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SpeleoDisc: A 3-D quantitative approach to define the structural control of endokarst
An application to deep cave systems from the Picos de Europa, Spain

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ABSTRACT

The influence of geological structure on endokarst can be studied by establishing the relationships between discontinuities (faults, joints and bedding) with a cave survey. The cave survey elaborated by speleologists represents the directions and inclinations of the cave conduits and can be compared to the strike and dip of the discontinuities of a karst massif. This paper proposes a methodology, the SpeleoDisc method, which is effective in defining the structural control of the endokarst. The method has been designed and applied in a pilot area from the alpine karst massif of the Picos de Europa, where long and deep cave systems are well developed, including more than 360 km of conduits in its entirety. The method is based on the projection of cave surveys on geological maps and cross-sections and the comparison between the direction and inclination of the cave survey data and the geometry of the massif discontinuities in three spatial dimensions (3-D). The SpeleoDisc method includes: 1) collection and management of topographic information; 2) collection and management of cave data; 3) definition of the groups of conduits; 4) elaboration of geological maps and cross-sections; 5) collection of discontinuity data (bedding, faults and joints); 6) definition of groups of discontinuities; and 7) comparison between the cave conduit groups and the families of discontinuities. The SpeleoDisc method allows us define the influence of the major and minor structures on the caves geometry, estimating percentage of caves forced by each group of massif discontinuities and their intersections in 3-D. Nevertheless, the SpeleoDisc approach is mainly controlled by 1) the amount and quality of the cave survey data and 2) the abundance of cave deposits covering the conduit, which can mask the original geometry.

1. Previous research on structural control in caves

The morphologic features of endokarst, particularly the spatial distribution of cave conduits, are commonly controlled by the structure of the bedrock. Discontinuities (joints, faults, bedding and foliation) control the preferential pathways of underground water in karst areas (Klimchouk and Ford, 2000; Audra and Palmer, 2013). The influence of structure on the endokarst can be studied considering the geometry of the caves and/or the groundwater flow paths (Kazemi et al., 2009; Goldscheider and Neukum, 2010). Previous works established the influence of the geological structure on the cave geomorphology and development, although the structural control is not usually the main aim of the research (e.g. Pasini, 2012; Tisato et al., 2012). Those works compare the shape, direction and position of the cave passages with the location, direction and dip of the discontinuities by combining two or more of the following techniques:

1) Evidence from photo-documentation. Photographs taken in the cave or from outcrops of relict caves provide clues on the influence of discontinuities on the geometry of the passages (Knez, 1998; Audra, 2001; Baroň, 2002; Ruggieri and Biswas, 2011). The reader should interpret the photographs, though sometimes the photographs are annotated showing the position, direction and dip of several discontinuities to highlight the relationships between the morphology of cave passages and specific discontinuities (e.g. Martini et al., 2004; Bodenhamer, 2007; Lundberg and McFarlane, 2012). The photographs depict local field evidence at a cave passage scale, and are commonly aimed at complementing the results provided by other techniques (Skoglund and Lauritzen, 2010; Kassa et al., 2012).
2) Cave survey and sections. The cave survey represents the projection of the accessible conduits on a plan. The strike and dip of discontinuities and fold axes are usually depicted on the cave survey, passage sections, or cave profiles to illustrate the influence

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of the structure on the geometry and spatial distribution of the cave passages. This method is the most commonly used to establish the structural control of caves (Häuselmann et al., 1999; Šebela et al., 1999; Armstrong and Osborne, 2001; Audra et al., 2002; Hajna, 2004; Martini et al., 2004; Jiménez-Sánchez et al., 2006; Bodenhamer, 2007; Alonso-Zarza et al., 2010; Ruggieri and Biswas, 2011; Skoglund and Lauritzen, 2011; Lundberg and McFarlane, 2012; Pasini, 2012; Sauro et al., 2012; Tisato et al., 2012). The cave surveys highlight visually the influence of specific faults, joint families and bedding planes with particular attitude and geometry on the cave system at different scales. In some tectonically active areas, offset caves may be used to identify and quantify displacement on active faults (Becker et al., 2006 and references therein). The structural control using the cave surveys is a qualitative technique that considers only two spatial dimensions (2-D). Nevertheless, three dimensional understanding can be reached by combining the cave plan view with transverse and/or longitudinal sections (Jaillet et al., 2011).

3) Segment analyses. The cave is divided into segments according to the geometry and morphology, establishing the structural control of each segment individually based on field evidence (Jameson, 1985). This approach evaluates the influence of structure on the direction, inclination, shape and genesis of the cavity in three spatial dimensions (3-D) from a passage scale to the scale of the entire cave system (Jameson, 2006). It provides accurate information from field data, but a great effort is needed for their collection.
4) Geological maps. Cave surveys are occasionally projected on geological maps to relate the structure of the bedrock with the cave entrance or with the direction of cave conduits (Miller, 2004; Koša and Hunt, 2006; Piccini, 2011a,b). The geological maps show that the directions of some conduits are guided by specific faults or lithological contacts, or are parallel to sets of faults characterized by a particular strike, type or age (Menichetti, 2001; Hung et al., 2007). Sometimes, the maps depict together the inclination of the cave passages and the attitude of bedding, joints or foliation, and can be taken as a basis to relate cave entrances with fractures or with contacts between limestone and impermeable rocks (Doctor et al., 2008; Parise, 2011). Rarely, geological maps, combined with other structural data, are used to link the cave development with the directions of the main stress field or with extensional or transpressional structures (Čar and Zagoda, 2005; Sauro et al., 2013). The structural control established by plotting the cave survey on a geological map is carried out from a cave scale to a massif scale, but only in 2-D. Nevertheless, the cave survey can be projected on the geological cross-sections in order to consider the z dimension, showing the relationships between the inclination of the cave passages and the structural features (Piccini, 2011a; Tisato et al., 2012).
5) Rose diagrams. The strike of fractures and cave passages can be classified and represented in rose diagrams using intervals of 5 to 20°, displaying the relative frequency of each interval (Plan et al., 2010; Skoglund and Lauritzen, 2010; Piccini, 2011a,b). The rose diagram of the discontinuities may be produced with data of discontinuities mapped by photointerpretation (Florea et al., 2002), remote sensing (Kassa et al., 2012) or field work (Šebela et al., 1999; Sauro et al., 2012). The rose diagram of the cave passages is constructed with the directions of the survey shots (Koša and Hunt, 2006) and frequently the rose diagram of the passage directions is provided directly by the survey software (p.e. Fish, 2001; David, 2009). In many cases, the percentage of each interval of directions is calculated. These diagrams are compared to link the main azimuths of the fractures with the directions of the cave passages at the cave scale, or by conduits classified according to their altitude (Plan et al., 2010).
6) Stereographic projection. Occasionally, the massif discontinuities measured in the field work can be statistically classified according with their strike and dip by stereographic projection, in order to characterize the geometry of the structures that control the cave morphology (Baroň, 2002; Plan et al., 2010; Skoglund and Lauritzen, 2010, 2011). These projections are visually compared to the cave survey to establish the influence of the structural factor on the direction and inclination of the cave conduits in 3-D, from a passage to a cave scale. The strike and dip of the discontinuities are considered jointly during the analyses.
7) The angle between the bedding and the conduit inclination. The use of the angle between the dip of the bedding and the inclination of the cave conduits was proposed by Filipponi et al. (2009) to analyze the influence of the stratigraphy on the vertical distribution of cave levels. The dip of the bedding is measured by field work or from geological cross-sections, and the inclination of the cave passages is taken from the survey shots. The cave conduits are classified according to the value of the angle, which reach values near zero when the conduit is guided by the bedding (Plan et al., 2009).
8) Fractal analyses on caves. The number, length, vertical range, sinuosity and other parameters of cavities can be studied by fractal analyses to establish geometrical patterns. The results of fractal analyses can be compared to the presence or absence of faults, or the distance of caves to the faults, showing, for example, that caves located in the vicinity of faults are more frequent and shorter than those situated at greater distance (Kusumyudha et al., 2000; Verbovšek, 2007).
9) The distance between fractures or lineaments to the cave. The distance between fractures or others lineaments and the cave can be analyzed to establish the influence of major structures. In this case, fractures and other lineaments are mapped by aerial photointerpretation and other remote sensing techniques. The results of this kind of approach show that the abundance of caves is related to the presence and orientation of the lineaments (Hung et al., 2007).
10) Karst models. The structural influence on karst conduits can be considered in computer models of the geometry and evolution of caves and karst aquifers (Kaufmann and Braun, 2000; Gabrovšek et al., 2004; Kaufmann, 2009). The massif discontinuities (mainly joints and bedding) together with properties such as strike, nature, density and opening, are introduced into the models under different conditions. Hydraulic conditions, discretization ranges and the geometry of conduits are usually selected (see Kovács and Sauter, 2007). The resulting models evaluate quantitatively the influence of joint sets and bedding on the position and geometry (connectivity and looping) of the cave conduits, evidencing, for example, that the presence of vertical faults favors the development of a cave with multiple loops (Kaufmann and Romanov, 2008).

