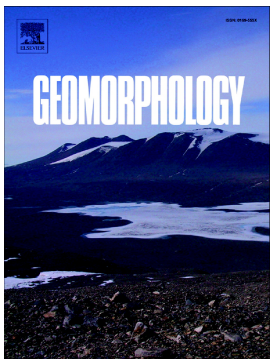


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**Quaternary regional evolution based on karst cave geomorphology in Picos de Europa (Atlantic Margin of the Iberian Peninsula)**

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Abstract

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

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

Keywords: alpine karst, geomorphology, geochronology, speleogenesis.

## 1. Introduction

Alpine caves are dominated by successions of vadose canyons and shafts developed in mountain karst areas (Maire, 1990), which correspond frequently to glaciokarsts (Ford, 1987). Alpine caves are of interest as they are developed close to the zero degrees isotherm. This makes them very sensitive to climatic and environmental change (Johnston et al., 2013; Luetscher et al., 2015). In these areas, low temperatures limit the vegetation productivity, reducing soil $pCO_2$, acid organics and drip water saturation (Lauritzen and Skoglund, 2013; Zhou et al., 2015). Alpine caves support important speleothems and ice records in glaciated areas of South Europe

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

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

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

Geomorphological studies have shown that alpine karst are probably of Miocene age, and have been strongly modified by later fluvial modifications and Quaternary glaciations (Audra et al., 2002, 2006; Hobléa et al., 2011; Columbu et al., 2015). Flowstone formation usually occurred during warm environmental conditions while detrital sedimentation took place during glacial periods in the Alps (Europe) and Canadian Rocky Mountains, in North America (Ford, 1993; Plan et al., 2009). Therefore, these sediments constitute records of glacial timing, including glacier advances and retreats. Combining absolute dating and geomorphological studies, alpine caves allow the estimation of uplift since the Pliocene, including phases of abrupt valley over-deepening, as the abrupt glacial valley incision occurred at 0.8 Ma in the Alps (Häuselmann et al., 2007), or Quaternary fluvial incision acceleration in the Pyrenees (Calvet et al., 2015). These works also quantified fluvial incision rates, with ranges of 0.1-0.8 mm $a^{-1}$ for the Quaternary, based on the presence of ancient phreatic conduits perched hundreds of meters above the current watertable. Locally, the study of alpine caves reveals sea-level changes. Alpine caves also hold evidence the timing and deformation mechanism of neotectonic movements based on speleothem damage and displacements in karst conduits, as reported in caves of the Austrian Alps (Plan et al., 2010).

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

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

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

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

## 2. Setting

Picos de Europa (43.2ºN, 4.8ºW) is a discrete mountainous area up to 2648 m in elevation and covering 700 $km^2$, forming part of the Cantabrian Mountain range (Fig. 1c). Picos de Europe has an Atlantic maritime climate with 1000-1800 mm of precipitation distributed evenly through the year. Average air temperatures range from -3 to 17ºC. Above 1500 m altitude, snow cover is present 6-9 months a year.

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

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

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

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

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

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

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

## 3. Methodology

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

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

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

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

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

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

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

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

of the study area (117 $km^2$ in extension), derived from fieldwork, photointerpretation and a GIS analyses.

## 4. Results

### *4.1 Cave conduits*

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

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

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

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

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

*4.2 Cave deposits*

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

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

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

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

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

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

*4.3 Cave geochronology*

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

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

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

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

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

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

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

## 5. Discussion

### 5.1 Generations of speleothems

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

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

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

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

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

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

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

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

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

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

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

*5.2 Regional evolution model*

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

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

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

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

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

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

rate of around 0.15-0.25 $mm \cdot a^{-1}$ since the Pliocene. This value is consistent with the rates deduced by geomorphological and thermochronological studies in the Cantabrian Mountains (Table 4). The obtained rate is similar to the rates proposed for the Pliocene-Quaternary and is one order of magnitude larger than the rates proposed for the Neogene-Paleogene in the Cantabrian Mountains. A rejuvenation of the relief during the Pliocene can explain these differences, as it was suggested by apatite fission track dating in the Pyrenees (Babault et al., 2005; Jolivet et al., 2007).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**6. Conclusions**

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

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

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

- Phase 1 (Pliocene): development of a karst partially or totally covered by an Alpine sedimentary cover, showing the incipient forming canyons of the consequent rivers of the region. Coevally, the main development of cave levels of 800-1300 m altitude was formed by a SE-directed flow in the Western Massif of Picos de Europa. Phreatic flow was toward the Cares River which incision favoured the descent of the water tables.
- Phase 2 (Calabrian to Middle Pleistocene): erosion of the Permian-Mesozoic cover and capture of the northern Wester Massif by the Casaño River. Vadose canyons and shafts were developed, affected by locally important breakdown processes.
- Phase 3 (220-145 ka, ~MIS 7-6): cave infill by speleothems and fluvial sediments derived from the erosion of Stephanian sandstone and shale that crops out locally in the highest areas of Picos de Europa.
- Phase 4 (125-45 ka, ~MIS 5-3): erosion of the previous cave infill by fluvial incision.
- Phase 5 (45-25 ka, ~MIS 3-2): apparent pause in the speleothem deposition under a dry and cold environment dominated by glacial retreat and cryogenic processes.
- Phase 6 (since 25 ka; ~MIS 2-1): reactivation of the speleothem precipitation and speleothem precipitation by a general increase of temperature and

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

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

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

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**Figure Captions**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

| Cave | | Torca Teyera | Torca La Texa | El Frailín de Camplengu | Pozu Llucia | 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 $^{234}U/^{230}Th$ 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) | $^{234}U/^{238}U$ | $^{230}Th/^{232}Th$ | $^{230}Th/^{234}U$ | 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 Llucia | | | | | | | | | | |
| 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) | $^{26}Al/^{10}Al$ | 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 ($mm \cdot a^{-1}$) | 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) |

