A multi-method approach for speleogenetic research on alpine karst caves. Torca La Texa shaft, Picos de Europa (Spain)

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Abstract

Speleogenetic research on alpine caves has advanced significantly during the last decades. These investigations require techniques from different geoscience disciplines that must be adapted to the methodological constraints of working in deep caves. The Picos de Europa mountains are one of the most important alpine karsts, including 14% of the World's Deepest Caves (caves with more than 1 km depth). A speleogenetic research is currently being developed in selected caves in these mountains; one of them, named Torca La Texa shaft, is the main goal of this article. For this purpose, we have proposed both an optimized multi-method approach for speleogenetic research in alpine caves, and a speleogenetic model of the Torca La Texa shaft. The methodology includes: cave surveying, dye-tracing, cave geometry analyses, cave geomorphological mapping, Uranium series dating ($^{234}U/^{230}Th$) and geomorphological, structural and stratigraphical studies of the cave surroundings. The SpeleoDisc method was employed to establish the structural control of the cavity. Torca La Texa (2,653 m length, 215 m depth) is an alpine cave formed by two cave levels, vadose canyons and shafts, *soutirage* conduits, and gravity-modified passages. The cave was formed prior to the Middle Pleistocene and its development was controlled by the drop of the base level, producing the development of the two cave levels. Coevally to the cave levels formation, *soutirage* conduits originated connecting phreatic and epiphreatic conduits and vadose canyons and shafts were formed. Most of the shafts were created before the local glacial maximum, (43-45 ka) and only two cave passages are related to dolines developed in recent times. The cave development is strongly related to the structure, locating the cave in the core of a gentle fold with the conduits' geometry and orientation controlled by the bedding and five families of joints.

Key words: cave level, karst massif, shaft, structural control, vadose canyon, *soutirage* conduit.

1. INTRODUCTION

Alpine karst systems are caves with important vertical development (several hundred meters deep), dominated by vadose features connecting high basins to the local base level, usually situated at the bottom of the valleys surrounding a karst massif (Audra et al., 2007; Plan et al., 2009). These caves also show phreatic and epiphreatic conduits with frequent loops, forming cave levels perched today above the saturated zone of the karst, representing sequential stillstands of the water table deepening (Audra, 1994; Häuselmann, 2002). During the last decades, speleogenetic research shows a noteworthy advance, including the development of investigations in European alpine karst massifs, such as, for instance, the Canin Mountains, Sieben Hengste-Hohgant, Tennengebirge, Totes Gebirge, Dolomiti-Bellunesi and Vercors massifs in the Alps

(Audra, 1994, 2000; Audra et al., 2002; Häuselmann, 2002; Plan et al., 2009; Szabó, 2009; Sauro et al., 2013), the Alpi Apuane mountain range in Italy (Piccini et al., 2008, Piccini, 2011a), the Picos de Europa mountains in Spain (Smart, 1986; Ballesteros et al., 2011, 2014), Aladaglar massif in Turkey (Klimchouk et al., 2006) and Arabika massif in Western Caucasus (Klimchouk et al., 2009) (Fig. 1). The Pliocene and Quaternary evolution of some of these caves has been established in different geological settings, including phases of genesis, infilling and erosion of the conduits during the drop of the water table (Audra et al., 2002, 2007; Piccini, 2011a, b). Moreover, the influence of the lithology and of the geological structure on cave development has been identified, defining stratigraphic horizons, and geological structures that control the geometry and position of the conduits (Filipponi et al., 2009; Plan et al., 2009; Sauro et al., 2013). Links between the caves and the landscape evolution have been established. For instance, Häuselmann et al. (2007), Piccini (2011a) and De Waele et al. (2012) defined the relationships between cave development, glaciations and the evolution of the valleys surrounding the karst massifs.

Speleogenetic studies in caves require methodologies deriving from different disciplines, including Speleology, Geomorphology, Geochronology, Structural Geology, Stratigraphy Hydrogeology and Mineralogy (Häuselmann, 2002; Piccini et al., 2008). Nevertheless, these methodologies must be adapted to the cave constraints, taking into account logistic problems such as complex and technical access to the vertical sections of the caves, the presence of narrow passages, extremely long passageways that require several days of permanence in the caves in environments with low temperatures (0 to 5ºC) and high humidity indexes. These methodologies include data collection in the cave and its surroundings, elaboration of cave surveys, 3D modeling, geomorphological mapping of the conduits, morphometric analyses, sampling and stratigraphic characterization of cave deposits, petrographic and geochemical analyses of the speleothems, dye-tracings and geochronological dating, as well as geological maps and cross-sections (Audra et al., 2002, 2007; Häuselmann et al., 2007; Filipponi et al., 2009; Plan et al., 2009; Ballesteros et al., 2011; Piccini, 2011a; Sauro et al., 2013).

The Picos de Europa National Park (North Spain) is considered one of the most important karst areas in the world since it contains 14% of the World's Deepest Caves (Gulden, 2014). This Spanish National Park is an international reference in Karstology (Fernández-Gibert et al., 2000; Ford and Williams, 2007), and in Speleology and Geoheritage, and has being considered as a Global Geosite in 2011 by the Geological Survey of Spain (IGME) due to its geomorphological interest. More than 355 km of cave conduits have been discovered and documented, although only 0.4% of them have been studied. The main studied caves are Cueva del Agua, Torca del Cueto los Senderos, Torca La Barga, Mina Tere and Mina Sara from the Eastern Massif of Picos de Europa (Smart, 1984, 1986); Trave System from the Central Massif (Bigot, 1989); and Pozo del Cuetalbo (Senior, 1987) and Torca Teyera shafts (Ballesteros et al., 2011) from the Western Massif. These works detail the geometry of these caves and their deposits, recognizing phreatic and vadose conduits and establishing the cave evolution in relation to the geological structure and the incision of the fluvial network.

Currently, the Spanish GEOCAVE research Project (MAGRAMA-OAPN) is being developed in selected caves from the Picos de Europa mountains in order to establish speleogenetic models and to develop new methodologies based on previous works (Jiménez-Sánchez et al., 2006a, 2006b, 2011; Benischke et al., 2007; Filipponi et al., 2009; Ballesteros et al., 2011, 2014; Piccini, 2011a, b; Pardo-Iguzquiza et al., 2011).