2. Aims and motivation

Cave surveys made by speleologists during their explorations characterize the geometry of the cavities by means of a 3-D survey line formed by a set of straight lines (survey shots) and vertexes located at the survey stations (Jeannin et al., 2007; Jaillet et al., 2011; Piccini, 2011b). The survey shots are defined by one set of polar coordinates comprising the length, the direction and the inclination between two successive survey stations. The survey shots are representative of the geometry of the cavities in 3-D (Klimchouk, 2006; Pardo-Iguzquiza et al., 2011). Consequently, the polar coordinates of the survey shots can be statistically analyzed and compared to the geological, geomorphological and hydrogeological data in a Geographical Information System, in order to establish the influence of the lithology, geological structure, groundwater flow and surficial process on karst evolution (Ballesteros et al., 2011). Therefore, the structural factor can be evaluated by comparing the cave survey data and the massif discontinuities in 3-D. Stereographic projection is a useful technique commonly used in structural geology that allows us to represent and statistically analyze lines and planes according their directions and dips (see Howarth, 1996).

The aim of this paper is to propose the "SpeleoDisc" method as a useful means for evaluating quantitatively the influence of the structural factor on the direction and inclination of cave conduits by analyzing the statistical relationship between spatial cave and structural data. The structural control is addressed considering three operational scales: the massif scale (the area of study scale), the cave scale (few kilometers) and the cave conduit or passage scale (few meters to hundreds of meters). The methodology has been designed and applied to 12.3 km of cave conduits that reach 738 m in depth developed in a 3-D pilot area from a large alpine karst.

3. Setting

The study area is located in the Picos de Europa (north Spain) at coordinates 43° 11.86′ N, 4° 50.36′ W (Fig. 1). The Picos de Europa is a mountainous massif situated at the central area of the Cantabrian Mountains, 15 km south of the Cantabrian Sea. The Picos de Europa shows a rough relief with 700 km^2 of extension and includes more than 30 peaks higher than 2500 m altitude. The landscape is divided by narrow canyons up to 1500 m in depth as the Cares, Los Beyos or La Hermida gorges, carved by the Cares, Sella and Deva rivers that flow from south to north. From a geological point of view, the area is located in the Cantabrian Zone, a fold-and-thrust belt of the Variscan domain characterized by many nappes involving Paleozoic bedrock (Alonso et al., 2009). The massif is mainly formed by more than 1200 m thickness of calcareous series of Carboniferous age, although Ordovician Quartzite is also cropping out in the northern part of the massif (Merino-Tomé et al., 2009a). The calcareous series includes the Barcaliente Formation (Serpukhovian dark laminated limestone), the Valdeteja Formation (Bashkirian breccia and boundstone) and the Picos de Europa Formation (Moscovian to Kasimovian breccias, boundstone, grain-coarse and skeletal limestone and shale). Considered as a whole, the Valdeteja and Picos de Europa formations are divided in three strata domains: a) strata domain of the toe of slope and basin, formed by breccia, grain-supported limestone, chert and shale; b) strata domain of the slope, involving massive limestone, breccia and boundstone; and c) strata domain of the platform top, with well-stratified and grain-supported limestone (Bahamonde et al., 2007). The bedrock is affected by a complex and imbricate thrust system and other faults (Merino-Tomé et al., 2009a). The thrusts show an E–W to NW–SE strike with dips ranging from 30 to 90° to the N, being overturned in the N and NW of the Picos de Europa. The detachment level of the thrust system usually dips 30 to 45° to the N and is located above the Carboniferous sandstone and shale that crop out to the S of the massif. The other faults frequently display NW–SE, NE–SW and N–S strikes with dips ranging from 30 to 90°. Most of the geological structures are Carboniferous in age, and were generated during the Variscan Orogeny. Nevertheless, some of them could be originated or reactivated during the Permian–Mesozoic extensional phase, and during the Alpine Orogeny, when the uplifting of the Cantabrian Mountains took place (Alonso et al., 1996).

The landscape of the Picos de Europa is a karst with alpine morphology classified as Pyrenean type (according to Ford and Williams, 2007) and molded by fluvial, gravity, snow, glacial and periglacial processes, already described by several authors (e.g. Fernández-Gibert et al., 2000; Ruiz-Fernández et al., 2009). The karst evolution began in the Carboniferous Period, since Carboniferous–Permian paleokarst formed by coarse-grain fill, laterites and bauxites (Merino-Tomé et al., 2009b). At least during the Quaternary, polyphase cave systems were developed by the drop of the general base level and subsequent incision while the massif was covered by glaciers several times (Smart, 1984; Fernández-Gibert et al., 2000; Ballesteros et al., 2011). Glacial action overprinted previous karst features and generated a glaciokarst characterized by closed depressions with up to 2 km long (Smart, 1984). Although the geomorphological relationships between glacier evolution and speleogenesis are not well known, it has been suggested that waters from melting glaciers were concentrated into certain sinkpoints, contributing to the genesis of shafts in these places (Smart, 1986; Senior, 1987). Glaciers occupied the area at least two times: the oldest one was prior to 276–394 ka (Alonso et al., 1996, 2013), while the younger glaciation reached its local maximum prior to 36–43 ka (Moreno et al., 2010; Serrano et al., 2012; Jiménez-Sánchez et al., 2013). Nowadays,

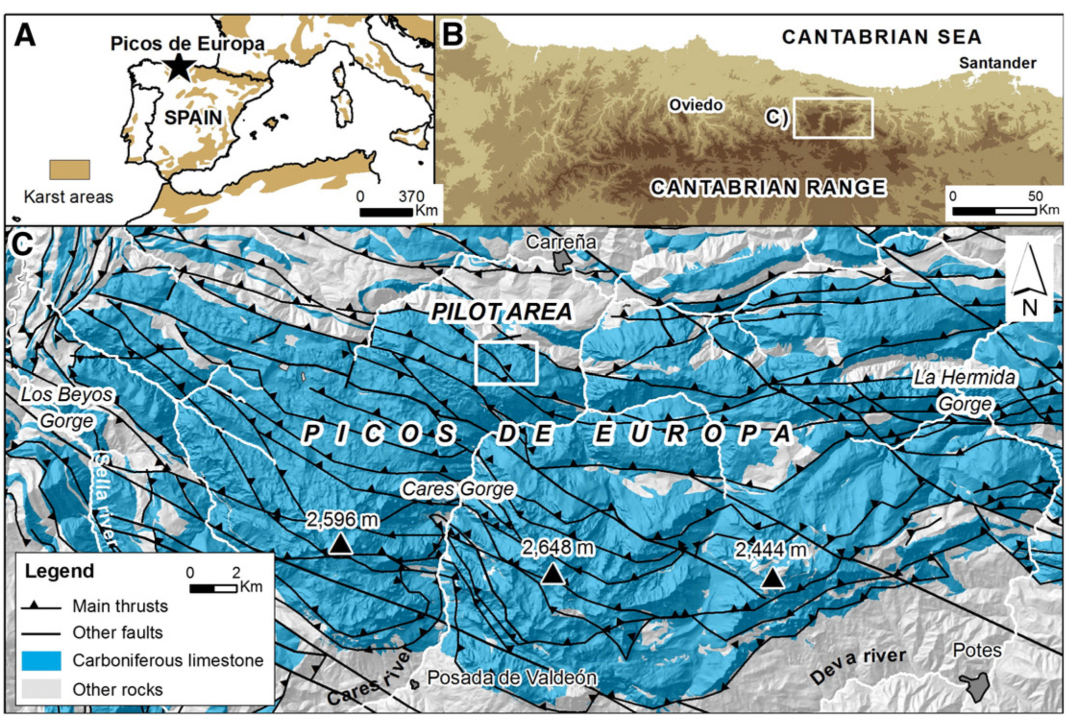

Fig. 1. A) Karst areas of Southern Europe and location of the Picos de Europa mountains (karst areas distribution is based on Ford and Williams, 2007); B) Cantabrian Range (N Spain) and location of Picos de Europa; C) Geological map of the pilot area, showing the spatial distribution of the Carboniferous limestone outcrops and the main geological structures, consisting of a thrust system and other faults (after Merino-Tomé et al., 2011, 2013).

glaciokarstic features are modified by subsequent snow, gravity and dissolution processes, which also contribute to the development of dolines, karren, cave conduits and poljes (Alonso, 1998; Jiménez-Sánchez and Farias, 2002; Ballesteros et al., 2011). The Picos de Europa is known by the presence of deep karst systems, including 14% of the caves deeper than 1 km known in the World. More than 360 km of cave passages are documented by cavers, and every year 4 to 10 km of new conduits are discovered (Estévez, 2011; Marang et al., 2011). The Picos de Europa

Fig. 2. A. Panoramic view of the pilot area from the west, showing the position of the entrances of six of the studied cavities. Some examples of geomorphological features from Torca Teyera shaft: B and C show phreatic and epiphreatic tubes modified by fluvial incision (located at 850 m a.s.l.). D. Narrow vadose canyons carved by a permanent stream. E. 14 m shaft with a lake located at its bottom (765 m a.s.l.).

includes caves with dimensions ranging from few meters to up to 19 km in length and up to 1589 m in depth (Margaliano et al., 1998; Puch, 1998). The cavities are often formed by vadose shafts and canyons and phreatic and epiphreatic conduits. The phreatic and epiphreatic conduits are organized in more than 17 cave levels perched up to 1100 m above the current water table during the low water stage (Senior, 1987; Bigot, 1989; Fernández-Gibert et al., 2000; Ballesteros et al., 2011). The evolution of the caves is conditioned by the superposition of dissolution processes, underground fluvial sedimentation, speleothem precipitation and rock fall action. The age of several speleothems from the cave levels placed at 800 to 1300 m exceeds the lower limit of the U–Th dating method; this is consistent with an origin of cave levels prior to Upper Pleistocene times (Smart, 1984; Ballesteros et al., 2012).