Highlights

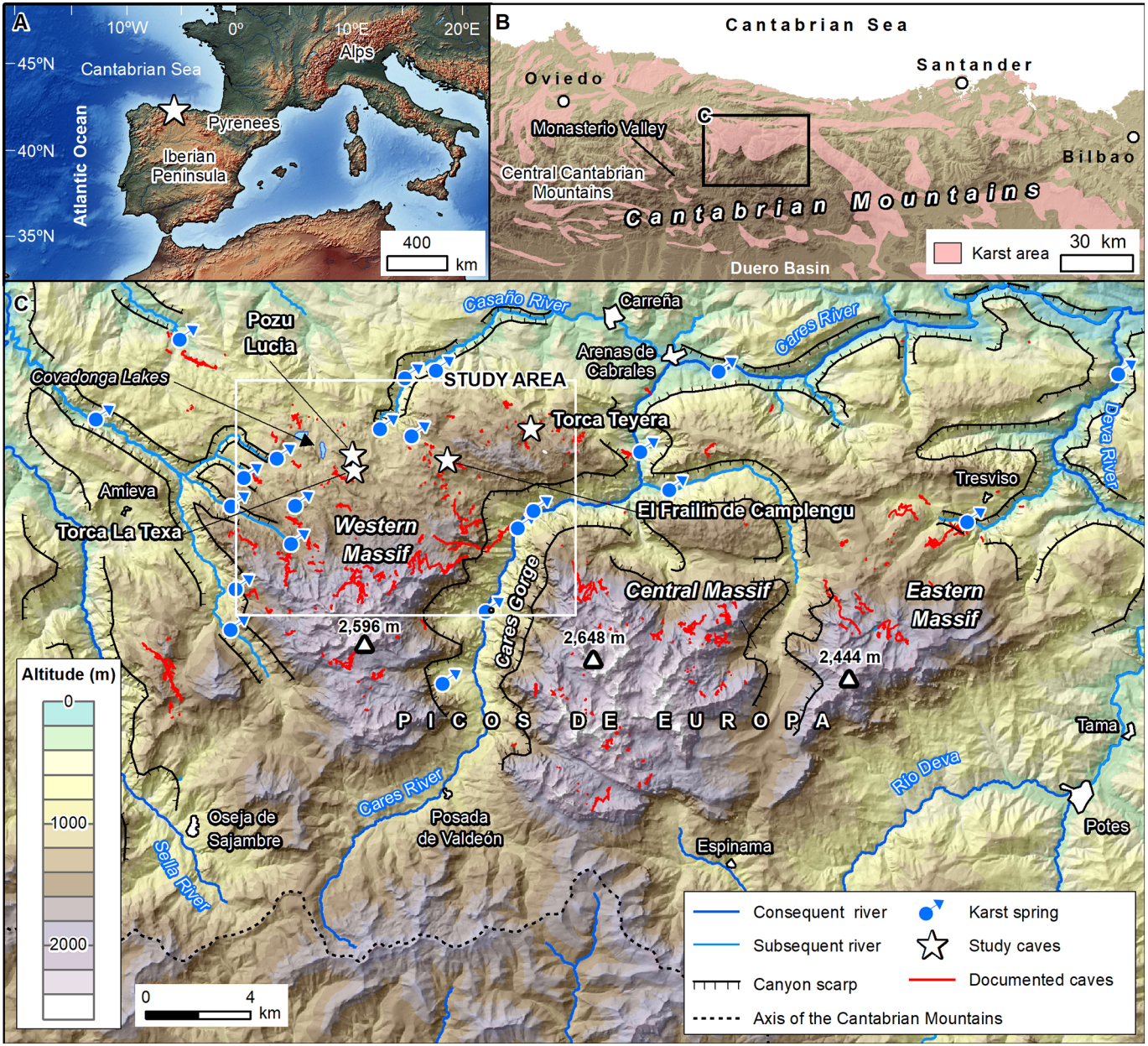
A regional landscape evolution based on cave geomorphology and geochronology.

Cave levels and subsequent vadose incision were formed at least Middle Pleistocene.

Cave sedimentary infill likely occurred at 220-145 ka from detrital rock erosion.

Cave infill was probably eroded at 125-45 ka.

Ancient presence of detrital rocks at the surface controlled the speleogenesis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Pyrenees
Iberian Peninsula
Atlantic Ocean
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B
Cantabrian Sea
Santander
Oviedo
Monasterio Valley
C
Bilbao
Central Cantabrian Mountains
Cantabrian Mountains
Duero Basin
Karst area
30 km
C
Pozu Lucia
Casaño River
Carreña
Cares River
Arenas de Cabrales
Covadonga Lakes
STUDY AREA
Torca Teyera
Deva River
Tresviso
Amieva
Torca La Texa
Western Massif
El Frailín de Camplengu
Central Massif
Eastern Massif
Cares Gorge
2,596 m
2,648 m
2,444 m
PICOS DE EUROPA
Tama
Río Deva
Potes
Oseja de Sajambre
Cares River
Posada de Valdeón
Espinama
Sella River
Altitude (m)
0
1000
2000
0 4 km
Consequent river
Subsequent river
Canyon scarp
Axis of the Cantabrian Mountains
Karst spring
Study caves
Documented caves

Figure 1

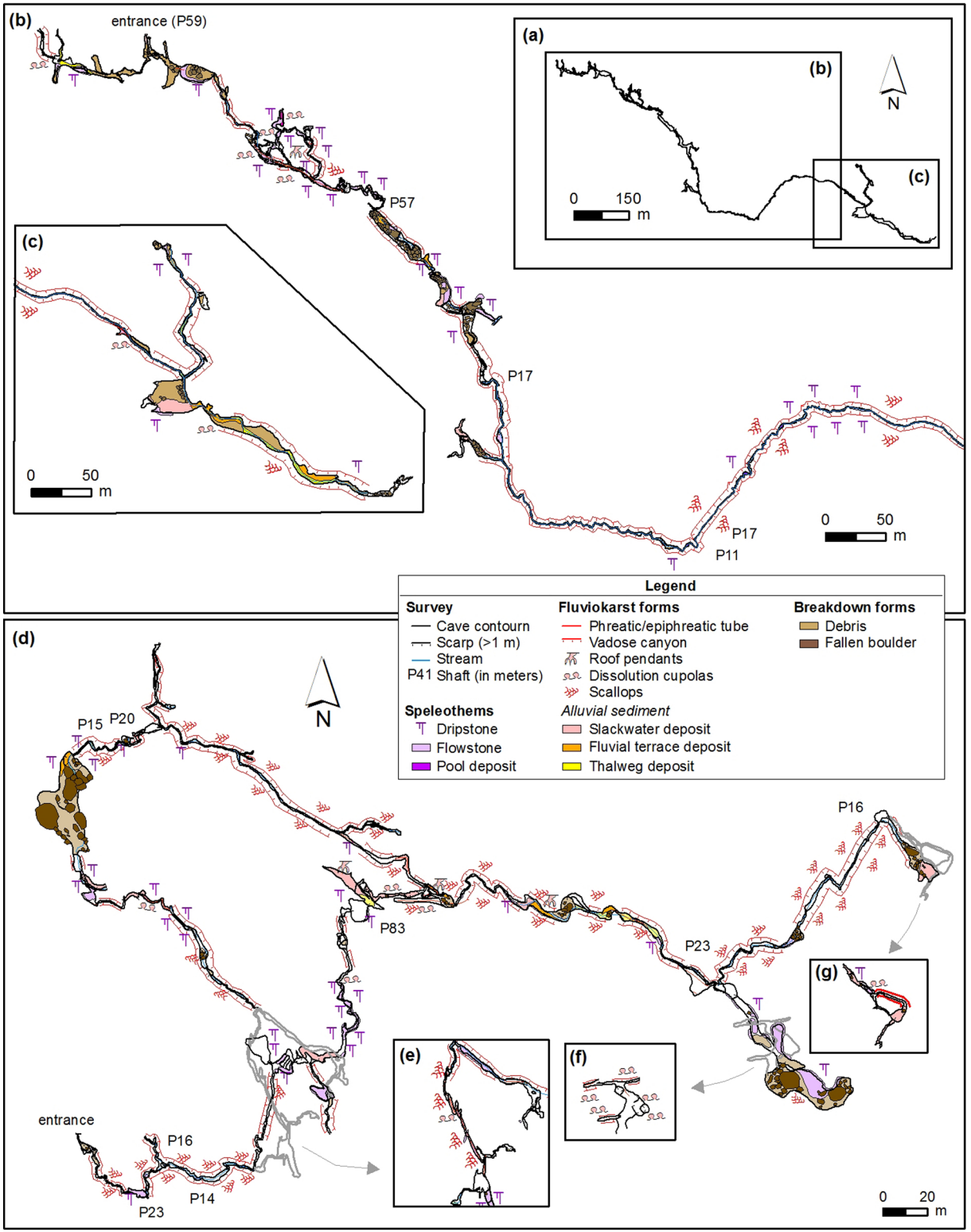
(b)
entrance (P59)
P57
P17
P17
P11
0 50 m
(a)
(b)
(c)
N
0 150 m
(c)
0 50 m
Legend
Survey
Cave contourn
Scarp (>1 m)
Stream
P41 Shaft (in meters)
Speleothems
Dripstone
Flowstone
Pool deposit
Fluviokarst forms
Phreatic/epiphreatic tube
Vadose canyon
Roof pendants
Dissolution cupolas
Scallops
Alluvial sediment
Slackwater deposit
Fluvial terrace deposit
Thalweg deposit
Breakdown forms
Debris
Fallen boulder
(d)
N
P15
P20
P83
P16
P23
(g)
(e)
(f)
entrance
P16
P14
P23
0 20 m