The aims of this article are: 1) to optimize a multi-method approach for speleogenetic studies in alpine caves, including the characterization of their geometry, geomorphology (cave deposits study) and geochronology and their relationships with the geological structure and landforms; and 2) to propose a speleogenetic model of the Torca La Texa shaft.

2. SETTING

The Torca La Texa shaft (4º 58’ 6.43” W, 43º 15’ 46.43” N, 1,305 m altitude) is located in the northwest of Picos de Europa (Cantabrian Mountain Range, North Spain) (Fig. 2). Picos de Europa is a mountainous massif, located 15 km south of the Cantabrian Sea, with 30 peaks higher than 2,500 m altitude. Picos de Europa shows a rough relief divided into Western, Central and Eastern massifs by the fluvial network. This fluvial network is formed by rivers that flow from South to North, developing deep canyons, as Cares, Los Beyos, and La Hermida gorges. From the climatic point of view, these mountains are included in the oceanic domain marked by high-mountain influence; the mean annual precipitation (rain and snow) reaches 2,000 mm/year, and the temperature usually ranges from -20º to 30ºC.

From the geological point of view, Picos de Europa is mainly formed by more than 1,200 m thick Carboniferous limestones, although Ordovician and Carboniferous sandstone and shale crop out in some places (see Bahamonde et al., 2000, 2007, 2014 for further details); some areas of these mountains were covered by Permian and Mesozoic sandstone and shale, which are only preserved in few outcrops. These limestone series show a Carboniferous-Permian paleokarst formed by grain-coarsed infill, laterites and bauxites (Merino-Tomé et al., 2009a). The entire bedrock is affected by a complex and imbricate thrust system and other faults developed during the Variscan orogeny, the Permian-Mesozoic extensional episode and the Alpine orogeny (Alonso et al., 1996; Merino-Tomé et al., 2009b). Moreover, the bedrock is strongly fractured by up to seven joints families which age is today unknown (Ballesteros et al., 2011).

Picos de Europa was uplifted during the Alpine orogeny and its evolution is not well known yet. These mountains are mainly formed by an alpine (or high-mountain) karst dominated by dissolution, snow and gravitational processes, including also periglacial action in areas higher than 2,200 m, and fluvial activity at the bottom of the valleys (e.g. Alonso, 1998; Ruiz-Fernández et al., 2009; Serrano et al., 2012). The Picos de Europa mountains were occupied by glaciers at least twice: the old glaciation took place prior to 276-394 ka BP (Villa et al., 2013), while the younger one reached its local maximum before 36-43 ka BP (Moreno et al., 2012; Serrano et al., 2012; Jiménez-Sánchez et al., 2013).

Picos de Europa includes almost 3,650 caves with more than 355 km of conduits (Jiménez-Sánchez et al., 2014), with dimensions ranging from few meters to up to 19 km in length and up to 1,589 m in depth (Fig. 3) (Margaliano et al., 1998; Puch, 1998). During, at least, the Quaternary, the karst development was conditioned by fluvial network incision and erosion of the Permian-Mesozoic cover, glacial action, and karst aquifer geometry (Smart, 1986; Senior, 1987; Bigot, 1989; Fernández-Gibert et al., 2000; Ballesteros et al., 2011). The Quaternary karst was overprinted by glaciers generating enlarged glaciokarst depressions up to 2 km long (Smart, 1984). Later, glaciokarst features were modified by snow, gravity and dissolution processes, contributing to the development of dolines, karren and caves (Alonso, 1998). Regarding the endokarst, Fernández-Gibert et al. (2000) proposed a speleogenetic model for the evolution of the Picos de Europa caves with two phases. In the first one, phreatic conduits were developed in a karst aquifer partially confined by the Permian-Mesozoic cover. During the second phase, the mountains were uplifted, the cover was eroded and vadose conditions were established coevally with the drop of the regional water table. In this second phase, new phreatic passages were developed and vadose shafts and canyons were deepened, intercepting the perched phreatic conduits. Radiometric dates obtained by Uranium-series (234U/230Th) in speleothems from the 800 m and 1,300 m cave levels evidence that these levels were originated, at least, prior to the Middle Pleistocene (Smart, 1984). Fernández-Gibert et al. (2000) and Smart (1986) suggest that waters from melting glaciers were concentrated into certain sink points, contributing to the genesis of vadose shafts. Nevertheless, the geomorphological and geochronological links between glacial evolution and speleogenesis are not well established yet.

3. METHODOLOGY

The methodology employed to characterize the Torca La Texa shaft and its surroundings has included speleological, geomorphological, hydrogeological, geochronological and geological techniques. A study area of 7x6 km (42 km^2) was defined around the Torca La Texa shaft in order to establish the geomorphological and geological setting of the cave, as well as to define the influence of the surface processes and the geology of the bedrock on the cave development. The methodology was divided into seven phases: 1) cave survey, 2) definition of the base level by dye-tracing, 3) cave geometry analysis, 4) cave geomorphological mapping, 5) radiometric dating, 6) geomorphological mapping of the study area, and 7) lithological and structural study.

3.1 Cave survey

The survey or mapping of the cave was carried out to position the conduits with respect to the surface and to project the scientific information taken in the cave. The cave survey was elaborated at a 1/500 scale according to the speleological cave survey method performed by Frumkin and Fischhendler (2005), Jeannin et al. (2007), Jaillet et al. (2011) and Piccini (2011b). The employed methodology included the definition of survey stations along the cave conduits, the measurements of polar coordinates (distance, direction and inclination) between stations and the measurement of the vertical and horizontal sections of the passage in each station. The survey was carried out according to the UISv1 5-2-BCEF grade defined by Häuselmann (2011), collecting the measures by a DistoX laser range finder designed by Heeb (2009). The cave survey included 498 stations and 534 sets of polar coordinates (survey shots). The collected data were elaborated by Compass software (Fish, 2001) in order to obtain the survey polyline, the 3D model and the survey precision. The survey polyline (line that connects all the survey stations), the position and the horizontal diameter of the stations were exported as a SHP file to a Geographic Information System (GIS), and projected on the referenced orthophotography and topographic map obtained from the National Geographic Institute of Spain. The 3D modeling methodology of the cave geometry is described by Fish (2001).The model was constructed jointing octagonal prisms defined between survey stations. The axis of each prism was defined by the polar coordinates and its dimensions corresponded to the horizontal and vertical approximate diameter of the stations. The transition between successive prisms was smoothed dividing it in three segments and two corners. The precision of the survey was calculated according to Fish (2007), involving eight closed polylines that represent 23% of the cave length. Moreover, the altitude of 32 stations was checked by an altimeter with 8 m precision. The precision obtained in the three dimensions is 2.3 ± 0.9%. Finally, a detailed cave survey was drawn in a GIS, projecting in the map 435 contours of the conduits, 202 scarps higher than 1 m and 534 approximated topographic contours.