The study area chosen as a pilot zone to design the SpeleoDisc method is located to the north of the Cabeza Llerosos peak, to the NW of the Picos de Europa (Figs. 1, 2A). It has been defined as a 3-D target block of the karst massif that contains the caves used for this study. The upper limit of the block is defined by the landscape surface, with altitudes ranging from 1000 m to 1700 m, whose projection in plan-view defines a rectangle of 2.6 km × 1.7 km (4.42 km^2). The lowest limit of the pilot area is represented by an imaginary plan section situated at the position of the lowest cave passage (597 m a.s.l.), located at 738 m depth from the entrance of the cave. The target block includes 133 caves documented by caving reports with a total length of 15.2 km. The caves are shafts with lengths up to 4.4 km and their vertical ranges vary from 2 to 738 m. The cavities (Fig. 2B–E) were originated prior to 300 ka and cut three perched levels represented by looped phreatic and epiphreatic galleries located at 1300, 800–900 and 615 m a.s.l. (Borreguero, 1986; Ballesteros et al., 2011, 2012).

4. Materials and methods

The methodology of work is summarized in Fig. 3 and includes the following steps: 1) collection and management of previous data; 2) definition of groups of cave conduits; 3) elaboration of geological maps and cross-sections; 4) definition of families of discontinuities; 5) projection of caves on maps and cross-sections; and 6) comparison between cave groups and discontinuities. In this work, the terms strike and dip are used to describe the geological discontinuities; the words strike and plunge are utilized to detail the intersection of the discontinuities; and

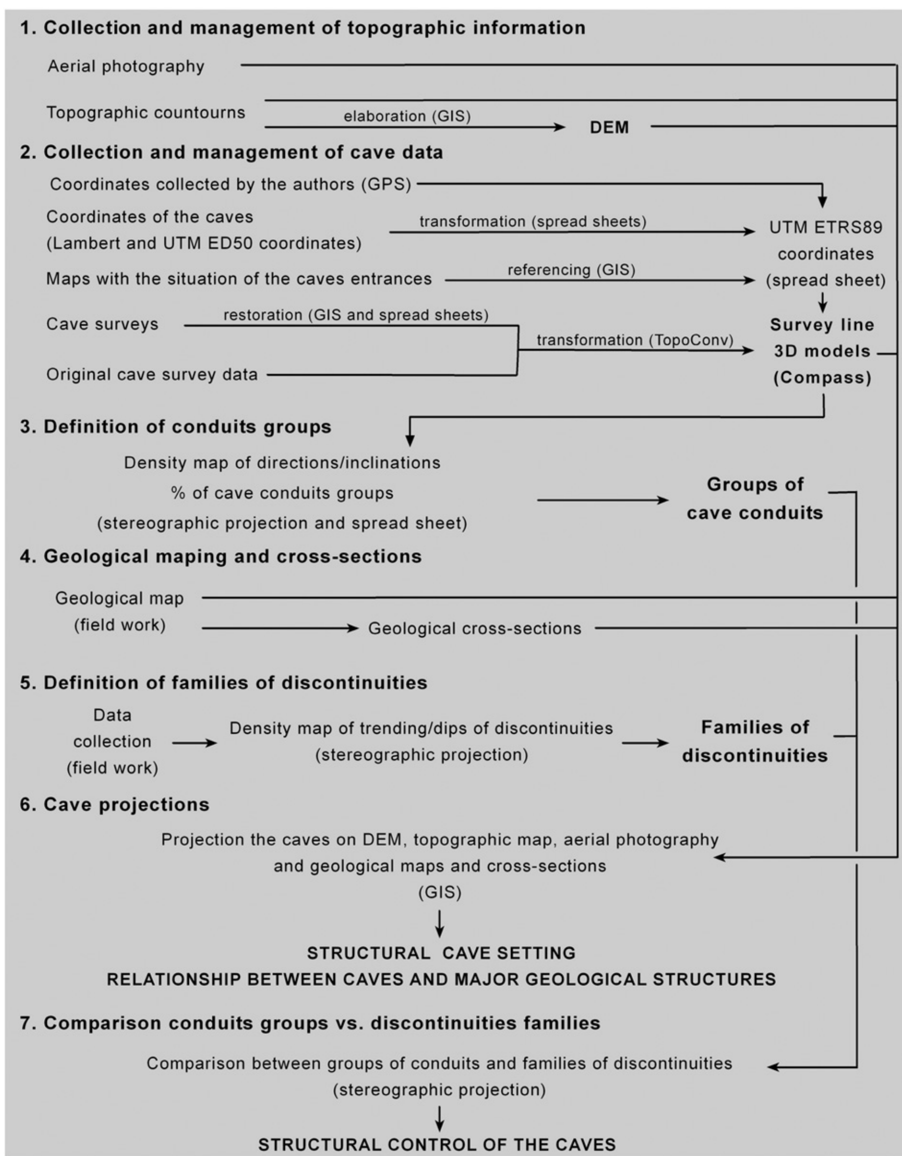

Fig. 3. Flow diagram of the SpeleoDisc method, showing the methodological steps and procedures of each stage of work and the relationships between them.

the terms direction and inclination are used to define the cave conduits (or cave passages).

4.1. Collection and management topographic information

The topographic information is collected to elaborate the topographic base of the work in a Geographic Information System (GIS) where all the geological and cave data are plotted (Ohms and Reece, 2002; Kershaw, 2012), and is used also to build the Digital Elevation Model and to calculate the volume of the 3-D block of the pilot area. The topographic information was provided by the National Centre of Geographic Information of Spain (CNIG) and includes the SHP files with the topographic contours (each 10 m altitude) and the ECW file with the aerial photography of 0.25 m resolution. The Digital Elevation Model (DEM) of the pilot area has been performed in a GRID file from the topographical contours data using GIS tools, showing a resolution of 25 m. As previously said, the block of study is the portion of karst massif enclosed between the topographic surface and the horizontal plane located at the altitude of the lowest conduit of the caves, located at 597 m a.s.l. The volume of the block is calculated cutting the DEM by the boundaries of the target area and subtracting the altitude of the horizontal plane placed at the lower cave passage from the cut DEM.

4.2. Collection and management of cave data

This section includes the collection of the cave data from the speleological documentation in order to elaborate a database of the coordinates of cave entrances and cave survey data. This base data allows us to select the caves to which we apply the SpeleoDisc method and to calculate five morphometric parameters of the cavities. The cave data were collected from five unpublished caving reports (Borreguero, 1986; Groupe de Spèlèologie de Dubois, 1988, 1989; Carbajal Rodríguez and Saiz Barreda, 2003; Carbajal et al., 2008) and seven articles published in speleological magazines (Borreguero and Perotti, 1981; Rossi, 1984; Schaerrer, 1988; Corbaz et al., 1990; Grauer, 1993; Tissot and Laurent, 1999; Ballesteros et al., 2010). These works include almost 50 cavities explored since 1978 to the present, showing frequently the position of the cave entrances by means of topographic maps with the UTM coordinates. The speleological documentation includes 42 surveys of cavities with 15.2 km of cave passages. The coordinates of the cavities are collected in three ways: 1) projecting the old coordinates included in the caving reports to the ETRS89 reference system; 2) referencing the topographic maps to the projection of the cave entrances; and 3) using a GPS to collect the coordinates in four cases. The cave survey data were either collected directly from 25 files that include the original data collected by the cavers in Visual Topo software (David, 2009) or carried out by means of the restoration of the survey line. The restoration of the survey line is performed from the previous surveys placing the referenced cave plan-view and profile in GIS and calculating the Cartesian coordinates (XYZ) of comparable points of the same map and profile. Afterward, the XYZ coordinates are transmuted to polar coordinates by trigonometric relations. The cave survey data were formed by 1226 sets of polar coordinates that contain the distance, direction and inclination between survey stations and the dimensions (widths and heights) at each station. Distances and station dimensions are 0.3 to 120 m, the direction varies in 0 to 360° respect to the magnetic north and the inclination ranges from 90° to −90°. Positive or negative dipping values indicate ascending or descending passages respectively, according to the direction of the surveying.

Only the major caves containing most of the conduits are considered by the SpeleoDisc approach, since 20% of the caves contain approximately the 80% of the conduits. Thus, the objective is to consider the highest percentage of the cave conduits choosing a small number of cavities. The best criterion to select the caves is to measure their length because it is the most common parameter for defining their morphometry (Klimchouk, 2006). The minimum value of the length to consider a cave in the SpeleoDisc is defined as the 1% of the whole of the known caves of the studied area. In the case of study, this value is 152 m, so only thirteen cavities have been considered. These caves include 12,283 m of cave conduits that represent the 81% of the whole of the known caves of the studied area (Table 1).

The cave survey data are managed using Compass software in order to build the survey line and the 3-D model of the cavities in UTM referenced space (Fish, 2001). Vtopo and text files containing respectively the original and the restored survey data are transformed to Compass files by TopoConv software (De Bie, 2008). The 3-D modeling is undertaken considering each survey shot as an octagonal prism whose axis is defined by the polar coordinates of the shot (Fish, 2001). The sections of these prisms are arranged in vertical position in each survey station considering the dimension data taken at each survey station. The links between the different prisms are smoothed, rounding the corner and contours of the prism by an algorithm that transforms each corner into four smaller corners. Then, two SHP files containing the survey line and the 3-D model of the caves are exported to GIS to combine cave data with the topographic and geological information.