Figure 2

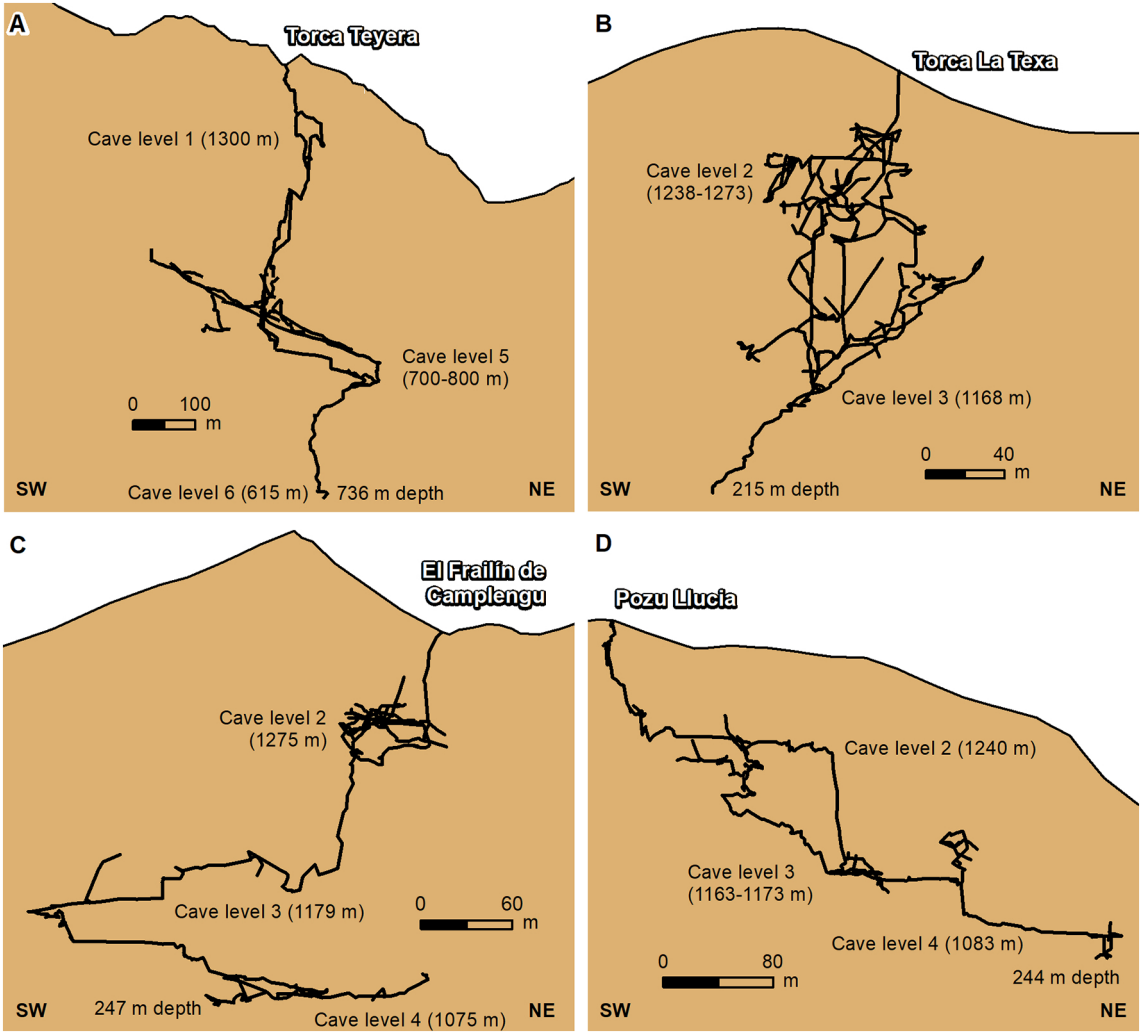
A
Torca Teyera
Cave level 1 (1300 m)
Cave level 5
(700-800 m)
0 100
m
SW
Cave level 6 (615 m)
736 m depth
NE
B
Torca La Texa
Cave level 2
(1238-1273)
Cave level 3 (1168 m)
0 40
m
SW
215 m depth
NE
C
El Frailín de
Camplengu
Cave level 2
(1275 m)
Cave level 3 (1179 m)
0 60
m
SW
247 m depth
Cave level 4 (1075 m)
NE
D
Pozu Llucia
Cave level 2 (1240 m)
Cave level 3
(1163-1173 m)
Cave level 4 (1083 m)
0 80
m
244 m depth
SW
NE