3.2 Definition of the cave base level by dye-tracing

As the cave exploration and survey were limited to the conduits wider than 0.3 m (human exploration limit), and the base level was not reached, a dye tracing was necessary to define the related actually saturated zone (Perrin and Luetscher, 2008; Kovačič et al., 2012). The base level of the cave allowed us to infer the position of the vadose and saturated zone of the karst aquifer, providing the lowest altitude where the air-filled cave could developed. The base level was defined considering the altitude of the karst spring that collects, at least, part of the water from the Torca La Texa shaft. In this way, a dye-tracing was done, following the methodology reported in Goldscheider (2005) and Benischke et al. (2007). The injection point was located in the SE sector of Torca La Texa, in a small river with a discharge of 0.9 l/s, where 300 g of Na fluorescein were diluted on October, 1th 2011. The four control points corresponded to three perennial karst springs (Oyu La Madre, Fuentona de Fana and Oyu del Doñea) and the source of the Ercina Lake (Fig. 2). Oyu La Madre and Oyu del Doñea springs are among of the main karst springs of the area, with more 100 $l \cdot s^{-1}$ discharge; Fuentona de Fana spring is a small springs with 2-10 $l \cdot s^{-1}$ discharge, which flow disappears after 50 m running on the surface. The active coal detectors were placed in the control points and were collected 24 hours before the injection and 4, 24 and 168 hours after the injection. Therefore, sixteen active coal detectors were analyzed by fluorimetry at the Environmental Test Unit of the Scientific and Technical Services of the University of Oviedo.

3.3 Cave geometry analyses

The geometry of the Torca La Texa shaft was analyzed in order to relate the conduit development with the hydrogeological and structural factors. These analyses are based on numerical approaches that allows us to obtain quick and objective information of the cave geometry and some insight about its speleogenesis. The aim of these approaches is the obtaining of the maximum information based on the cave survey, the comparison of caves using objective parameters and to provide a guide for the following steps of the study. The analysis included the calculation of 14 morphometric parameters and indexes, the definition of conduits groups, and the establishment of cave levels

3.3.1 Morphometric parameters and indexes

Fourteen morphometric parameters and indexes described by Klimchouk (2006), Pardo-Iguzquiza et al. (2011) and Piccini (2011b) were selected to characterize the cave geometry. These parameters and indexes, together with their name, symbol, meaning and calculation method are summarized in Table 1. The dimensions of the cave were defined by the real length, plan length, cave area and cave volume (Klimchouk, 2006; Piccini, 2011b), whereas the geometry of the conduit section was approached by the asymmetry ratio (Filipponi et al., 2009; Pardo-Iguzquiza et al., 2011). The relations between length, area and volume of the cave were studied by measuring the specific volume, passage density, areal coverage and cave porosity (Frumkin and Fischhendler, 2005; Klimchouk, 2006; Finnesand and Curl, 2009; Lazaridis, 2009; Piccini, 2011b). The relation of the vertical and horizontal development of the caves was measured using the vertical, horizontal and horizontal complex indexes, and quantifying the tortuosity of the cavity with the linearity index (Piccini, 2011b).

3.3.2 Definition of conduits groups

Cave conduits were classified according to Ballesteros et al. (2011, 2014) to characterize their directions and inclinations and to establish the structural control of the cave (section 3.6). The conduits were classified using a density map of the directions and inclinations of the conduits plotted on stereographic projection. The values of directions and inclinations were taken from the polar coordinates of the cave survey (section 3.1).

3.3.3 Definition of cave levels

Cave levels represent ancient positions of the water table (Audra and Palmer, 2013). In this work, the cave levels are defined for specific altitudes according to three criteria: 1) the presence of phreatic and epiphreatic conduits reported in the cave geomorphological map (see section 3.4), 2) the quantification of density values of cave conduits at a specific altitude located above other altitudes; and 3) the presence of elliptic to round shaped sections of conduits, evidenced by values of the asymmetry ratio (R) close to 1. The first and second criteria were analyzed from the vertical distribution profiles of the cave length (Lr) and the asymmetry ratio (R) parameters (Filipponi et al., 2009), using altitude intervals of 5 m.

3.4 Cave geomorphological map

The geomorphological map of the Torca La Texa shaft was elaborated in order to describe the presence, extent and spatial relationships of cave forms and processes. The map was carried out plotting the cave erosive and sedimentary forms on the cave survey (Jiménez-Sánchez et al., 2006a, b, 2011; Ballesteros et al., 2011; Delannoy et al., 2012). The scale of the geomorphologic map is 1/500. The cave presents forms at the floor, walls and roofs which representation together in a 2-D map is complex. The forms located on floor are plotted between the conduit contours of the survey, while the forms on the walls are schematically represented on the outside contour of the passages. These features were brought down on the walls along an axis located on the edge of the contour. The forms of the roofs are not generally represented, except the phreatic and epiphreatic tubes that are represented by a line plotted on the cave survey. The erosive features and deposits on the cave floor and roofs were classified into three genetic groups: fluviokarst forms, chemical deposits (speleothems) and breakdown forms. These features were projected on the cave survey using the previously created GIS. The geomorphological map covers an area of 5,858 m^2, involving 401 deposits, 144 linear erosive features and 286 local erosive and sedimentary features. The map was complemented with eight stratigraphic sections carried out in the outcrops of fluvial deposits and speleothems.

3.5 Uranium series ($^{234}U/^{230}Th$) dating

Six samples taken from speleothems were dated using the Uranium-series (234U/230Th) method (Ivanovich and Harmon, 1992) in order to establish the age of some cave processes using alpha spectrometers BR-024-450-100 ORTEC OCTETE PLUS at the Institute of Earth Sciences Jaume Almera (ICTJA-CSIC). The chemical separation of the radioisotopes and purification followed the procedure described by Bischoff et al. (1988). The isotope electrodeposition was carried out using the method described by Talvitie (1972) and modified by Hallstadius (1984). Age calculations were based on the computer program by Rosenbauer (1991). While four samples allowed us to obtain reliable radiometric ages two speleothems could not be dated due to the high amount of siliciclastic insoluble residue (4.29 and 14.80 % wt., respectively).