In order to define the cave geometry, five morphometric parameters are calculated based on the survey line and the 3-D models by using Compass. Four of these parameters are calculated according to the definition proposed by Klimchouk (2006) and Piccini (2011b). These parameters are: the length of the cave (the sum of the total of survey shots in each cave), the vertical range of the cave (altitude difference between the highest and lowest passage of each cave), the surface of the cave (area occupied by the cave floor on the plan projection of the 3-D model), and the volume of the cave (volume enclosed into the prisms of the 3-D model). The fifth parameter is the percentage of the endokarst occupied by the known caves; this parameter is defined in this work as the percentage of the volume of all of the caves respect to the volume of the 3-D block of study.

4.3. Definition of groups of cave conduits

Cavity passages were classified in several groups according to their direction and inclination, statistically analyzing the length, direction and inclination of each survey shot. Statistical analysis is carried out using a density map plotted on stereographic projection. The density map is made by the von Mises–Fisher probability distribution (Tanabe et al., 2007), characterized by a spherical concentration. The map includes fourteen contours which range from 2 to 26% of the length of the entire caves. The stereographic projection is managed by the Dips software, representing the data in an equal area in the lower hemisphere of the stereographic projection.

The input data includes 12,283 sets of polar coordinates (Section 4.1). The cave can be surveyed by two ways: from the entrance of the cave to the deepest passages or from the bottom of the cave to the entrance. Depending on which way is considered, the direction will be an angle or its inverse, and the inclination will be positive or negative. Thus, in *cave surveying*, the direction of the survey shot is taken following its inclination up (positive plunging) or down (negative plunging). To solve this ambiguity, the cave survey data are homogenized according to the criteria used in geological investigations: the strike of a line is always measured by geologists following its plunge. The homogenization of the cave survey includes the transformation of the direction and inclination of the survey shots when the inclinations are positive. The directions are transformed adding or subtracting 180° in order to have all of the directions of the survey following the plunge, and the inclination is converted to negative. The values of the direction and inclination of each shot are plotted once for every meter of the shot distance on stereographic projections. For example, if the length, direction and inclination of a shot are respectively 12.3 m, 225° and −56°, the values "225" of the direction and "56" of the inclination are plotted together twelve times.

Table 1
Relation of the caves considered to establish the structural control by SpeleoDisc method.

Studied caves	Length (m)	Vertical range (m)	Percentage of the considered cavities (%)	References
Torca de Canal Mala	226	164	1.84	Carbajal Rodríguez and Saiz Barreda (2003)
LC-5	291	233	2.37	Carbajal Rodríguez and Saiz Barreda (2003)
Torca del Llobu	292	201	2.38	Carbajal et al. (2008)
Torca Mosquita Lago	355	165	2.89	Borreguero (1986)
Cuetón Cave	459	82	3.74	Carbajal Rodríguez and Saiz Barreda (2003)
Sima E	511	130	4.16	Tissot and Laurent (1999)
Torca del Zapo	544	230	4.43	Borreguero (1986)
Torca de las Campánulas	631	215	5.14	Groupe de Spèlèologie de Dubois (1989)
Torca del Camino	760	406	6.19	Tissot and Laurent (1999)
Bocón de las Ancolías	875	246	7.12	Borreguero (1986)
El Frailín	1084	380	8.83	Tissot and Laurent (1999)
Torca Llerosa	1817	686	14.79	Borreguero (1986)
Torca Teyera	4438	738	36.13	Ballesteros et al. (2010)
Total	12,283		100.00	

The classification of the cave conduits is done based on the density map, defining each group of conduits in the areas of the map where the density is higher than 4% of the whole of the cavities. Each group is defined by an average line and a range of variability. The average line is characterized by the direction and inclination related to the maximum value of the density map; the range of variability is delimited by the area of the map with similar values of direction and inclination. The survey shots are grouped according to the defined groups to calculate the abundance of each group of conduits as a percentage. The length of the conduits of each group is calculated summing the survey shots included in each group and their percentages are calculated with respect to the entire population of considered cavities.

4.4. Geological mapping and cross-sections

The geological map of the target area was carried out at a 1:5000 scale by means of field work and photointerpretation. The bedrock lithology was mapped and classified according to the stratigraphical criteria established by Bahamonde et al. (2007). 25 measures of the strike and dip of the bedding were taken. Additionally, the map was complemented by 16 petrographic studies including microscopic descriptions of limestone samples taken into caves and nearly outcrops. The geological map is complemented by two geological cross-sections across the NW and SE part of the target area. The cross-sections were constructed perpendicularly to the direction of the main structures. The geological map and cross-sections are elaborated in GIS, introducing the information in SHP files.

4.5. Definition of families of discontinuities

The families of discontinuities are defined using statistical analysis on stereographic projection (see Ragan, 2009). The considered parameters are the strike and the dip of the discontinuities measured in the study area. The statistical analysis involves a density map on stereographic projection similar to the plot used to establish the groups of cave conduits (Section 4.2). The density map includes five contours that range from 1.0 to 5.5% of the total data. The input data include 182 measures of trends and dips of discontinuities (157 joint data and 35 bedding data). 147 measures were carried out at the surface and 35 in Torca Teyera shaft. The definition of the families of discontinuities is based on the density map, establishing each family in the areas where density reaches values higher than the 3% of measures. Each family is represented by an average line characterized by the strike and dip related with the maximum values of density.

4.6. Projection of the caves on the DEM, maps and cross-sections

The caves are plotted on the DEM, topographic map and aerial photography to position them in the terrain. The cavities are also projected on the geological map and cross-sections in order to characterize their structural setting and to establish their relationships with the major structures (Piccini, 2011a,b; Tisato et al., 2012). When the caves are located far from the section line, the geological cross-sections cannot represent accurately their relationships with the structural features of the bedrock. So, in this study, only the cavities located at less than 700 m from the section line are projected on each cross-section.

4.7. Comparison between conduit groups and families of discontinuities

The numerical estimations of the influence of the discontinuities on cave passages are calculated comparing on stereographic projection the defined groups of cave passages and the families of discontinuities. The groups of cave conduits are represented by the density map of the directions and inclinations of conduits (Section 4.3) and the families of discontinuities are represented by their average plane (Section 4.4). This plot defines the structural control of each group of cave conduits, establishing what family, families or intersections between families of discontinuities force each group of conduits. As the percentage of each group of conduits is known (Section 4.3) and the structural control of each group is defined (Section 4.5), the percentage of conduits controlled by each family of discontinuities (or set of them) can be calculated. Therefore, the quantitative structural control of the caves is then established.

5. Results

The application of the SpeleoDisc method on the chosen pilot area provides the following results:

5.1. Spatial distribution of the caves

Fig. 4 displays the plan projection of the cavities over the orthophotography of the pilot area, obtained from the Geographic Information System, and Fig. 5 shows a view of the 3-D model of the shafts. The target block, with a volume of 2667 Hm^3, shows 12,283 m of conduits including horizontal galleries and vertical shafts from 13 cavities. The whole of the caves occupies an area of 43,466 m^2 that represents 0.98% of the pilot area and a volume of 1200 Hm^3 that corresponds to 2.97% of the studied zone.

5.2. Definition of groups of cave conduits

The cave conduits of each cavity are classified considering on the density map of directions and inclinations of the survey shots on the stereographic projection. Fig. 6 shows the density maps of the directions and inclinations of the cave conduits, Fig. 7 displays the defined groups of cavities and Table 2 summarizes the characteristics of these groups. Five groups of cave passages have been defined, although they are not

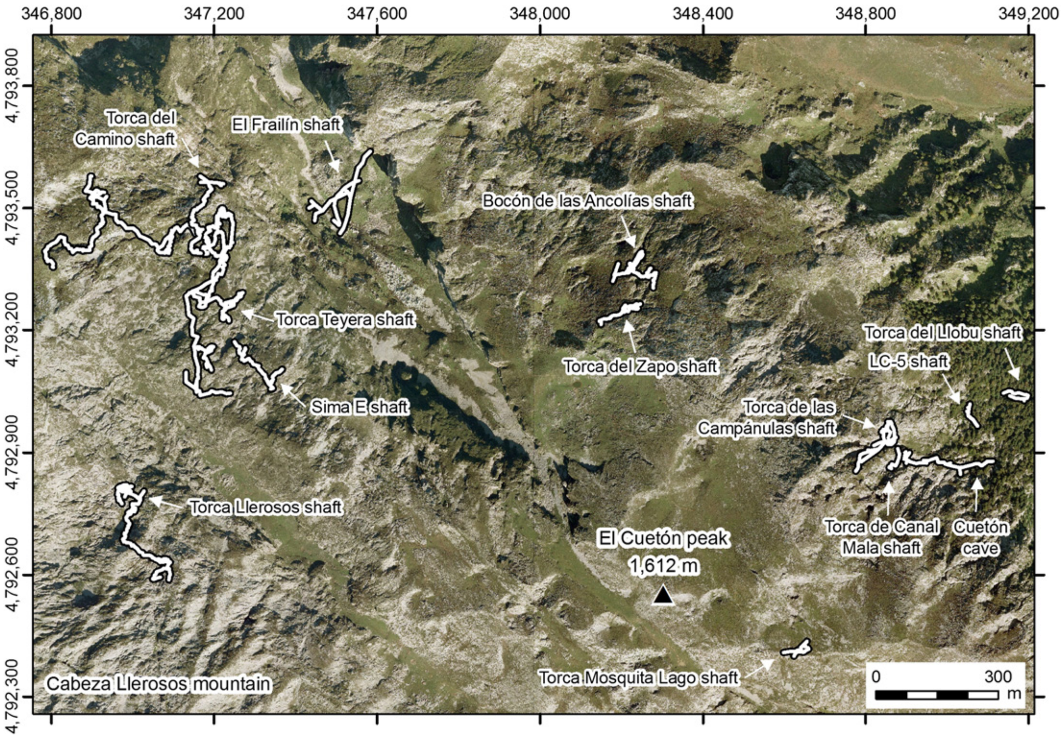

Fig. 4. Projection of plan view of the studied caves over the referenced orthophotography of the pilot area, obtained with the Geographic Information System.

always recognized in all of the studied cavities (Fig. 6). The established groups of conduits are summarized in Table 2. A percentage of 4% of the data is classified as "other directions and inclinations" that cannot be included into the established groups, since these values mainly correspond to survey shots not representative of the direction and inclination of the conduits. This subject is a limitation of the SpeleoDisc method and will be discussed in Section 6.2.