Figure 3

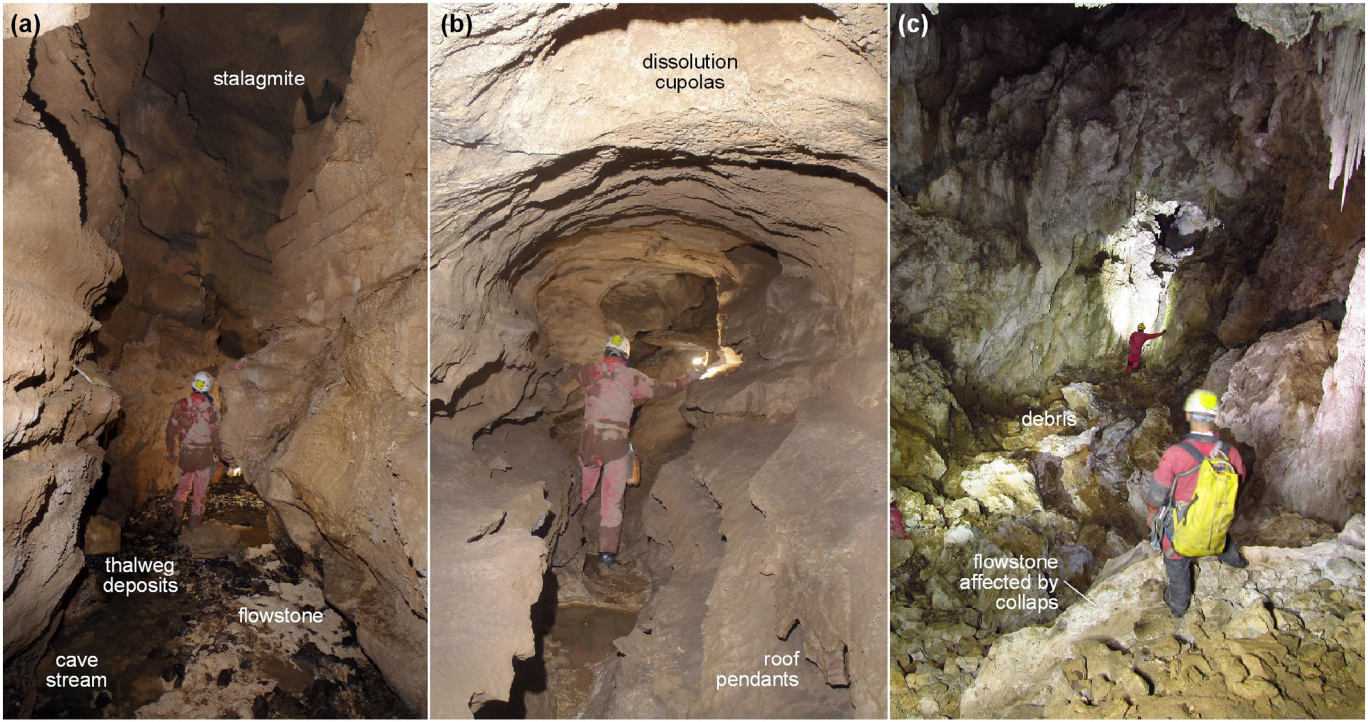
(a)
stalagmite
thalweg deposits
flowstone
cave stream
(b)
dissolution cupolas
roof pendants
(c)
debris
flowstone affected by collaps

Figure 4

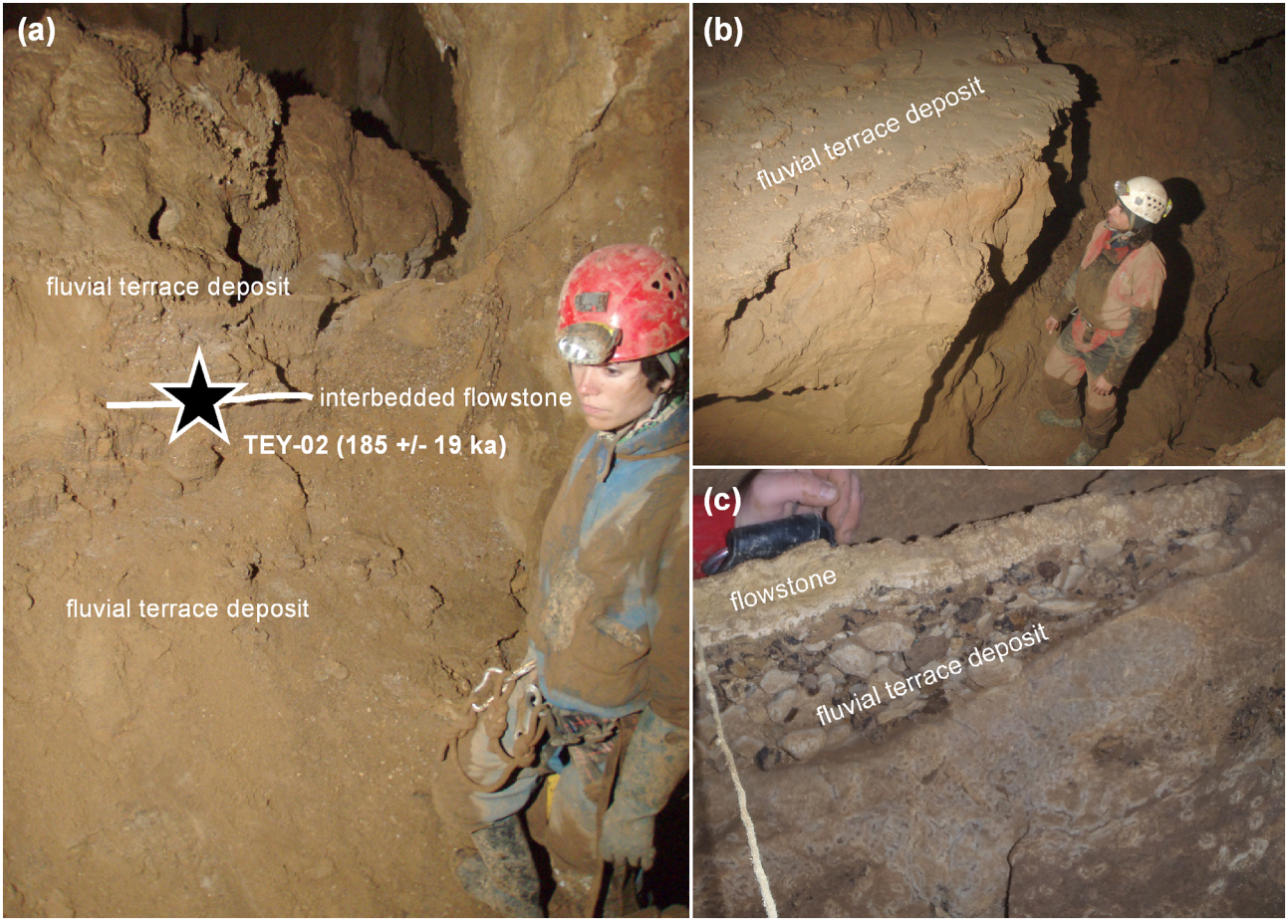
(a)
fluvial terrace deposit
interbedded flowstone
TEY-02 (185 +/- 19 ka)
fluvial terrace deposit
(b)
fluvial terrace deposit
(c)
flowstone
fluvial terrace deposit