3.6 Geomorphological map of the study area

The geomorphological map of the study area was carried out in order to: a) define the geomorphological setting of the Torca La Texa shaft, b) establish the spatial relationships between the cave and the karst massif and c) determine the influence of the surface processes on cave evolution. The map covers an area of 42 km^2 and was realized at a 1/5,000 scale by photointerpretation, field work and GIS. The features were classified into karst, glacier, slope, torrential, lake and mixed forms following genetic criteria (López-Vicente et al., 2009). The designed map involved 518 deposits and closed depressions and 18 erosive features. The conduits from Torca La Texa and from other caves were also plotted on the map. The survey data from other caves explored in the area were provided by different caving groups.

3.7 Lithological and structural study

The geological setting of Torca La Texa and the determination of the influence of the structure and lithology on cave development were established through a detailed geological characterization. This study included a geological map and cross-section, as well as the application of the SpeleoDisc method (Ballesteros et al., 2014) to establish the structural control of the cave. The geological map covers an area of 42 km2 and was carried out considering the stratigraphic criteria established by Bahamonde et al. (2007). The geological units and structures of the bedrock were characterized by photointerpretation, 127 field lithological descriptions, 48 measures of bedding and 14 thin sections descriptions. The map was complemented by a geological section along the studied cave and plotting the survey polyline following the N50ºE direction. The application of the SpeleoDisc method involved the following steps (Ballesteros et al., 2014): 1) systematic collection of 296 measures in 80 field stations placed near the cave and with 50 m of distance separation between them, 2) definition of the families of discontinuities based on the plot of 344 joint and bedding measures in stereographic projection; 3) comparison of the families of discontinuities and conduits groups (section 3.3.2) in stereographic projection; and 4) calculation of the percentage of cave conduits controlled by each family of discontinuities.

4. RESULTS

4.1 Cave geometry

Figure 4 depicts the position of the Torca La Texa shaft and other cavities in the studied area and the 3D model of the cave, while Table 2 displays the values of the calculated morphometric parameters and indexes. Torca La Texa is formed by 2,653 m of conduits located from 1,305 m to 1,090 m a.s.l, showing a vertical range of 215 m. The cave area and volume are estimated in 5,858 m^2 and 62,191 m^3 respectively, being the passage density 0.20 m/m^2, the areal coverage 45.42% and the cave porosity 0.10%. The values of passage density and areal coverage are similar to the measures collected by Klimchouk (2006) in caves originated in confined hydraulic settings, in contrast with the values of the cave porosity, typical of cavities developed in unconfined saturated aquifers. The geometry of the cave is complex and comprises vertical, horizontal and inclined conduits, most of them being horizontal meandering passages (VI=0.08, HI=0.78, LI=0.24). The complex horizontal index (CHI) is 3.45, lower than the values of other big alpine caves (CHI between 10 and 20 according to Piccini, 2011b).

Three direction zones of the cave (Z1, Z2 and Z3) were established considering the direction of the conduits (Fig. 4B). The Z1 zone corresponds to the NW sector of the cave and it is mainly formed by conduits with N-S and W-E directions. The Z2 zone is located in the center of the cave and it is composed of shafts (pitches) and ramps with SE-NE direction, although NW-SE direction galleries are also present. The Z3 zone includes the SE sector of the cave and it is dominated by SW-NE and NE-SE directions. The passages of Z3 highlight a volume several times higher than the conduits from Z1 and Z2. The three zones present shafts, but most of them are situated in zone Z3.

Figures 5A and 5B depict the density map of the direction and inclinations of the cave passages, showing that they are mostly distributed within five groups. The directions of the conduits are scattered without a preferential value, and their inclination varies from 0^o to 90^o. Table 3 summarizes the main features of these five groups, including their relative abundances, values of directions and inclinations and their presence or absence in the three direction zones of the cave. The B group occupies the 41% of the cave length. A, B and E groups are recognized in all the direction zones, C group is only identified in Z1 zone and D group is present in Z2 and Z3 zones.

Figure 5C shows the projection of Torca La Texa following the SW-NE direction to analyze its vertical development and Figure 5D displays the vertical distribution of the conduits and asymmetry ratio values respect to the cave length. Figure 5D evidences the presence of four density peaks of conduits in altitude values (1,273, 1,258, 1,238 and 1,168 m a.s.l.) where the density of conduits is higher than other elevations. In these four altitudes, the conduits show elliptic to round sections since the asymmetry ratio (R) is close to 1. This fact is validated by field observations. Considering this information and its combination with information about phreatic and epiphreatic features described in section 4.3., we propose the definition of two cave levels: 1) the cave level 1 corresponds to the altitudes of 1,273, 1,258 and 1,238 m a.s.l., that are considered together because 20 m is not enough to separate independent cave levels (Palmer, 1987; Strasser et al., 2009); and 2) the cave level 2 is placed at the 1,168 m a.s.l. elevation. The average direction of the conduits of the cave levels is generally E-W and the inclination varies from 19 to 32º. Sometimes, the cave levels present up to 13 m of vertical range due to the presence of loops. The cave levels can be approximated by a plane that dips between 2º and 9º to the SW, evidencing the ancient direction of water flow.

4.2 Definition of base level

The base level of the Torca La Texa shaft was defined as the altitude of the karst spring related to the cave. The spring was identified by means of a dye-tracing test with Na fluorescein injected in the point shown in Figure 4B. The fluorimetry analyses of the detectors placed in the control points are shown in Figure 6, evidencing that the fluorescein was detected in Oyu La Madre spring between 4 and 168 h after the injection. Oyu La Madre spring is located at 835 m a.s.l., at 1.612 m to the NE of the injection point in the cave. These results allowed us to establish the base level of Torca La Texa at 835 m a.s.l., estimating a maximum thickness of 470 m for the vadose zone.