5.3. Geological characterization: relationship between caves and major structures

Fig. 8 highlights the geological map and two cross-sections of the pilot area. This figure evidences that the Cabeza Llerosos massif is formed by c. 650 m of Ordovician quartzite (Barrios Formation), 1200 m of Carboniferous limestone (Valedeteja and the Picos de Europa formations), 10 m of Carboniferous shale (Áliva Formation) and several

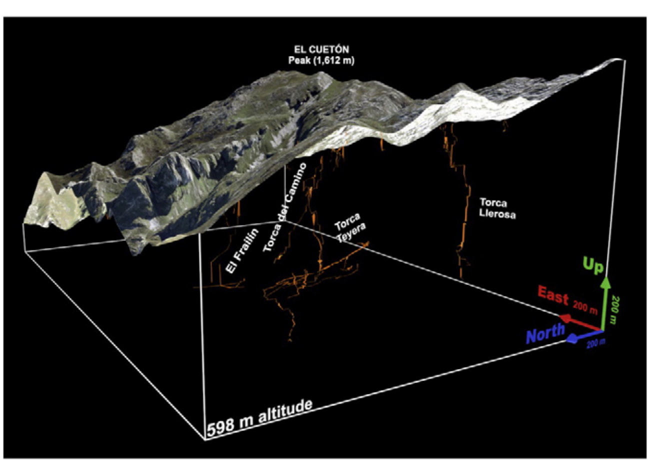

Fig. 5. A 3-D model including the Digital Elevation Model and the spatial distribution of some of the study caves where the SpeleoDisc approach was applied. The caves show different geometries formed by vertical and horizontal conduits.

post-Variscan andesitic dykes. The Barrios Formation crops out at the NW of the pilot zone, the Valdeteja and Picos de Europa formations occupy most of the study area, the Áliva Formation is only recognized at a little outcrop situated at the middle part of the geological map, and the dykes are recognized at karst surface and into some cave passages located at the western part of the geological map. Following the stratigraphic criteria of Bahamonde et al. (2007), the Valdeteja and Picos de Europa formations are divided together into three strata domains whose specific features in the pilot area are detailed below:

a) Slope: this strata domain crops out at the middle and south parts of the geological map and consists of 200 to 600 m of massive limestone, breccia and boundstone with botryoidal cement fans.
b) Platform top: this domain is shown in the middle and the north of the studied zone and includes 250 to 350 m of well-stratified rocks mainly formed by skeletal to ooidal pack- to grainstone limestone and pink fossil-rich packstone limestone.
c) Toe of slope and basin: this domain is recognized at the middle part of the study area and includes 10 to 20 m of alternation of breccia, bioclastic packstone limestone, chert and shale. The toe of slope and basin domain can be interpreted as an interbedded layer into the platform top domain in the studied area.

The rocks are affected by several sub-vertical imbricate thrusts with NW–SE strike, deformed by other faults. Two sequences of thrusts have been recognized based on their geometric relationships; the first sequence consists of four sheets of thrusts that dip from 50 to 75° to the NE. These structures over-thrust the Ordovician quartzite or Carboniferous limestone over the latter. These thrusts are crossed by the second sequence of thrusts, formed by two out-of-sequence thrusts. These thrusts crop out in the middle part of the map dipping 80° to 90° to the NE. Sometimes, these structures place the upper beds of the strata domain of platform top over the lower rocks of this strata domain. On the other hand, both thrust systems are affected by sub-vertical faults with NW–SE, NE–SW or N–S strike. The NE–SW and NW–SE faults constitute a conjugated system and have a sinistral and dextral pattern, respectively.

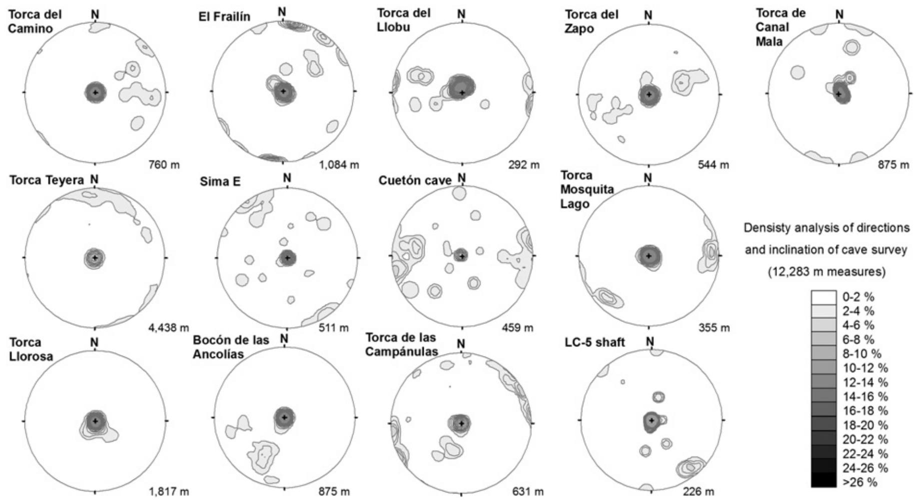

Fig. 6. Density map of the directions and dipping of the cave conduits performed by stereographic projection (equal area, lower hemisphere, von Mises–Fisher concentration). The length of each cave is shown at the bottom of each stereographic projection.

The geological maps and cross-sections allow us to estimate how many conduits are developed in each geological unit and illustrate qualitatively that some cave passages are parallel to particular faults, bedding and the boundaries between geological units (Fig. 8). 43% of the cave conduits is developed within the well-stratified limestone (platform top domain) and the 57% is carved in massive limestone (slope domain). Some NW-dipping and NW–SE strike conduits from Torca Teyera, Torca Llerosa, Sima E, Torca del Llobu, Torca del Camino and El Frailín shafts are parallel to the bedding and the thrusts, while SW-dipping and NW–SE or NE–SW bearing passages from Torca Llerosa, Torca Teyera, Bocón de las Ancolías and Torca del Zapo shafts are parallel to the conjugated system formed by NW–SE and NE–SW strike faults. The cave passages are not generally controlled by the position of the faults and lithological boundaries, although the entrances of cavities and few passages are controlled by local fractures that can be recognized in the field or in the projection of the caves on the orthophotography (Fig. 4). Moreover, the geometry of some passages from Torca Llerosa, Torca del Llobu and LC-5 shafts are linked to particular faults, showing changes in the length, direction and inclination of the cave conduits associated with the presence of thrusts and the strata domains. The inclination of the conduits of Torca Llerosa shaft (Fig. 8A) is related with the strata domains. The inclination of the conduits developed into the slope strata domain (massive limestone) is higher than the conduits carved into the strata domain of platform top (well-stratified limestone). The geometry of the Torca del Llobu and LC-5 shafts shows small changes on the inclination of the conduits that can be related to the boundary between the strata domains of slope and platform top. The inclination of these conduits should be related to the presence or absence of bedding planes. In massive limestone the vertical conduits are dominant, whereas in well-stratified limestone the proportion of vertical conduits is diminished. The conduits placed in massive limestone could follow subvertical fractures, developing along them shafts that are more than 100 m high. On the contrary, cave passages carved in well-stratified limestone are conditioned by vertical fractures and the moderately-dipping bedding planes, showing a combination of vertical and inclined conduits.