Figure 5

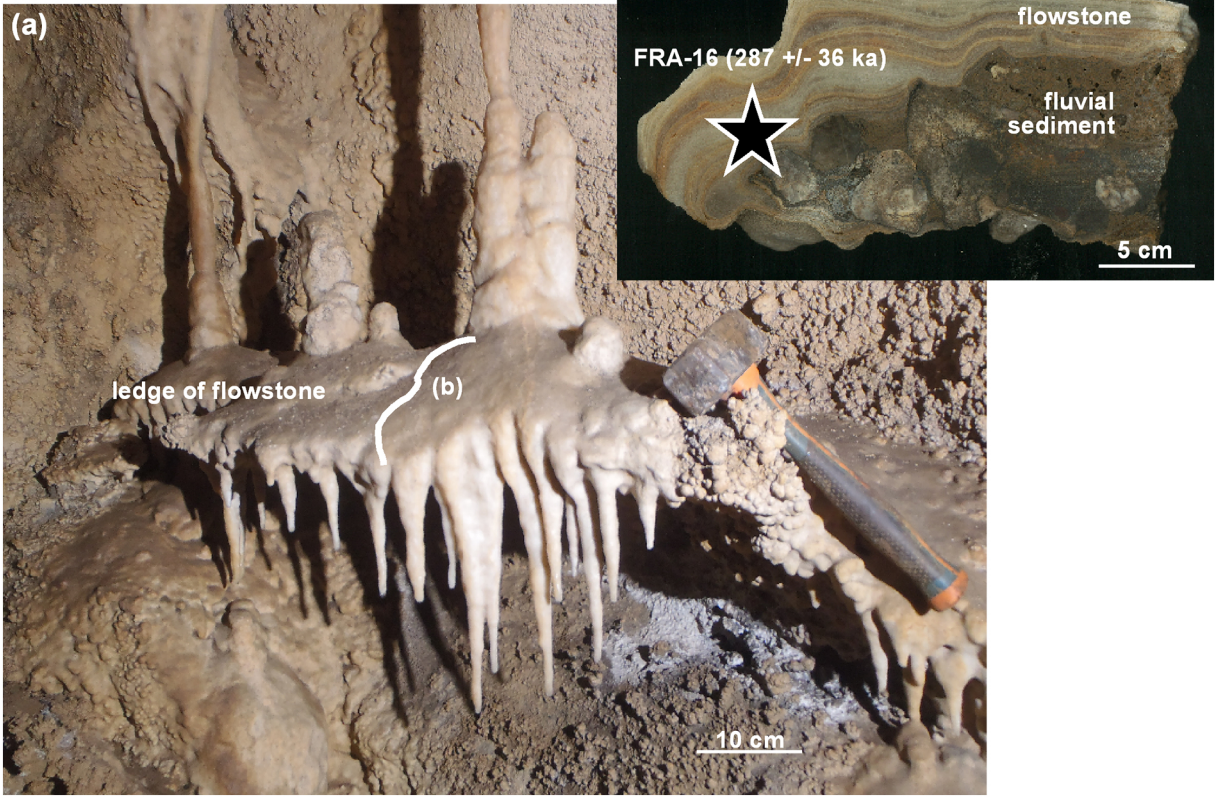
(a)
ledge of flowstone
(b)
10 cm
(b)
flowstone
FRA-16 (287 +/- 36 ka)
fluvial
sediment
5 cm

Figure 6

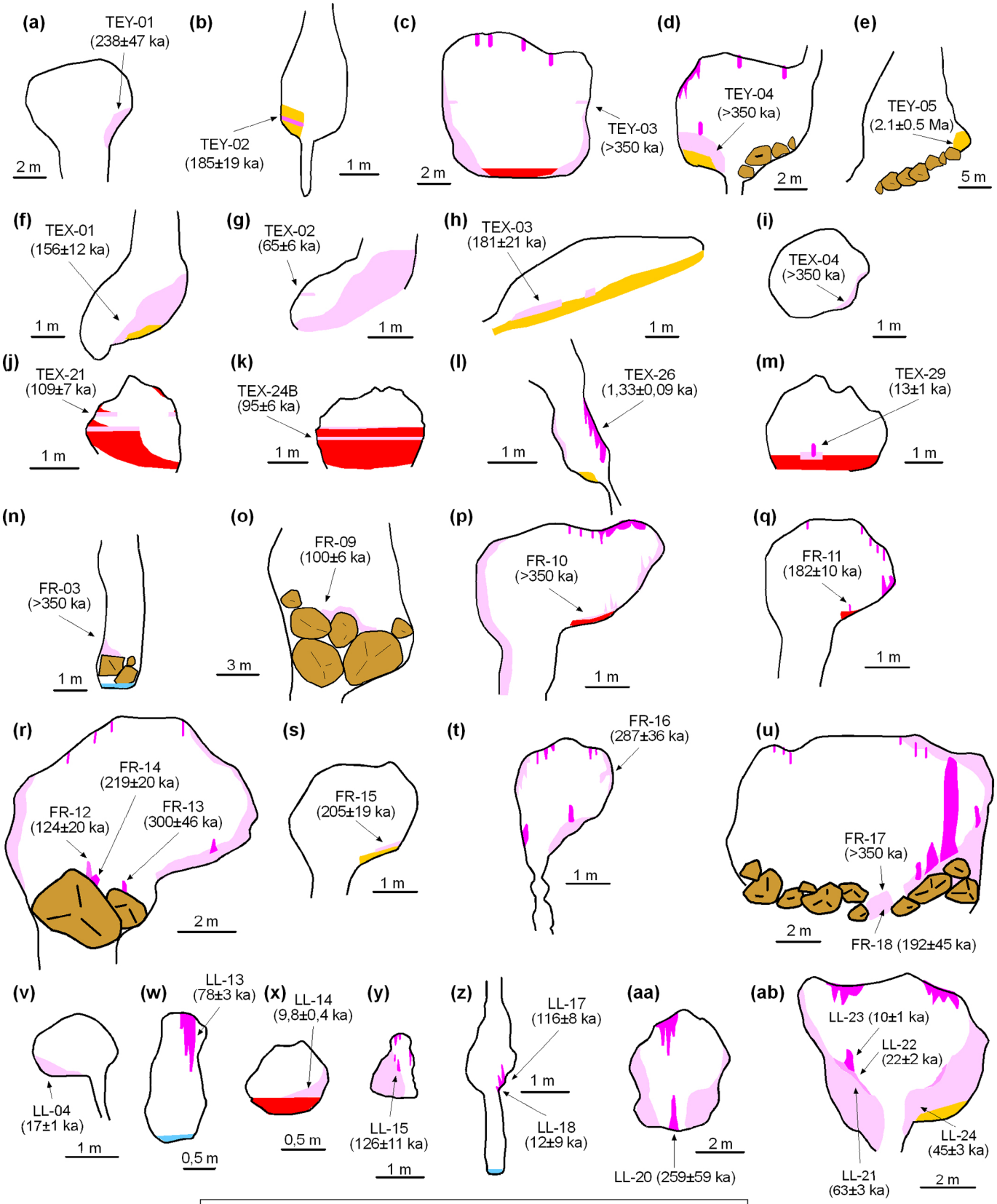
(a)
TEY-01
(238±47 ka)
2 m
(b)
TEY-02
(185±19 ka)
1 m
(c)
TEY-03
(>350 ka)
2 m
(d)
TEY-04
(>350 ka)
2 m
(e)
TEY-05
(2.1±0.5 Ma)
5 m
(f)
TEX-01
(156±12 ka)
1 m
(g)
TEX-02
(65±6 ka)
1 m
(h)
TEX-03
(181±21 ka)
1 m
(i)
TEX-04
(>350 ka)
1 m
(j)
TEX-21
(109±7 ka)
1 m
(k)
TEX-24B
(95±6 ka)
1 m
(l)
TEX-26
(1,33±0,09 ka)
1 m
(m)
TEX-29
(13±1 ka)
1 m
(n)
FR-03
(>350 ka)
1 m
(o)
FR-09
(100±6 ka)
3 m
(p)
FR-10
(>350 ka)
1 m
(q)
FR-11
(182±10 ka)
1 m
(r)
FR-14
(219±20 ka)
FR-12
(124±20 ka)
FR-13
(300±46 ka)
2 m
(s)
FR-15
(205±19 ka)
1 m
(t)
FR-16
(287±36 ka)
1 m
(u)
FR-17
(>350 ka)
2 m
FR-18 (192±45 ka)
(v)
LL-04
(17±1 ka)
1 m
(w)
LL-13
(78±3 ka)
0,5 m
(x)
LL-14
(9,8±0,4 ka)
0,5 m
(y)
LL-15
(126±11 ka)
1 m
(z)
LL-17
(116±8 ka)
1 m
LL-18
(12±9 ka)
(aa)
2 m
LL-20 (259±59 ka)
(ab)
LL-23 (10±1 ka)
LL-22
(22±2 ka)
LL-24
(45±3 ka)
LL-21
(63±3 ka)
2 m
Flowstone
Dripstone
Fluvial terrace deposit
Slackwater deposit
Debris
Cave stream