4.3 Cave geomorphology

Figure 7 shows the geomorphological map of the cave and Figure 8 depicts the main morpho-types of conduits documented. The most representative passages are displayed in Figures 9 and 10 together with the main geomorphological features. Since these representative passages were not at the same altitude, they were superimposed and plotted in the same place in the survey. The geomorphological map of the cave includes fluviokarst forms with phreatic, epiphreatic and vadose origin, breakdown deposits and speleothems (mainly dripstone and flowstone). 51% of the conduits length is formed by vadose canyons, 42% by cave levels, 5% by gravity-modified passages and 2% by *soutirage* conduits. 61% of the cave floor area is occupied by deposits (38% speleothems, 13 % alluvial sediments, and 10 % breakdown deposits). Speleothems are mainly formed by flowstone and, secondarily, dripstones (stalactites and few stalagmites), and few pool deposits (rimstone dams, pool spars and shelfstones); fluvial sediments includes slackwater, terrace and thalweg deposits; finally, breakdown deposits are mainly related with rock fall processes (Fig. 7). The characteristics of the conduits and their related forms (vadose canyons and shafts, cave levels, gravity-modified passages and *soutirage* conduits) are detailed below.

4.3.1 Vadose canyons and shafts

Vadose canyons are formed by B type conduits (section 4.1) up to 300 m long, 0.3 to 1 m wide and up to 20 m high, including sometimes shafts up to 100 m high (A type conduits) (Fig. 8A). Vadose canyons and shafts are dominated by erosive fluviokarst forms (dissolution grooves, scallops and few potholes), breakdown deposits and speleothems.

Dissolution grooves are found along the walls of shafts and canyons and can reach up to 15 m height and 0.6 m width. The grooves dip downwards the flow direction of the canyons, evidencing that the Migration Meander Vector (Farrant and Smart, 2011) is facedown.

4.3.2 Cave levels

Cave levels correspond mainly to the C, D and E conducts (Fig. 5B) type up to 250 m and having diameters ranging from 0.5 to 2.5 m. Figure 8B shows the two cave levels defined at 1,273-1,238 and 1,168 m a.s.l. from the morphometric analysis and cave survey (section 3.3.3.). The cross-sections mainly display elliptic to rounded shapes modified by vadose and breakdown processes.

Cave levels are mainly formed by phreatic and epiphreatic tubes with roof pendants and dissolution pockets in some places. Figure 8C depicts the position of the phreatic and epiphreatic tubes, which can be up to 40 m long and 2.4 m in diameter. Their sections are round to elliptic and are usually modified by fluvial incision. These tubes present scallops oriented towards either the SE or the SW of the cave. These conduits are occupied by speleothems (flowstones and dripstones), fluvial sediments (slackwater and terrace deposits) and breakdown deposits.

Figure 9A shows the geomorphological map of a part of cave level 1 (Andaricu Passage), representative of the main features of the cave levels of Torca La Texa. Flowstones are placed along the walls and floor of the conduits, reaching up to 1.7 m in thickness. Flowstones are composed of laminated carbonates involving quartz and clays, showing some hiatuses. Detrital components decrease from the bottom to the top of these speleothems. These carbonates precipitated directly on the bedrock conduits and only occasionally on top of fluvial or breakdown deposits. Stalactites, stalagmites and a few bell canopy flowstones are recognized on top of the flowstones, sometimes completely filling the conduit.

Slackwater deposits are usually found at the cave levels and other conduits of the cave, covering more than 223 m^2 and being up to 2.8 m thick (Fig. 9). These deposits are formed by massive to laminated clays and silt originated by water-filling processes (Fig 9 B, C). The surface of the slackwater deposits can either depict erosive scarps related to water circulation or display flowstones, dripstones and fallen boulders. Sometimes, they can be affected by small debris flows and present interbedded flowstones that can be up to 6 cm thick (Fig. 9D).

Breakdown deposits appear locally at the intersection of the cave levels with the vadose canyons and shafts. Their thickness ranges from 0.2 to 0.5 m. These deposits are formed by debris to boulders fallen from the walls and roofs of the caves. In some cases, breakdown deposits can be recognized above terraces and slackwater deposits.

Fluvial terraces are rare deposits situated on the walls of the conduits, perched above the channel of cave streams. Most of them were not mapped due to their small extent and size, below the scale of the geomorphological map. Terraces are formed by less than 0.8 m thick deposits of pebbles and sand. The pebbles are usually composed of Paleozoic carbonates covered by a dark coating, while the sands include quartz and carbonate grains. Terrace deposits are interbedded with fallen rocks and are frequently covered by levels of flowstones 2 to 4 cm thick.

4.3.3 Gravity-modified passages

Gravity-modified passages (Fig. 8A) are conduits up to 110 m long, 20 m wide and 40 m high mainly originated by the strong modification of previous conduits (Figs. 7B and 9B). The geometry of these passages is usually irregular, showing E-W, N-S and NW-

SE directions and inclinations ranging from 20º to 65º. Gravity-modified passages are dominated by breakdown deposits, scarps related to the breakdown processes and, locally, speleothems. Breakdown deposits accumulate in some places more than 3 m of rock boulders centimeter to meter in size, including blocks reaching up to 4 m^3 of volume. Small flowstones and dripstones locally have formed upon these deposits.

4.3.4 *Soutirage* conduits

In this work, *soutirage* conduits are epiphreatic tubes that connect the ancient phreatic/epiphreatic passages and correspond to passages that represent the drainage of the waters of epiphreatic conduits towards the perennial phreatic tubes after flooding (Häuselmann et al., 2003; Audra et al., 2007). *Soutirage* conduits are constituted by B type conduits (N261ºE direction, 30º inclination) 9 to 18 m long and between 0.5 to 1 m in diameter (Fig. 8D). They are linear conduits with tubular geometry, without preferred directions and inclinations between 25º to 50º. *Soutirage* conduits frequently connect different the horizontal galleries of cave level 1. The junction between *soutirage* conduits and these galleries is usually located on the floor of the looped galleries. *Soutirage* conduits are evidenced by epiphreatic tubes and scallops, and, rarely, present breakdown deposits and small dripstones. Figure 10 shows *soutirage* conduits in a cave profile from a selected site of the center of Torca La Texa.