5.4. Definition of the families of discontinuities

Fig. 9 highlights the groups of discontinuities derived from statistical analysis of stereographic projection, established from a sample of 182 field measures. The discontinuities are classified according to their strike and dip and their nature (joint or bedding), including the bedding set (S0) and six families of joints (J1 to J6). The strike and dip of the

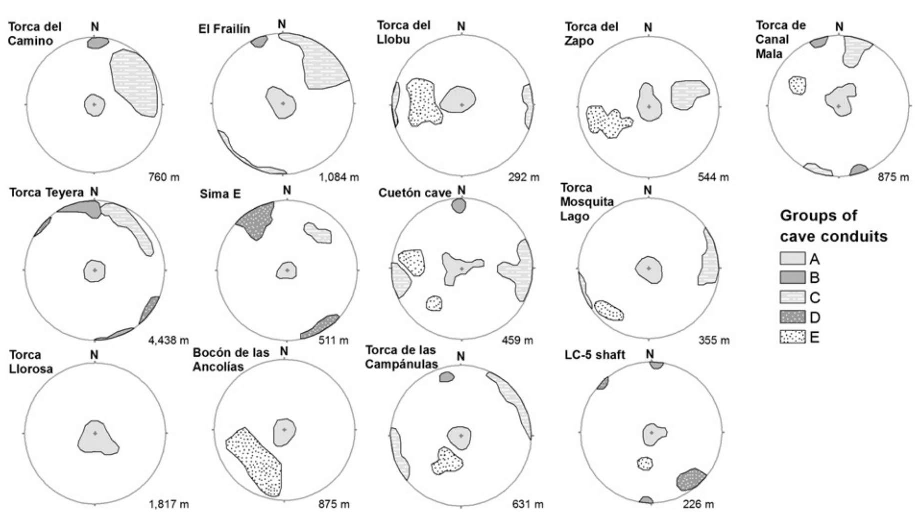

Fig. 7. A to E statistical groups of cave conduits per each cave plotted on stereographic projection (equal area, lower hemisphere, von Mises–Fisher concentration). The length of each cave is shown at the bottom of each stereographic projection.

Table 2
Characteristics of the groups of cave passages defined on stereographic projection.

Groups of cave passage	Direction (°)	Dip (°)	% of all the cavities
A	–	80 to 90	61
B	N 340–10 E	3 to 20 N	13
C	N 5–120 E	0 to 50 N	13
D	N 125–145 E	0 to 30	6
E	N 185–270 E	20 to 65 SW	3
Other directions and inclinations			4
Total			100

average plan of each family of discontinuities and their relative abundance are detailed in Table 3. The abundance of the families of joints is variable, ranging from 5 to 24%. Their strike and inclination take similar values in the study area, except the J1 family, that is rotated 10° to E to the SE. The families of discontinuities are usually related to some structures: the J1 family is parallel to the mapped NE–SW strike faults; J2 is

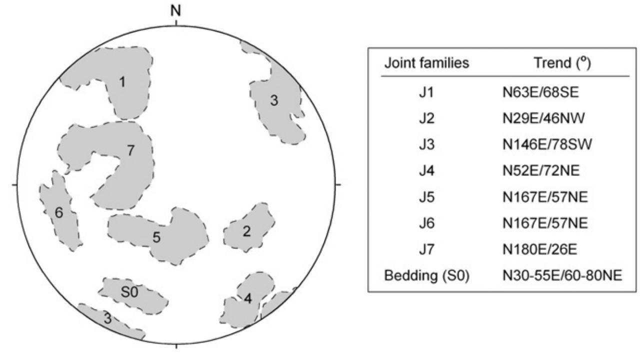

Fig. 9. Joints families and bedding set defined on stereographic projection from 182 field measurements. Joints families are denoted by a "J" and a number, whereas the beddings are named as "S0". The average direction and inclination of the sets of discontinuities are shown in the table.

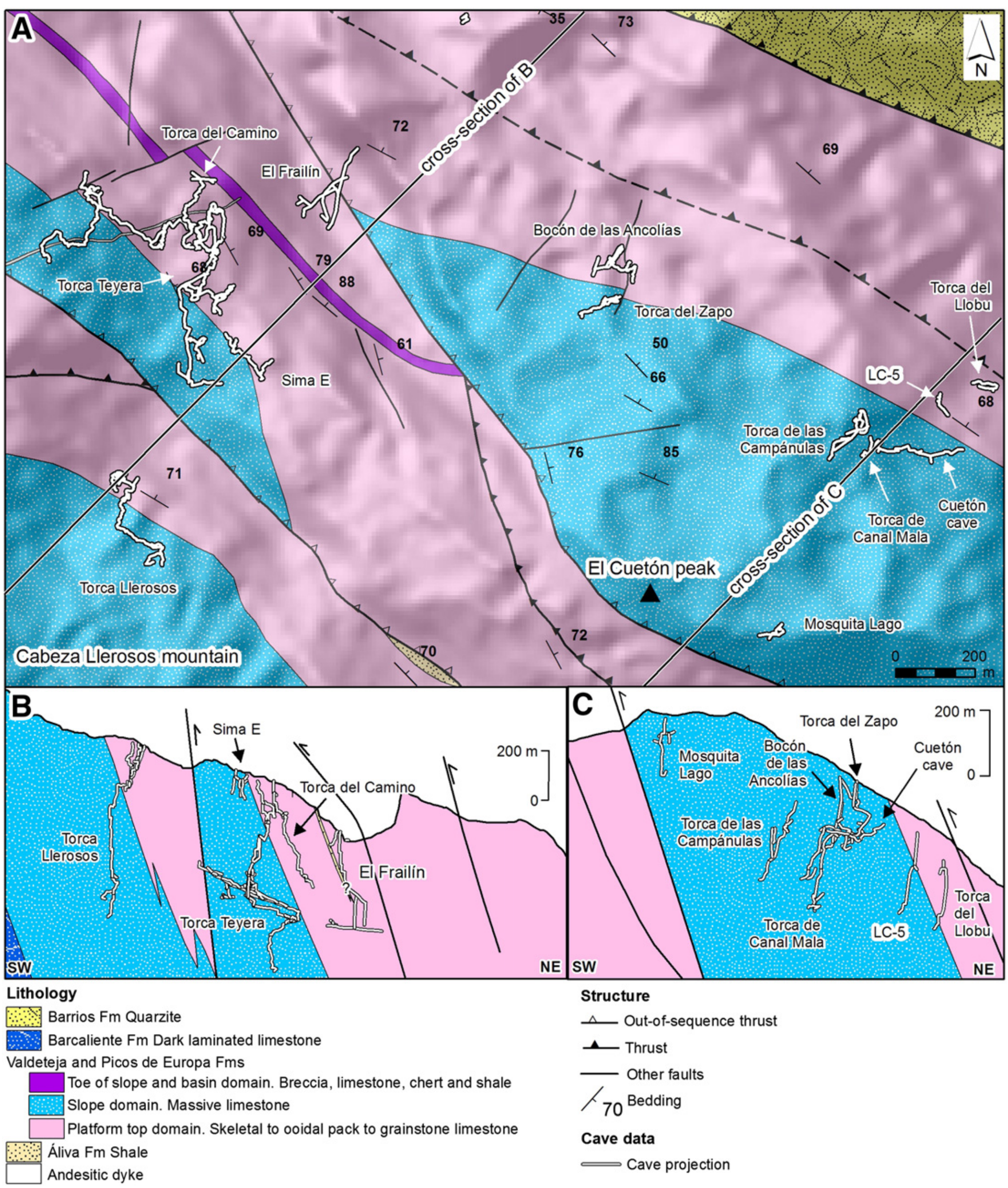

Fig. 8. Geological map (A) and two cross-sections (B and C) of the pilot area with the caves projection. Torca Teyera, Torca del Camino, El Frailín, Sima E and Torca Llerosos are plotted on the cross-section of B, whereas Bocón de las Ancolías, Torca del Zapo, Torca del Llobu, LC-5, Torca de las Campánulas, Torca de Canal Mala, Mosquita Lago and Cuetón caves are plotted on the cross-section of C.

Table 3
Trending and dip and percentage of average plane of each family of joints. The percentage of abundance is referenced to the 168 measures of joints carried out by field work.

Family of discontinuities	Trending (°)		Dip (°)		Percentage of relative abundance (%)
	Average	Range	Average	Range	
Joint family 1	N 63 E	N 30–90 E	68 SE	40–90 NE	24
Joint family 2	N 29 E	N 10 E–N 60 W	46 NW	20–60 NW	5
Joint family 3	N 146 E	N 120 E–N 165 W	78 SW	10 SW–35 NE	12
Joint family 4	N 129 E	N 70–160 E	17 NE	10–60 NE	13
Joint family 5	N 167 E	N 148 E–N 176 W	57 NE	50–72 NE	6
Joint family 6	N 180 E	N 125 E–N 150 W	26 NE	15–55 NE	20
Bedding	N 126 E	N 54 W–N 87 E	75 NE	60–80 NE	18

related to NE–SW strike faults, the J3 family is associated to the thrusts and J4 is parallel to N–S strike faults. Other properties of the joints are quite similar between families. Thus, all of the families include joints from few decimeters to several meters long, and the separation between joints frequently takes values from 5 to 20 cm. The joints are usually open from few millimeters to several centimeters and sometimes are partially filled by carbonate. In some cases, the families J4 and J6 exhibit hydrothermal quartz crystals up to 0.3 m in size. The bedding was only recognized in areas with bedrock from the strata domains of top platform and toe of slope. The bedding shows 120 to 145° strike and its dip varies from 60 to 80° to NE.

5.5. Definition of the structural control

Fig. 10 shows the comparison between joints, bedding and cave survey data in order to establish the relationship between each family of discontinuities and the directions and inclinations of the caves. The families of discontinuities are represented by an average plane, so the conduits related with each family of discontinuities are not precisely plotted over their average plane. The cave conduits related to several families of discontinuities are plotted near the average plane of the family. The “A” group of passages is related to the joint families J1, J3 and J5, as well as their intersections; the “B” group is related by the intersection between families J4 and J5 (Fig. 11A); the “C” group is conditioned by the intersection between families J1, J2, J5 and J6 (Fig. 11C); the “D” group follows the bedding (Fig. 11B); and the “E” group is related to the families J1, J2 and J3. Consequently, each group of cave conduits is related with several families of joints, their intersections or the bedding.

