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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).