Figure 7

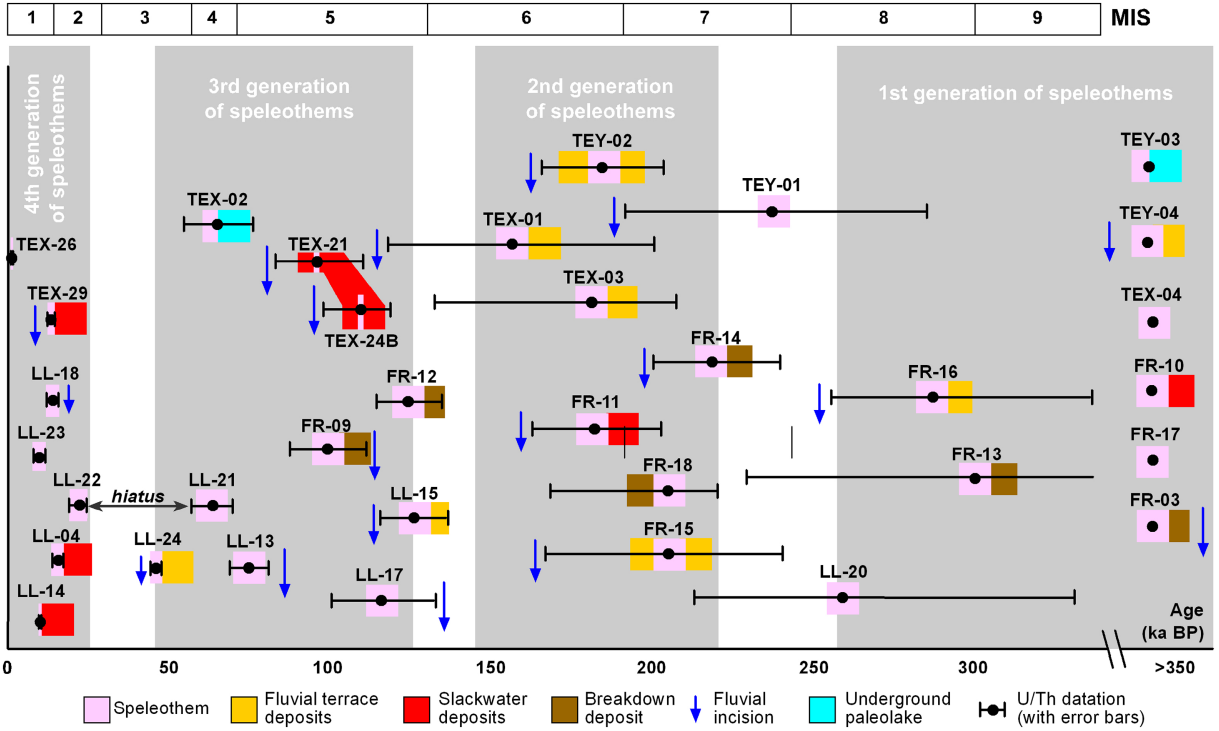
1
2
3
4
5
6
7
8
9
MIS
4th generation of speleothems
3rd generation of speleothems
2nd generation of speleothems
1st generation of speleothems
TEX-26
TEX-29
LL-18
LL-23
LL-22
hiatus
LL-21
LL-04
LL-24
LL-13
LL-14
TEX-02
TEX-21
TEX-24B
FR-12
FR-09
LL-15
LL-17
TEY-02
TEY-01
TEX-01
TEX-03
FR-14
FR-11
FR-18
FR-15
LL-20
FR-16
FR-13
TEY-03
TEY-04
TEX-04
FR-10
FR-17
FR-03
Age (ka BP)
0
50
100
150
200
250
300
>350
Speleothem
Fluvial terrace deposits
Slackwater deposits
Breakdown deposit
Fluvial incision
Underground paleolake
U/Th datation (with error bars)