4.4 Speleothem ages

Figure 11 (A, B) depicts the geomorphological map of Topo Juan Passages (cave level 1, see location in Fig. 7), where speleothems were sampled for radiometric dating. A view of the passage is shown in Figure 11C and D. Four samples were taken from three flowstones and one pool deposit. The obtained calendar ages are displayed in Table 5. Although all the samples were contaminated with detrital material (mostly clays) the ages are robust enough to allow the establishment of a preliminary chronology of the main speleogenetic processes. TEX-01 (Figure 11C) and TEX-03 samples were taken in two laminated flowstones that cover fluvial terrace deposits. The top of this fluvial sequence was probably eroded before the precipitation of the speleothem. Their respective ages are 156 ± 12 ka BP and 181 ± 23 ka BP, and both represent the minimum age of the fluvial sedimentation at this level of the cave. TEX-02 (Fig. 11E) was collected from a pool deposit associated with a small paleolake placed to the SE of Topo Juan Passages. This pool deposit precipitated above a flowstone more than 1 m thick. Therefore, the age of TEX-02 (65.3 +/- 5 ka BP) is younger than the end of the growth of the big flowstones present in this part of the cave. TEX-04 was taken at the bottom of a laminated flowstone, precipitated over the bedrock and subsequently eroded. This sample is in isotopic equilibrium (^{230}Th/^{234}U = 1.00 +/- 0.05) and therefore its age is higher than 350,000 years. This result suggests that the formation of the conduit is prior to this age.

4.5 Geomorphology of the karst massif

The geomorphological characterization of the karst massif was established based on the geomorphological map of the studied area (Fig. 12). The massif presents karst, glacial, glaciokarst, slope, torrential and anthropic forms.

Alpine karst features occupy 69% of the studied area including karren, dolines, karst deposits and one border polje located to the NE of the map. The border polje is filled by approximately 60 m lacustrine, peat, karst, alluvial fan and other deposits; the onset of the lacustrine sequence took place at least around 43-45 ka BP ago (Jiménez-Sánchez and Farias, 2002; Moreno et al., 2012; Jiménez-Sánchez et al., 2013). Glacial activity is documented by till (10 % of the studied area), *arêtes*, horns, cirques and U-shaped valleys (9%) that are frequently overprinted by karst forms. Till occupies the central and NW part of the map and it includes boulders formed by autochthonous (limestone) and allochthonous (limestone, quartzite, shale, sandstone and igneous) rocks. Slope forms (11% of the map) were recognized in the whole study area including mainly talus (9% of the studied area), and rock fall deposits (1%), rock avalanches and mud flows (<1%). Glaciokarst forms are recognized to the SE of the geomorphological map, being mainly formed by closed depressions up to 700 m long and 300 m wide. These depressions are interpreted as modeled by karst, glacial, snow and slope processes (Smart, 1984; Alonso, 1998). Their sedimentary infill can reach 17 m in thickness, including till, rock fall, talus and karst deposits.

4.6 Structural control of the cave

The geological map and cross-section allowed us to establish the geological setting of the Torca La Texa shaft and its relationships with the bedrock lithology and structure (Fig. 13). The bedrock of the studied area is mainly formed by Carboniferous limestone of the Barcaliente, Valdeteja and Picos de Europa formations. Torca la Texa is developed on Valdeteja and Picos de Europa formations, formed by bioclastic to oolithic packstone to grainstone. This limestone is affected by a Carboniferous paleokarst similar to the one previously described in the Eastern Massif of Picos de Europa (Merino-Tomé et al., 2009b).

Torca La Texa is located between two overturned thrusts. These thrusts show NW-SE trending and 60º dip to the SW. Moreover, this structure is affected by other normal and inverse faults, with NW-SE, NE-SW and N-S trends and a high dip (more than 60º). According to the thrusts and bedding dip, two main sectors can be recognized. The first sector, composed of the central and southern parts of the studied area, is characterized by inverse thrusts dipping 35-75º to the SW. The second sector occupies the northern half of the studied area and is formed by thrusts dipping 60-90º to the North. The limit between both sectors is represented by the Enol thrust, which is an out-of-sequence thrust that puts the northern sector above the southern one (Fig. 13A). Torca La Texa is placed in the first sector, in a thrust sheet formed by Valdeteja and Picos de Europa formations (Fig. 13B). The cave is placed in the core of a smooth synclinal-antiform whose hinge is oriented N263ºE/41ºSE. The bedding of the northern limb of the fold is N174ºW/45ºSE and in the southern limb is N123ºE/55ºSE. The direction zones of the cave (Z1, Z2 and Z3) defined in section 4.1 are related to this fold. The Z2 zone corresponds to the position of the hinge zone, while the northern and southern limbs are respectively related to the Z1 and Z3 zones.

The structural control of the cave was defined by the SpeleoDisc method (Ballesteros et al., 2014), by comparing the stereographic projection of the family of discontinuities and the conduits groups defined in section 4.1. As a result, five families of discontinuities were defined: J1 (N120ºE/78ºSW) and J2 (N146ºE/52ºSW), both situated in the southern limb of the fold; J3 (N100ºE/59ºSW), J4 (N174ºE/45ºSE) and J5 (N78ºE/80ºS), only present in the northern limb. The geometric characteristics of the joints families are quite similar, with 10 to 50 cm of joint spacing and 5 cm to 1.5 m length. However, J1, J2 and J3 are usually more open and pervasive than other families of joints. Figure 14A displays the relationships between the families of discontinuities the hinge of the antiform and the conduit groups. The development of the A group of conduits is related to the J1 family in Z1 and Z3 zones and the intersection between J1 and J5 in the Z2 zone; B group is conditioned by the J1 and J2 families, their intersections, the bedding and the hinge of the fold; C group follows the trend of J5 family; D group is controlled by the J4 family, and E group is conditioned by J3 family and the bedding.

5. DISCUSSION

5.1 Speleogenetic model of Torca La Texa

The results presented in the previous sections allowed us to propose a speleogenetic model of the cave controlled by the geological structure and regional fluvial incision. The evolution of Torca La Texa began, at least, before the Middle Pleistocene, probably much older than 350 ka that took place during the uplift of the Cantabrian Mountain Range and Picos de Europa mountains. This uplift could have started before the Upper Cretaceous (Martín-González et al., 2011), producing the general drop of the base level and the creation of deep fluvial gorges as Cares Gorges and coevally the development of most caves of Picos de Europa.

The evolution model can be divided in four phases (Fig. 15). In each phase, canyons and shafts were developed in response to different stages of lowering of the base level. The four phases proposed for the cave evolution are:

Phase 1) Cave level 1 was developed involving phreatic and epiphreatic tubes from 1,273 to 1,238 m of current altitude (Fig. 15). At the same time, *soutirage* conduits are created connecting these tubes. The conduit growth and evolution was controlled by the bedding and all of the joint families. The sedimentation in the cave mainly consisted in fluvial deposits. Furthermore, flowstones precipitated between periods where the passages were partially to completely filled by water. As the TEX-04 age suggests (older than 350 ka BP), this cave level would have been originated, at least, during Middle Pleistocene.