As the relative abundance of each group of cave conduits has been established in Section 5.2, the percentage of the caves forced by each family of discontinuities can be defined (Table 4). Some 61% of the conduits (“A” group) is conditioned by the joint families J1, J3 and J5 and their intersections; 13% of the conduits (“B” group) is controlled by the intersection between families J4 and J5; 13% of the caves (“C” group) is governed by the intersection between families J1, J2, J4 and J6; 6% of the conduits (“D” group) is guided the bedding; and 3% (“E” group) is forced by the families J1, J2 and J3. The direction and inclination of the 4% of the survey data plotted on stereographic projection are not defined, so the structural control of the 4% of the caves cannot be established using the SpeleoDisc approach. Consequently, 64% of the cave passages (“A” and “E” groups) is controlled by vertical joints related to the thrusts and other faults, and 26% of the cavities follows the intersection of vertical and horizontal joints. The bedding only guides the 6% of the cave conduits, although it should be considered that 43% of the cave conduits is developed into well-bedded limestone.

Fig. 12 shows the structural control of three modeled cave passages chosen in order to elaborate the model of the influence of joints and bedding on the endokarst. Fig. 12A highlights how shallow-dipping passages from Bocón de las Ancolías shaft are forced by the intersection between the J2 and J5 families, while the family J1 controls inclined cave conduits. Fig. 12B displays that steeply-dipping passages from Torca Llerosa shaft are conditioned by J1 and J3 families and their intersections. Fig. 12C illustrates that horizontal passages from Torca Teyera shaft are forced by the guidance of the bedding, whereas shallow-dipping passages are guided by the intersection of the sub-horizontal J4 and the sub-vertical J1 families.

6. Discussion

The obtained results evidence that the SpeleoDisc is useful for establishing the influence of the structure on the cave conduits by statistically analysing, identifying and evaluating the role of the families of

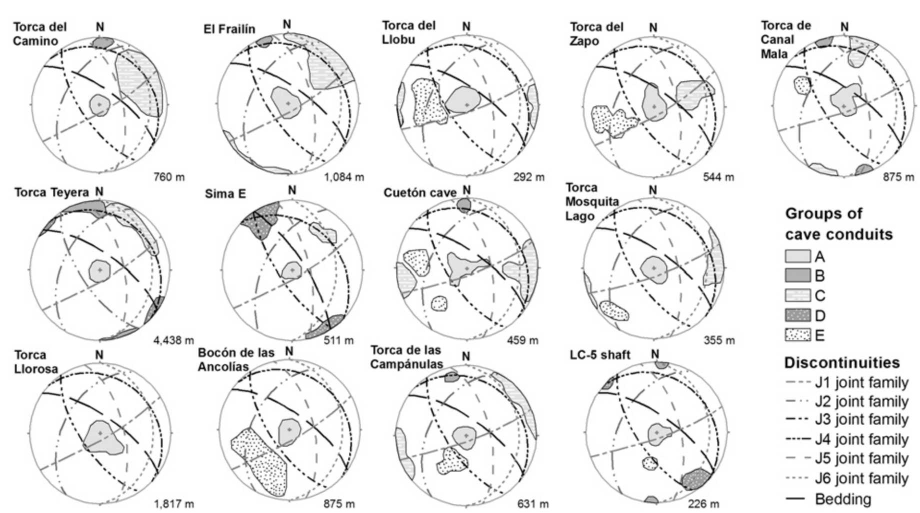

Fig. 10. Comparison of families of joints and bedding and density map of cave survey data on stereographic projection. The lines projected on the stereographic projection represent the average plane of each family of joints. The structural control of each group of conduits is obtained through the stereographic projection, linking the direction the conduits and the discontinuities.

Fig. 11. Evidence of structural control taken from cave passages of Torca Teyera shaft. The evidence is marked by cave features developed following a discontinuity or an intersection between two of them. A. Vadose rift passage controlled by the bedding. B. Vadose rift conditioned by the bedding. C. Phreatic tube controlled by the intersection of the J2 and J6 families of joints.

discontinuities that control the directions and inclinations of the conduits. The comparison of the SpeleoDisc method with previous approaches presents some improvements and limitations that should be considered when applying the method.

6.1. Improvements of the SpeleoDisc method

The SpeleoDisc method is a useful approach to establish the structural control in the endokarst since it allows: 1) evaluation of the influence of the structures on the endokarst; 2) quantitative evaluation; and 3) application of the approach to complex geomorphological and geological settings.

1) The influence of the structure on the endokarst is established considering together the influence of the major and minor structures in 3-D. The geological maps and cross-sections provide the structural control of the major structures (faults and contacts), while the comparison on stereographic projection between discontinuities and cave survey data defined the influence of minor structures (joints and bedding). Since the analyses are made in 3-D, it is possible to establish the role of the strike and dip of the discontinuities and the intersection between them in the endokarst morphology.
2) The SpeleoDisc method provides a quantitative evaluation of the structural control by means of the calculation of the percentage, direction and inclination of the cave conduits forced by joints and bedding. Those estimations allow us to compare different karst areas, reducing the subjective interpretation of the researchers.
3) The SpeleoDisc method can be successfully applied in a complex geomorphological and geological setting, to define the structural control in deep cave systems, as shown by this case in which deep caves are developed in a large and homogeneous calcareous series affected by three episodes of deformation (Variscan and Alpine orogenies and Mesozoic extension).

6.2. Limitations of the SpeleoDisc method

The methodology and their results are conditioned by four limitations that affect mainly the estimations of the influence of the structure on the cave development: 1) the representation of the caves by speleological surveys; 2) the accuracy of the cave surveys; 3) the modifications of the original geometry of the conduits by the processes of cave evolution; and 4) the parameters and criteria used to define the groups of conduits and families of discontinuities on stereographic projection.

Table 4
Summary of the structural control of the caves. The percentage of cave conduits is calculated with respect to the cave survey data plotted on stereographic projection (12,283 measures).

Group of cavity conduits	Percentage of all the cave conduits (%)	Structural control of the cave conduits
A	61	J1, J2 and J5 and their intersections
B	13	Intersections of J4 and J5
C	13	Intersections of J1, J2, J4 and J6
D	6	Bedding
E	3	J1, J2 and J3
Other conduits	4	Unknown

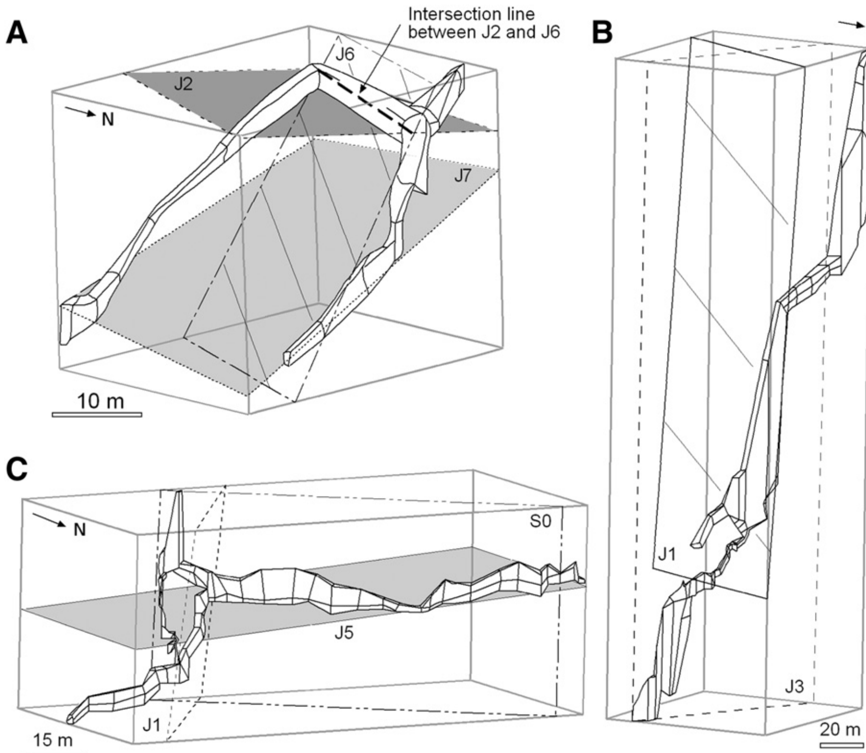

Fig. 12. Structural control of selected passages from (A) Bocón de las Ancolías shaft, (B) Torca Teyera shaft and (C) Torca Llerosos shaft. The structural control is evidenced by the spatial relationships between the planes of the discontinuities and the geometry of the cavities. J1 to J6 are the families of joints and S0 is the bedding.

