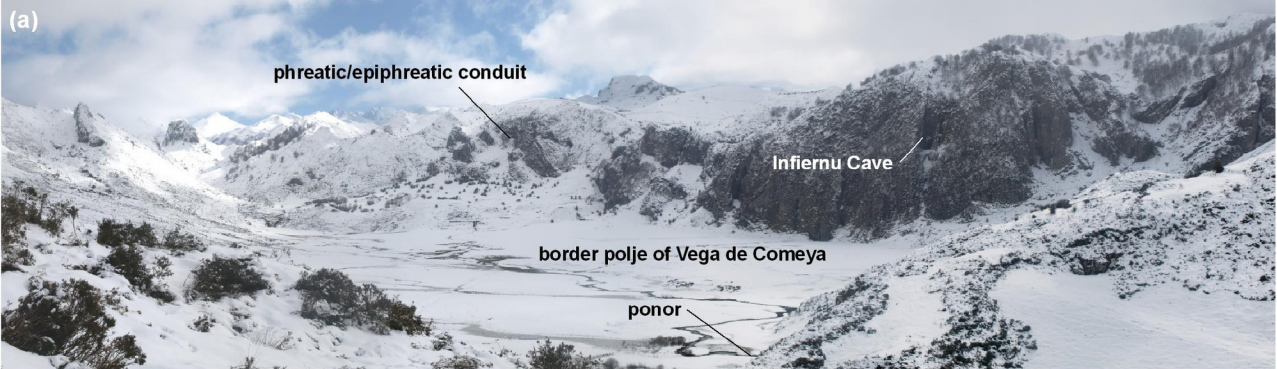
Erosive forms

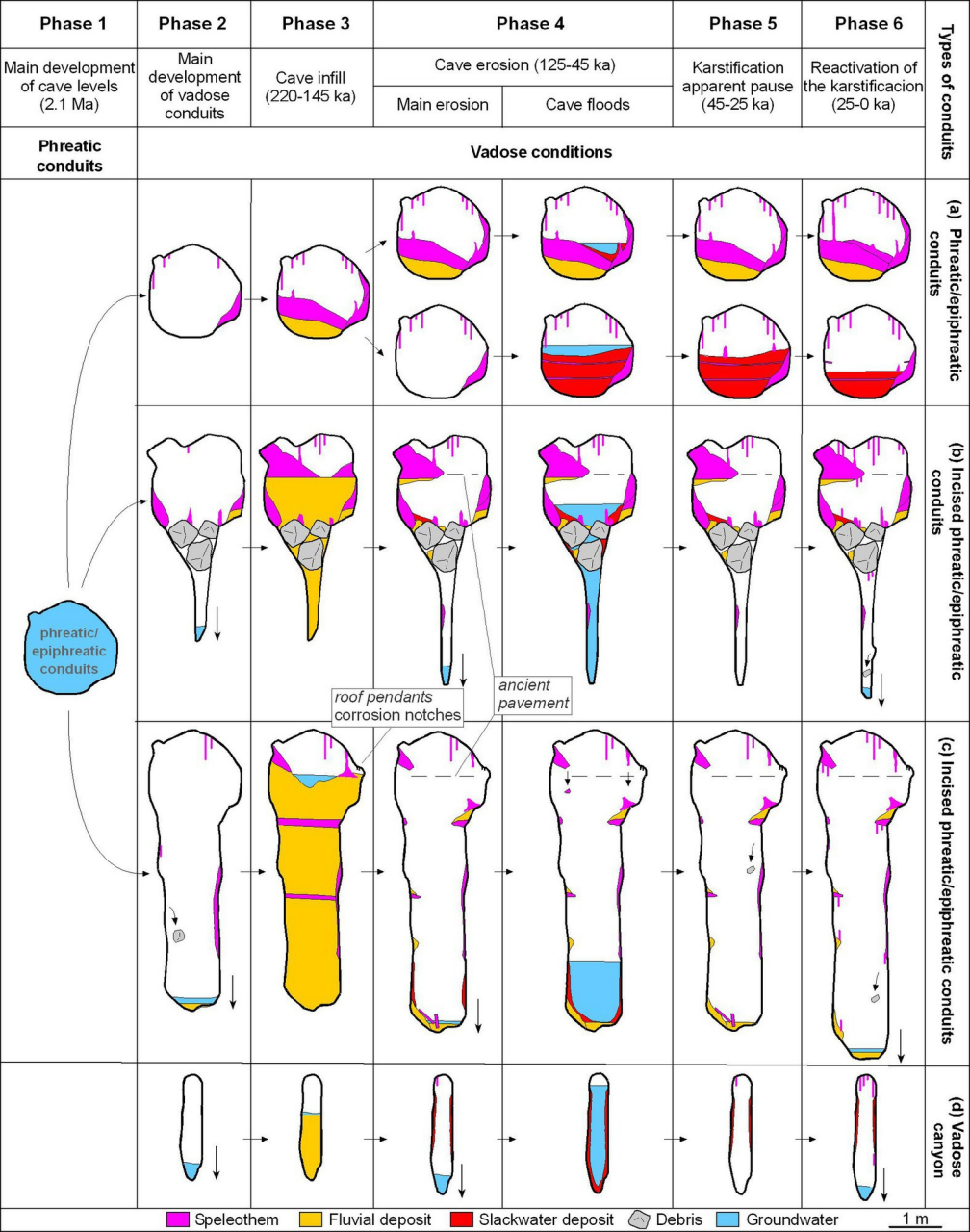
- Doline
- Glaciokarst depression
- Border polje
- Scarp of fluviokarst canyon
- Glacial cirques and arêtes
- △ Horn
- Documented cave conduits
- Karst spring