Phases 2 and 3) During the phase 2, the water table dropped of 70 m and the cave level 2 developed in phreatic/epiphreatic conditions due to the control of both the bedding and the J3 joint family (see Fig. 11C). Later, the phase 3 took place with the lowering of the water table below 1,168 m a.s.l. allowing the evolution of cave level 2 in vadose conditions. During the phases 2 and 3, many flowstones were precipitated covering fluvial sediment in cave level 1, at least, from 181 ± 23 to 156 ± 12 ka BP.

Phase 4) The last phase would have taken place since 156 ka BP until present times (MIS6 to MIS1), including the Last Glacial Cycle (120-11.6 ka BP, Moreno et al., 2012). In the study area, glaciers covered the karst massif with glacial fronts descending until 1,030 m asl; the local glacial maximum took place around 43-38 ka BP (Moreno et al., 2010; Jiménez-Sánchez et al. 2013), when the glacial fronts began to retreat. During the phase 4, the water table descended to its current position, close to 835 m a.s.l. Many flowstones would have been precipitated at the beginning of this phase, probably before the Last Glacial Cycle. During the glaciation, glacial ice melting led to the water filling the cave, producing the sedimentation of slackwater deposits and creating small pools dammed by flowstone around 65 ± 6 ka BP. During the most recent times of this phase, new cave levels have probably developed below the position of Torca La Texa. The Bogavante Meander (deepest cave passage) was created following the fold axis, whereas Brañasotres doline originated at the surface (Fig. 13B). Finally, the landscape would have acquired its present morphology.

5.2 Structural control of the cave

The results of the geological study and the application of the SpeleoDisc method in Torca La Texa evidenced the influence of the geological structure on the cave evolution. The results clearly define the type of conduits that are controlled by the discontinuities and the hinge zone of the fold. The vadose canyons and shafts and the *soutirage* conduits are generally controlled by the J1, J2 and J5 families of discontinuities, the bedding and the fold hinge zone. The shafts (A group of conduits) are partially related to the core of the fold (Z2 direction zone of the cave) and are conditioned by J1 and J5 families. Nevertheless, shafts are also located in Z1 and Z3 zones, which are controlled by the J2 family in the latter case. The vadose meanders, mainly related to B group, are ruled by J1 and J2 families and the hinge zone, as the case of the Bogavante Meander, the deepest part of the cave, (Fig. 14F). The phreatic and epiphreatic conduits (C, D and E groups) follow the trend of the J3, J4 and J5 families and the bedding. However, the cave level 1 presents a horizontal gallery that crosses the hinge zone. This conduit, with a NW-SE trending, shows a change in its direction close to the hinge zone, displaying an ENE-WSW direction parallel to the axis plane. This fact can be explained by the fold development. During the folding, fractures parallel to the hinge plane would have been generated in the fold core, these fractures being included in the J5 joint family. These fractures can be related to mechanisms of tangential longitudinal strain produced during the folding, as the result of the extension of the external arc of the antiform (Fig. 16).

The relationships of the cave conduit groups, direction zones of the cavity, families of discontinuities and the fold are summarized in Table 6. This table evidences that the vertical conduits are mainly located in the Z1 zone, corresponding to the hinge zone of the fold. The galleries are developed in all the cave zones, showing different main directions of conduits in Z1 and Z3 zones. The main direction of Z1 zone is N-S, while the main direction of Z3 is NW-SE. Therefore, shafts are preferentially developed in the limits between cave zones with different directions. This pattern can be recognized in other caves from the Picos de Europa mountains, as Trave System (Bigot, 1989), Pozu Hultayu shaft (Mumford and Cooper, 1998) or Torca Teyera shaft (Ballesteros et al., 2011).

5.3 Comparison with speleogenetic models of other caves

The proposed speleogenetic model of Torca La Texa is comparable to other results obtained by previous authors in caves from Picos de Europa and other alpine karst regions.

In Picos de Europa, the proposed model corresponds to the second phase of the general model established by Fernández-Gibert et al. (2000), although the first stage of their model has not been recognized. In the second phase, all the caves of the mountain massif were developed as a result of the lowering of the base level. During this base level drop, several cave levels were developed, being afterwards intercepted by vadose shafts and canyons. The model of Torca La Texa can be partially correlated with other studies in the Eastern Massif of Picos de Europa, where several cave levels between 500 and 1,660 m a.s.l. were originated during, at least, the Middle Pleistocene during the incision of the fluvial network (Smart, 1984, 1986). The model of evolution of Torca Teyera (Ballesteros et al., 2011), established three cave levels located at 1,300, 800-900 and 615 m a.s.l. that were developed during the drop of the water table. Speleothems ages (238±47 ka, 185±19 ka and >300 ka BP) evidenced that the upper and middle levels of Torca Teyera were developed prior to the Middle Pleistocene. The upper level, placed at 1,300 a.s.l., can be correlated at a massif scale with the cave level 1 of Torca La Texa (1,273-1,238 m a.s.l.).

The evolution of Torca La Texa is similar to other alpine caves in the world, as the Austrian systems of Burgunderschacht and Sonnenleiter from the Totes Gebirgemassif (Plan et al., 2009), the Swiss caves of Bärenschacht, Fitzlischacht and Sieben Hengste-Hohgant (Häuselmann, 2002; Häuselmann et al., 2003; Filipponi et al., 2009), and the Italian shafts from Monte Corchia, Spluga della Preta and Piani Eterni (Piccini, 2011a; Sauro et al., 2012, 2013). These caves were developed in close relation to the geological structure of the bedrock and the continuous dropping of the base level during, at least, the Quaternary period. Nevertheless, many features of the setting and evolution of those caves are different, as the structure, neotectonic processes, the causes and rates of the drop of the base level, the effects of the glaciations, or the changes in groundwater flows. In these cavities, cave levels originated in phreatic conditions and, later, progressed under epiphreatic and vadose conditions. Most of these cave levels are perched above the water table and their minimum age ranges from many thousand to few millions of years (Audra et al., 2007). During the epiphreatic phase, previous phreatic conduits increased their size and *soutirage* conduits were formed connecting cave levels (Audra, 1994; Häuselmann, 2002). In the vadose phase, vadose shafts and canyons were carved entrenching, intercepting and modifying previous cave levels (Häuselmann et al., 2007; Plan et al., 2009; Piccini, 2011a; Sauro et al., 2012, 2013).