Figure 8

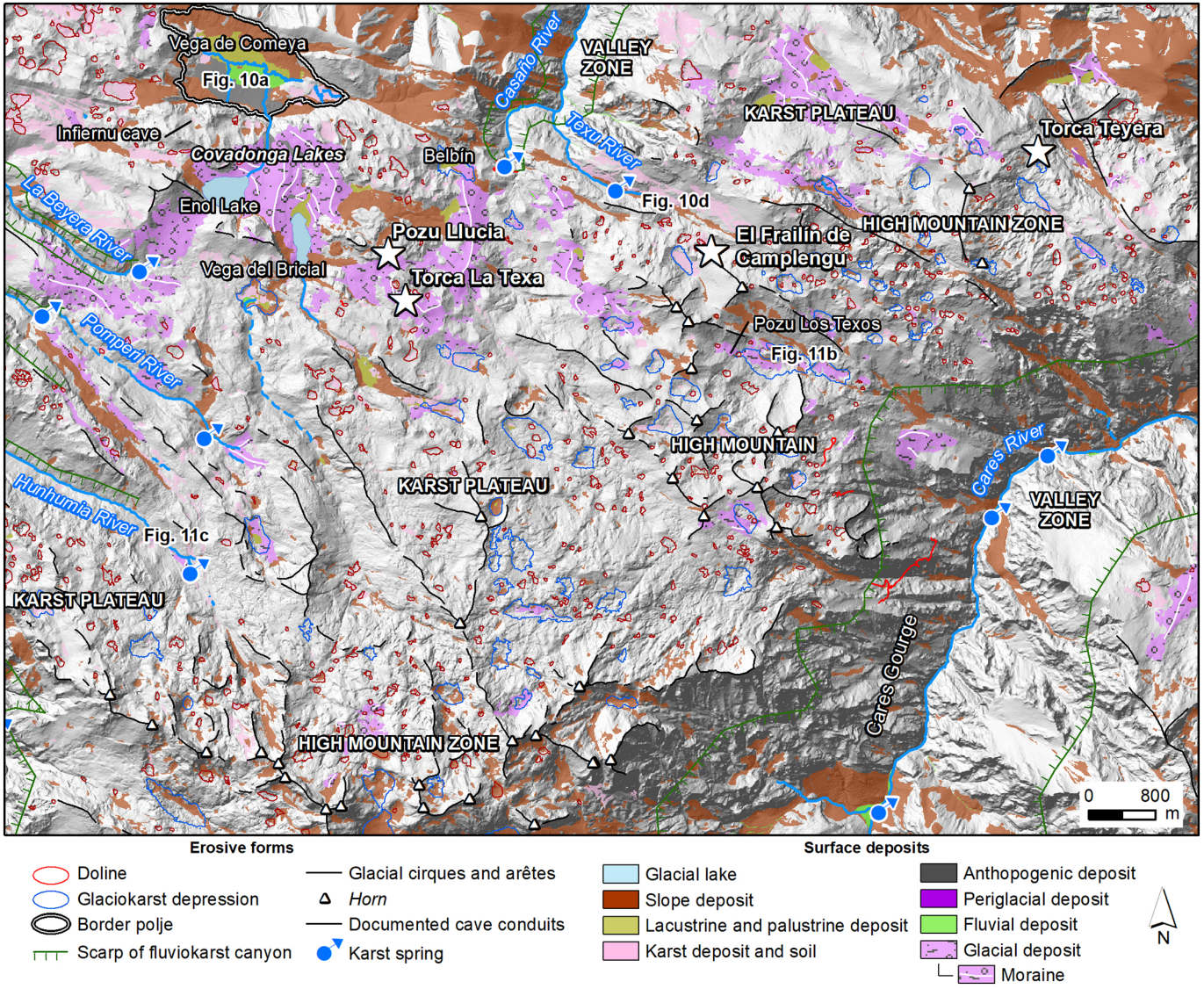
Vega de Comeya
Fig. 10a
Infiernu cave
Covadonga Lakes
Enol Lake
La Beyera River
Vega del Bricial
Pozu Llucia
Torca La Texa
Pomperi River
Hunhumia River
Fig. 11c
KARST PLATEAU
HIGH MOUNTAIN ZONE
Belbín
Casaño River
VALLEY ZONE
Texu River
Fig. 10d
KARST PLATEAU
Torca Teyera
El Frailín de Camplengu
HIGH MOUNTAIN ZONE
Pozu Los Texos
Fig. 11b
HIGH MOUNTAIN
KARST PLATEAU
Cares River
VALLEY ZONE
Cares Gourge
0
800
m
N
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
Anthopogenic deposit
Periglacial deposit
Fluvial deposit
Glacial deposit
Moraine

Figure 9


(a)
phreatic/epiphreatic conduit
Infiernu Cave
border polje of Vega de Comeya
ponor
(b)
decapitated shaft
Pozu de Los Texos
glacial ice flow
till
till
till
(c)
karst spring of
Hunhumia river
glacial ice flow
till
(d)
phreatic/epiphreatic
conduit
doline

Figure 10

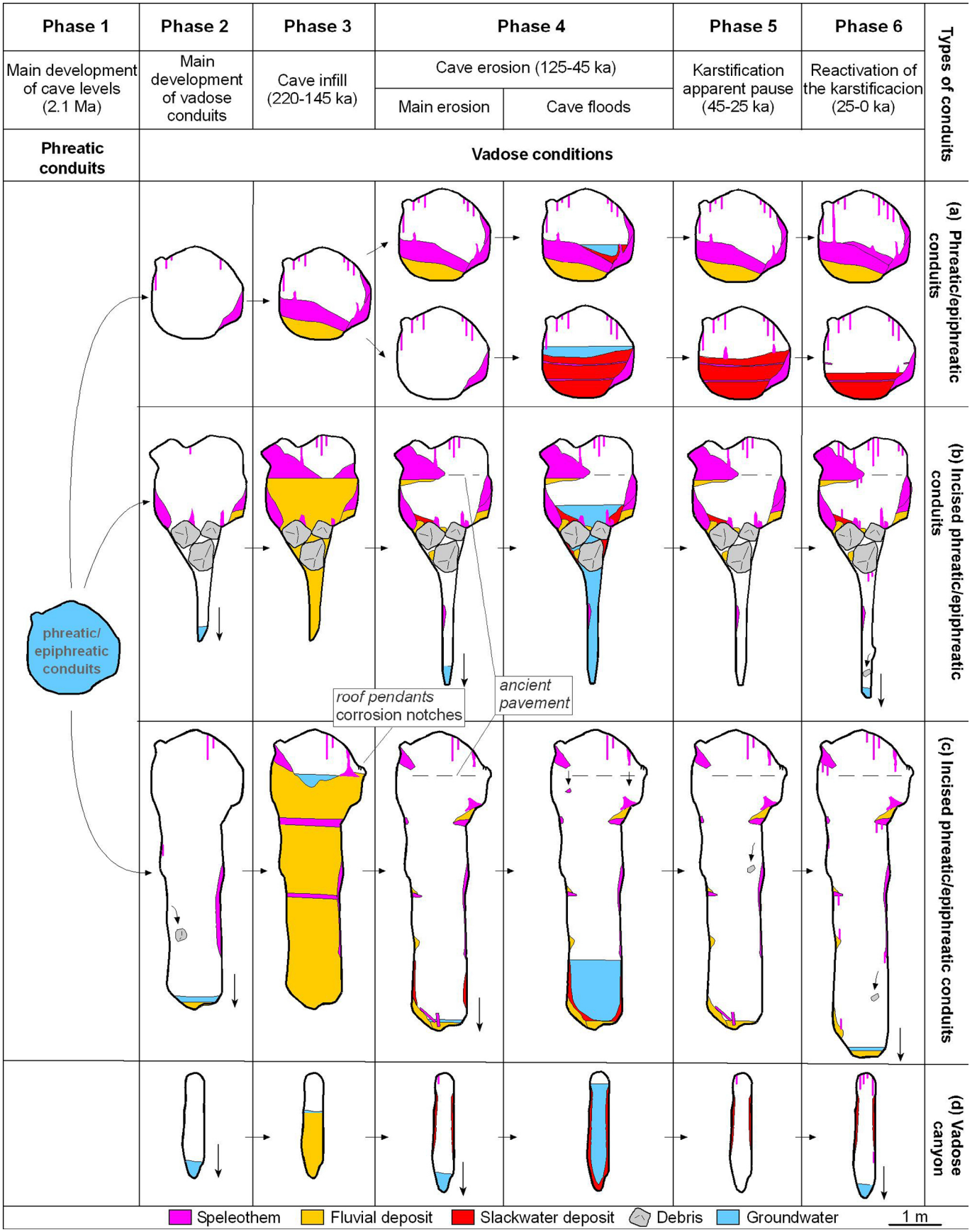
Phase 1
Phase 2
Phase 3
Phase 4
Phase 5
Phase 6
Types of conduits
Main development of cave levels (2.1 Ma)
Main development of vadose conduits
Cave infill (220-145 ka)
Cave erosion (125-45 ka)
Main erosion
Cave floods
Karstification apparent pause (45-25 ka)
Reactivation of the karstificacion (25-0 ka)
Phreatic conduits
Vadose conditions
(a) Phreatic/epiphreatic conduits
(b) Incised phreatic/epiphreatic conduits
(c) Incised phreatic/epiphreatic conduits
(d) Vadose canyon
phreatic/ epiphreatic conduits
roof pendants
corrosion notches
ancient pavement
Speleothem
Fluvial deposit
Slackwater deposit
Debris
Groundwater
1 m