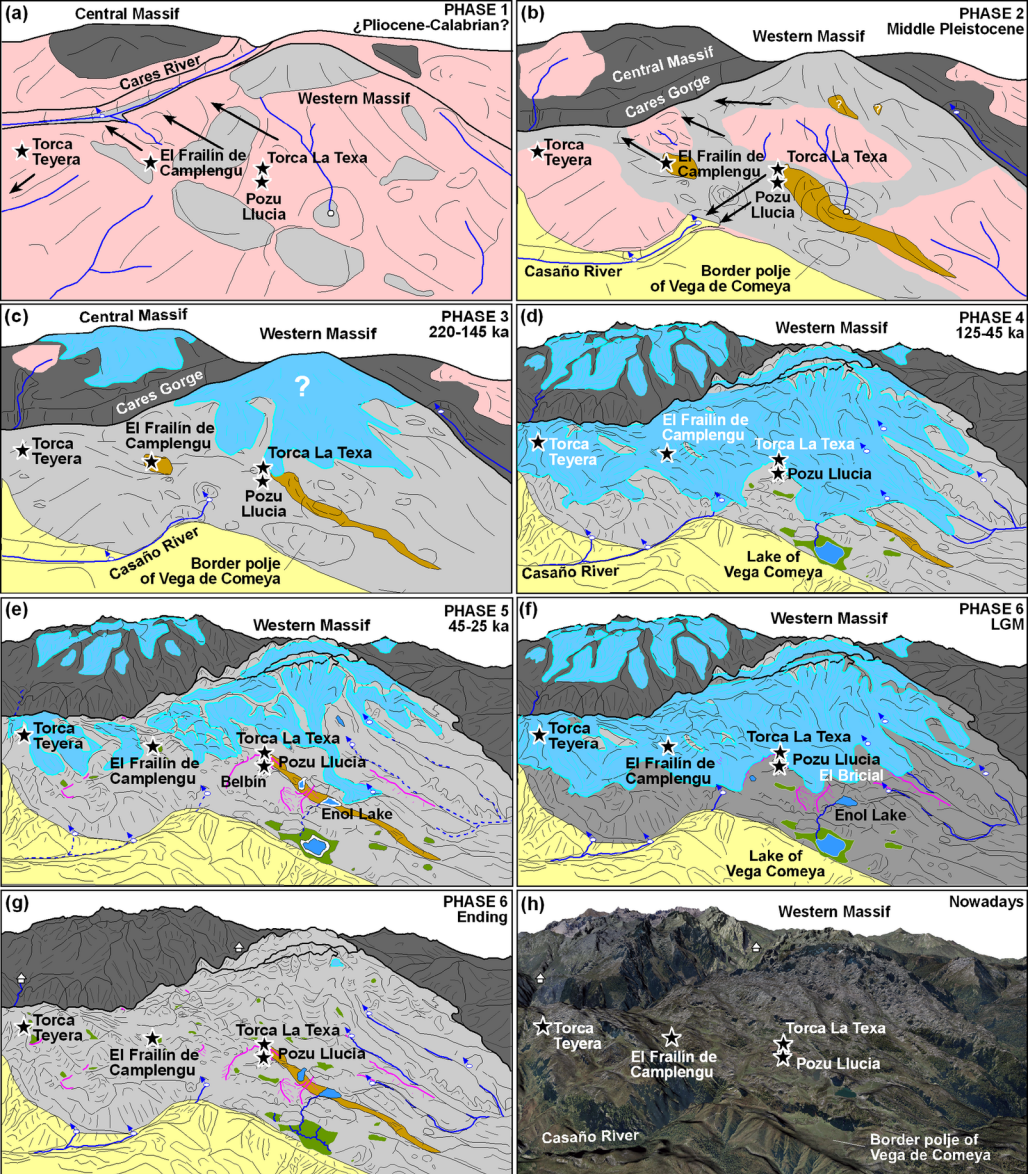
Surface deposits

- 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

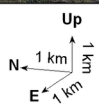


Table 1. Dimensions, type of conduits and cave levels of the studied caves.

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

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

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

| Indicator | Place | Uplifting rate (mm·a ⁻¹) | 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) |