6. CONCLUSIONS

The results of this work evidence that a speleogenetic model of an alpine cave system can be elaborated using a multi-method approach. This multi-method approach combines the study of cave geometry and geomorphology, speleothem ages obtained by Uranium series method, geomorphology of the karst massif, spatial relations between the cavity and the landforms, and the structural control of the cave and the management of information in a GIS.

In Torca La Texa shaft, vadose canyons and shafts (A and B groups of conduits) are conditioned by the J1, J2 and J5 families of joints, the bedding and the fold hinge, while the cave levels (C, D and E groups of conduits) are controlled by the trending of the J3, J4 and J5 families of joints and the bedding. In the cave, the shafts are preferentially developed in the limits between cave zones with different directions.

The evolution model of Torca La Texa establishes that the cave began to be developed since, at least, the Middle Pleistocene in relation to the base-level incision. The drop of the base level produced the development of two cave levels of 1,273-1,238 and 1,168 m a.s.l. During the development of the upper levels, *soutirage* conduits were originated connecting phreatic tubes. Vadose canyons and shafts were a consequence of cave deepening and the interception of previous conduits. In each cave level, two stages of development have been identified: an initial stage dominated by phreatic and epiphreatic conditions, characterized by the sedimentation of slackwater deposits and some flowstones, and, finally, a later stage developed in vadose conditions, controlled by fluvial incision, rock fall and precipitation of flowstones and dripstones. Speleothem ages suggest that the cave level 1 originated prior to the Middle Pleistocene and that the fluvial sedimentation took place before 181 ± 23 ka and 156 ± 12 BP. Also, flowstones of this level would have been formed before 65 ± 6 ka BP.

The speleothem ages are older than the age of the retreat of the glaciers after the last local glacial maximum determined by previous works. Therefore, most of the cave was developed before the last glaciation, although part of the cave seems to have a recent evolution related to a doline.

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Figure captions

Fig. 1. Some of karst massifs with speleogenetic researches of alpine caves. Karst areas are designated by Ford and Williams (2007).

Fig. 2. A. Setting of Picos de Europa in the Cantabrian Mountain Range. B. Position of the Torca La Texa shaft in the context of Picos de Europa, showing also the location of the cross-section depicted in the Figure 3. C. Simplified geological setting of Picos de Europa (afer Merino-Tomé et al., 2013a, 2013b).

Fig. 3. Idealized cross-section of the Western Massif of Picos de Europa, showing the vertical and horizontal development of the caves and the position of the Torca La Texa shaft. Cave data are courtesy of Oxford University Cave Club, SIE CE Áliga and GE Polifemo.

Fig. 4. A. Studied area showing the position of Torca La Texa shaft and other caves (Laverty, 1976; Singleton and Laverty, 1979; SES CE Valencia, 1984; SIE, 1987; J. Alonso et al., 1997; GE Diañu Burlón and AD Cuasacas, 2013). B. Torca La Texa shaft plan projected on the aerial photograph. 3D model of the Torca La Texa shaft cave viewed from the SW (C) and from the NE (D).

Fig. 5. A. Density map of conduits directions and inclinations on stereographic projection. B. Groups of conduits defined from the previous density map. C. Cave SW-NE projection. D. Vertical distribution of the conduits (expressed in percentage of cave length) and their asymmetry ratio vs absolute altitude.

Fig. 6. A. Results of the dye-tracing provided by the fluorimeter. The intensity of the Oyu La Madre samples collected 4, 24 and 168 h after the injection is higher than the samples from other control points. B. Oyu La Madre spring during the high water stage (courtesy of S. González-Lemos).

Fig. 7. Simplified cave geomorphological map (A) and pictures from representative features (B, C, D). The maps from the Andaricu and Topo Juan passages are shown in Figures 9 and 11. Picture from C is courtesy of S. Ferreras.

Fig. 8. Plan view of the cave showing: A. Cave conduits classified according to their origin. B Position of the two cave levels. C Projection of the phreatic and epiphreatic tubes on the cave survey. D Position of the soutirage conduits.

Fig. 9. A. Simplified geomorphological map of the lowest part of cave level 1 (Andaricu Passages), whose position is depicted in Figure 7. B. Selected site showing a 2.3 m thick slackwater deposit. C. Slackwater deposit located at the bottom of a phreatic/epiphreatic tube. D. Stratigraphic section from of deposit shown in C.

Fig. 10. NW-SE profile view of a selected part of Torca La Texa shaft (see location in Figure 8D), showing the vadose, phreatic and epiphreatic features. Soutirage conduits are highlighted connecting phreatic and epiphreatic passages located between 1,273 and 1,238 m altitude.

Fig. 11. A, B Geomorphological map of the Topo Juan Passages (cave level 1) showing pictures from a selected passage with a phreatic/epiphreatic tube, flowstone and slackwater deposits (11C, D, E) and the speleothem ages obtained by 234U/230Th dating.

Fig. 12. A Panoramic view of the studied cave surroundings. The cave entrance is close to the top of a small mountain covered by till. B Simplified geomorphologic map of the cave surroundings (the represented deposits occupy more than 800 m2). The projection of the conduits from Torca La Texa shaft is shown in the center of the map. The figure

also includes the projection of other caves provided by speleologists (Laverty, 1976; Singleton and Laverty, 1979; SES CE Valencia, 1984; SIE, 1987; Alonso et al., 1997).

Fig. 13. A. Simplified geological map of the studied area. B. Geological cross-section parallel to the fold axis in the cave location, showing the relationships between the discontinuities and cave development.

Fig. 14. A Comparison between conduit groups (A, B, C, D, E) and families of discontinuities (J1, J2, J3, J4, J5) on stereographic projection. B Conduit geometry controlled by two families of joints (J1 and J3) and the bedding (S0) from the South limb of the fold.

Fig. 15. Speleogenetic model of Torca La Texa, showing the evolution phases described in the text. Phase 1. Development of cave level 1 and *soutirage* conduits between 1,273 and 1,238 m a.s.l (before 350 ka). Phase 2. Lowering of the water table (1,168 m) and possible development of cave level 2. Phase 3. Lowering of the water table under 1,168 m. Phase 4. Development of new vadose passages since 156 ka BP and related to two dolines in surface.

Fig. 16. Joints family J5 related to the fold geometry plotted on the cave plan projection. J5 could be created by tangential longitudinal strain produced during the folding.