Figure 11

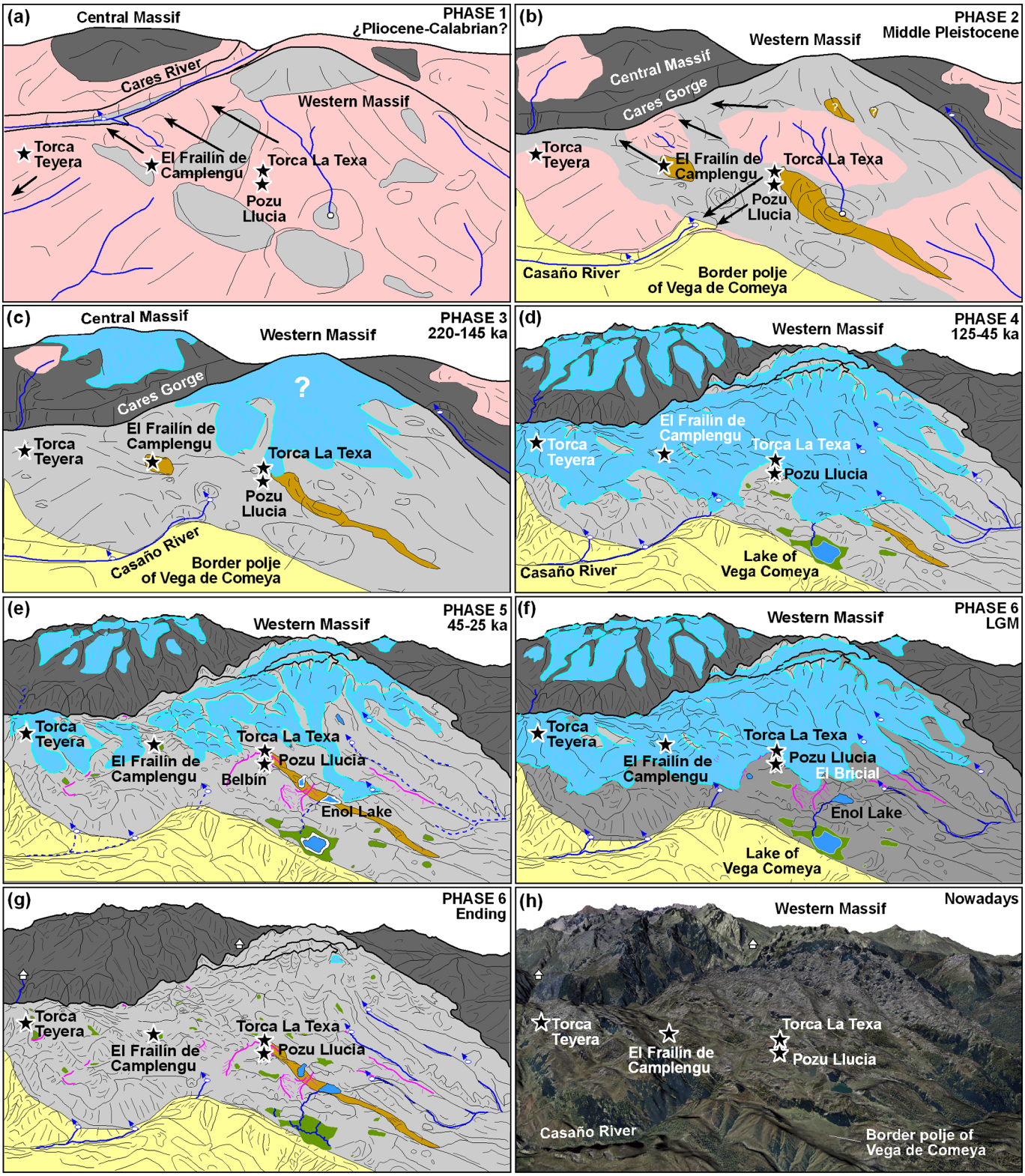
(a)
Central Massif
PHASE 1
¿Pliocene-Calabrian?
Cares River
Western Massif
Torca Teyera
El Frailín de Camplengu
Torca La Texa
Pozu Llucia
(b)
PHASE 2
Middle Pleistocene
Western Massif
Central Massif
Cares Gorge
Torca Teyera
El Frailín de Camplengu
Torca La Texa
Pozu Llucia
Casaño River
Border polje of Vega de Comeya
(c)
Central Massif
Western Massif
PHASE 3
220-145 ka
Cares Gorge
?
El Frailín de Camplengu
Torca Teyera
Torca La Texa
Pozu Llucia
Casaño River
Border polje of Vega de Comeya
(d)
Western Massif
PHASE 4
125-45 ka
El Frailín de Camplengu
Torca Teyera
Torca La Texa
Pozu Llucia
Casaño River
Lake of Vega Comeya
(e)
Western Massif
PHASE 5
45-25 ka
Torca Teyera
El Frailín de Camplengu
Torca La Texa
Pozu Llucia
Belbín
Enol Lake
(f)
Western Massif
PHASE 6
LGM
Torca Teyera
El Frailín de Camplengu
Torca La Texa
Pozu Llucia
El Bricial
Enol Lake
Lake of Vega Comeya
(g)
PHASE 6
Ending
Torca Teyera
El Frailín de Camplengu
Torca La Texa
Pozu Llucia
(h)
Western Massif
Nowadays
Torca Teyera
El Frailín de Camplengu
Torca La Texa
Pozu Llucia
Casaño River
Border polje of Vega de Comeya
Geology
Alpine cover (Permian-Mesozoic)
Stephanian sandstone and shale
Carboniferous limestone (karst)
Ordovician silicilastic rocks and others
Glaciology
Glacial ice
Glacial lake
Glacial morraine
Karst
Karst spring
Phreatic flow
Other
Depression infill
Rivers
Other areas
Up
N
E
1 km
1 km

Figure 12