1) The method is conditioned by the representation of the caves in speleological surveys. The representation depends on a) the criteria of the surveyors, b) the accessibility of the cave passages and c) the low representation of the endokarst using cave data, which results in deviations between the real endokarst geomorphology. The cavities were surveyed during 38 years by a lot of cavers that used, in many cases, different criteria. These differences in the criteria can be significant at the scale of cave conduits because the survey station can be placed at the passage walls, roof or floor, causing variations of few meters. Nevertheless, these differences are quite small in kilometric caves and at the massif scale. The accessibility of the cave passages controls the representation of the cave by the survey data since the survey stations are usually positioned in comfortable places. The surveys are usually accurate approaches for the galleries of the caves, where the survey stations are positioned near to the middle part of the conduits. On the contrary, the surveys are not always accurate approaches for the shafts, since the position of the survey stations is strongly conditioned by the location of the moorings (bolts) and rope used by the cavers. In addition, many cavers assume that the inclination of conduits looks completely vertical, but, in fact, the inclination of these conduits is 70–80°. These limitations provide inclinations of the shafts that seem to be higher than the actual ones. This distortion is important in the A group of conduits. The density maps of cave conduits plotted on stereographic projection show that the inclination of the A group varies from 80 to 90°, but really the minimum value of the range is less than 80°. On the other hand, in a karst massif, the volume of caves can reach 50% of the karstified limestone (Vadillo et al., 2012). In this case, the studied caves occupy only 2.9% of the studied portion of the enclosed volume of the massif. The amount of known caves depends of the degree of development of the caving explorations and the advance of the caving techniques (Klimchouk, 2006). Considering our data, the knowledge on the endokarst based on cave data is limited, since the mapped cavities only represent a small part of the conduits developed in the karst massif. In order to minimize the restrictions derived from the degree of knowledge of a karst massif, the SpeleoDisc approach should be applied in areas already well explored by the cavers, where the probability of discovering new caves is low.
2) The SpeleoDisc method is controlled by the accuracy of the cave surveys. The accuracy of the set of surveys of the studied cavities is unknown because they have not been checked in order to detect errors. The methods applied in other areas uses closed loops (Fish, 2007) or geophysical techniques (Sogade et al., 2004). However, we assume as a reference the values postulated by Jeannin et al. (2007) to the cave surveys in general. These values vary from 1 to 10%, although sometimes can reach more than 15% (Domínguez-Cuesta et al., 2012).
3) The modifications of the original geometry of the conduits provide a limitation to the quality of the SpeleoDisc results. The geometry of the conduits can be modified by the presence of cave deposits and, consequently, the survey data do not represent the inclination and direction of the original conduit. Speleothems, fluvial and breakdown deposits cover the surface of the conduits usually smoothing the contours and inclination of the passages. Sometimes, the deposits occupy almost the entire conduit and its original geometry is not recognized. This limitation can be an important problem in caves with a high percentage of cave deposits, where the application of SpeleoDisc method may not be possible. Therefore, the geometrical modifications induced by cave evolution can restrict the application of the SpeleoDisc method, especially in caves with a high percentage of cave deposits where the application of the method could not be possible.
4) The SpeleoDisc method also depends on the parameters and criteria used to define the groups of conduits and families of discontinuities. The definition of the groups of cave passages and families of discontinuities depends on the statistical parameters used to elaborate the density map on stereographic projection and the criteria used by the researcher to establish the limits of each group and family. The statistical parameters used in this work condition the final density

map displaying variations up to 1.5% in some places. On the other hand, the determination of the families of discontinuities and groups of cave passages is performed visually by the researcher, establishing approximately the limits of each family and group.

6.3. Implications in speleogenesis

The application of the SpeleoDisc approach in the pilot area studied in this work provides a conceptual model of the influence of the structural factor in the speleogenesis of the Picos de Europa. As the percentage of abundance, the genesis and the structural control of the conduits groups are known, the influence of the structure on conduits origin can be established, estimating the relative weight of the influence of the joints and the bedding on the cave evolution. Our studies (Borreguero, 1986; Ballesteros et al., 2011) evidences that “A” and “E” groups of conduits correspond generally to vadose shafts and meanders, while “B”, “C” and “D” groups are mainly phreatic and epiphreatic conduits modified usually by vadose action. Consequently, the 64% of the studied caves is vadose conduits controlled by sub-vertical joints (families J1, J2, J3 and J5) and their intersections; and 32% of the caves is phreatic and epiphreatic conduits controlled by the strike of the bedding and intersections between sub-vertical and inclined joints (between J4 and J5 and between J1, J2, J4 and J6). These relations between the speleogenesis of the conduits and its structural factor allow us to infer a hypothesis about the influence of the structure on the cave development in the hydrogeological framework. In the vadose zone of the aquifer, the water travels from the topographic surface to the water table using a sub-vertical path and developing shafts and narrow canyons (see Audra and Palmer, 2013). As these vadose conduits are controlled by sub-vertical joints and their intersections, the groundwater that travels from the topographic surface to the saturated zone is produced along sub-vertical joints and its intersections. On the contrary, in the saturated zone of the aquifer the water flows toward the springs with a small gradient, producing the genesis of phreatic and epiphreatic conduits (see Worthington and Ford, 2009; Jeannin et al., 2013). These conduits are developed following the strike of the bedding and sub-horizontal intersections produced by the intersection of sub-vertical and inclined joints, therefore, groundwater paths in the saturated aquifer are conditioned by these kinds of discontinuities.

Table 5 highlights the relative influence of the joints and bedding on cave evolution, showing the percentage of phreatic, epiphreatic and vadose conduits developed within massive and well-stratified limestone. 47% of the studied block is formed by well-stratified limestone, where the development of joints and bedding planes is high while the other 53% is massive limestone that only displays a high density of joints. On the other hand, 61% of the cave conduits is in well-stratified limestone and 39% is in massive limestone. These results suggest that the bedding favors the development of caves, contradicting apparently the previous results, that evidence that only 6% of the conduits is related to bedding planes. This apparent incoherence can be explained considering the relative abundance of vadose and phreatic and epiphreatic conduits. This works evidences that most of the limestone from the study area is affected by a high density of joints, showing six different families of joints with similar features. These joints are conditioning the development of phreatic, epiphreatic and vadose conduits. On the contrary, the bedding is only present in the well-stratified limestone and is only involved in the control of phreatic and epiphreatic conduits. Those conduits represent 12% of the caves, half of them being conditioned by the bedding. This discontinuity controls half of the phreatic and epiphreatic conduits developed within rock where the stratification is presence. Consequently, although the role of the bedding is only the 6% of the whole of the caves, the influence of the bedding planes represents 50% of the development of phreatic and epiphreatic conduits.

The particular geology of a karst area conditions the different investigate paths, concepts and methodological approaches proposed by the scientists in speleogenesis (Bakalowicz, 2006). Consequently, the ideas presented in this section should be checked in other karst region with other geomorphological and geological features. The application of the method in other karst regions would allow us to answer some questions about the structural control on caves, thus reducing the limitations provided by the use of different methods.

6.4. Geomorphological applications

The results of the SpeleoDisc in the pilot area evidence the applications and potential uses of the approach. The proposed method can be applied in speleogenetical research, karst aquifer investigations and tunnels construction in karst media. With respect to speleogenesis, the SpeleoDisc method establishes the structural factor of cave development, evaluating quantitatively how discontinuities control the morphology of cave conduits. Considering the role developed by groundwater in cave development, the structural control of the caves should be similar to the structural control of the water paths in karst aquifers. Consequently, SpeleoDisc identifies the discontinuities influencing water flow paths in both the vadose zone as the saturated zone. Finally, the SpeleoDisc method can be useful in the initial phases of civil engineering projects in karst regions, since the potential main directions and inclinations of groundwater flow paths are approached.

7. Conclusions

SpeleoDisc is a useful methodology for establishing quantitatively the influence of the structure on endokarst, considering the statistical comparison between the cave survey data and the structure of the bedrock. The method is divided in two steps: 1) elaboration and projection of cave surveys on geological maps and cross-sections, in order to define the relationships between cave conduits and the geological setting, particularly main structures as faults; and 2) the comparison of the direction and inclination of conduits with the massif discontinuities using stereographic projection, in order to establish the percentage of caves forced by each group of discontinuities (joint families and bedding). Consequently, SpeleoDisc allows us to establish the structural control of the caves in 3-D, considering together the influence of major and minor structures, as well as the intersections between discontinuities at a metric scale. Estimations of the influence of the structure on cave development are conditioned by: 1) the representation of the caves by speleological surveys; 2) the accuracy of the cave surveys, 3) the modifications of the original geometry of the conduits by the processes of cave evolution, and 4) the parameters and criteria used to define the groups of conduits and families of discontinuities on stereographic projection. These limitations reduce the accuracy of the calculations of the percentage of conduits controlled by the discontinuities and restrict the use of the method when few cave survey data are available, or when the geometry of the conduits is completely masked by cave deposits. The application of the method suggests a conceptual model of the structural control on the speleogenesis of the Picos de Europa karst. This model establishes that vadose shafts and canyons are conditioned by vertical joints and its intersections, while the phreatic conduits developed in the saturated zone are controlled by the strike of the bedding and the sub-horizontal intersections between joints. The influence of joints on endokarst is higher than the influence of the bedding, since 90% of the cave passages is controlled by joints and only 6% by bedding planes. Nevertheless, the half of phreatic and epiphreatic conduits developed in well-stratified are controlled by the bedding. Finally, this works evidences that SpeleoDisc is a systematic method for studying and evaluating the influence of structural factors in karst development, displaying a high potential in future speleogenetical studies as well in civil projects in karst areas.

Table 5
Comparison between the characteristics of the limestone bedrock, the development of discontinuities and abundance of the genetic kind of cave conduits. All the percentages of the cave conduits are referenced to the 100% of the whole of the cavities.

Bedrock	Percentage of 3D block volume	Development of joints	Development of bedding planes	Percentage of known caves	Percentage of phreatic and epiphreatic conduits	Percentage of vadose conduits
Massive limestone	53	High	Zero	39	20	19
Well-stratified limestone	47	High	High	61	12	49

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