Influence of the Rivers on Speleogenesis Combining KARSYS Approach and Cave Levels. Picos de Europa, Spain

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Abstract The influence of rivers on speleogenesis is studied analyzing the cave levels located in the underground drainage areas related to two fluvial basins. Cave levels are analyzed through their vertical distribution profiles. The underground limits of the fluvial basins are defined using a 3D geometric model of the karst aquifer established according to the KARSYS approach. The aim of this work is to analyze the influence of the rivers on cave evolution using cave morphology. The study area corresponds to the Western and Central massifs of Picos de Europa (Northern Spain), with 214 km of cave conduits up to 1.6 km vertical range. As a result, we established two sequences of development of the cave levels related to the differences of the incision rate of the Cares and Dobra Rivers, and the partial capture of the Western Massif by the Cares River.

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1 Introduction

The speleogenesis of the karst massifs is usually conditioned by the evolution of the fluvial network. Many studies relate together the fluvial incision, the drop of the base level, the descent of the water table, and the development of cave levels and vadose shafts (Häuselmann et al. 2007; Piccini 2011). The karst massifs may entail two or more fluvial basins which history can be diverse, producing differences on cave development. These differences are not well established due to the lack of knowledge on the underground limits between adjacent fluvial basins. In order to solve this uncertainty, the KARSYS approach (Jeannin et al. 2013) allows us to define these boundaries based on a 3D geometric model of the karst aquifer. On the other hand, the influence of the fluvial evolution on speleogenesis can be studied analyzing the vertical distribution of the cave conduits (Filipponi et al. 2009). The cave levels are indicators of the fluvial incision stages since they represent the past positions of the water table, related to the base level of the fluvial basins (Audra and Palmer 2013). The relationships between cave levels and river evolution can be approached classifying the caves levels according to the underground drainage areas defined by KARSYS and, later, comparing the cave levels between them on the basis of their vertical distribution profiles. The aim of this work is to analyze the capture of caves by fluvial streams as a result of the evolution of the large fluvial basin. The methodology of work is based on the hypothesis that the cavities were originated from the current underground basin. This allows us to compare initially the cave levels and the limits of the underground basin in order to establish their relationships and highlight fluvial captures and differences between basins.

2 Setting

The study area (20 × 25 km) corresponds to the Western and Central massifs of the Picos de Europa mountains (Northern Spain), which reach a maximum altitude at 2,648 m a.s.l. (Fig. 1). This area involves an alpine karst with few hundreds of kilometers of cave conduits, exceeding 500 m depth in 29 shafts. The fluvial network shows a low drainage density and includes eight rivers organized in two major basins. One of them is the basin of the Dobra River, ranging from 350 (base level) to 1,450 m a.s.l, which includes Hunhumia, Pomperi, and La Beyera tributaries and flows to the NW. The second basin corresponds to the Cares River, with altitudes ranging from 100 (base level) to 1,050 m a.s.l. (in the study area), which mainly flows to the NE, and it comprises the Casaño and Duje tributaries. All of these rivers are incised, carving fluvial canyons up to 2,000 m high as the Cares Gorge.

The study area is mainly formed by 2,000 m of Carboniferous limestone and, secondarily, Ordovician quartzite and Carboniferous and Permian-Mesozoic shale

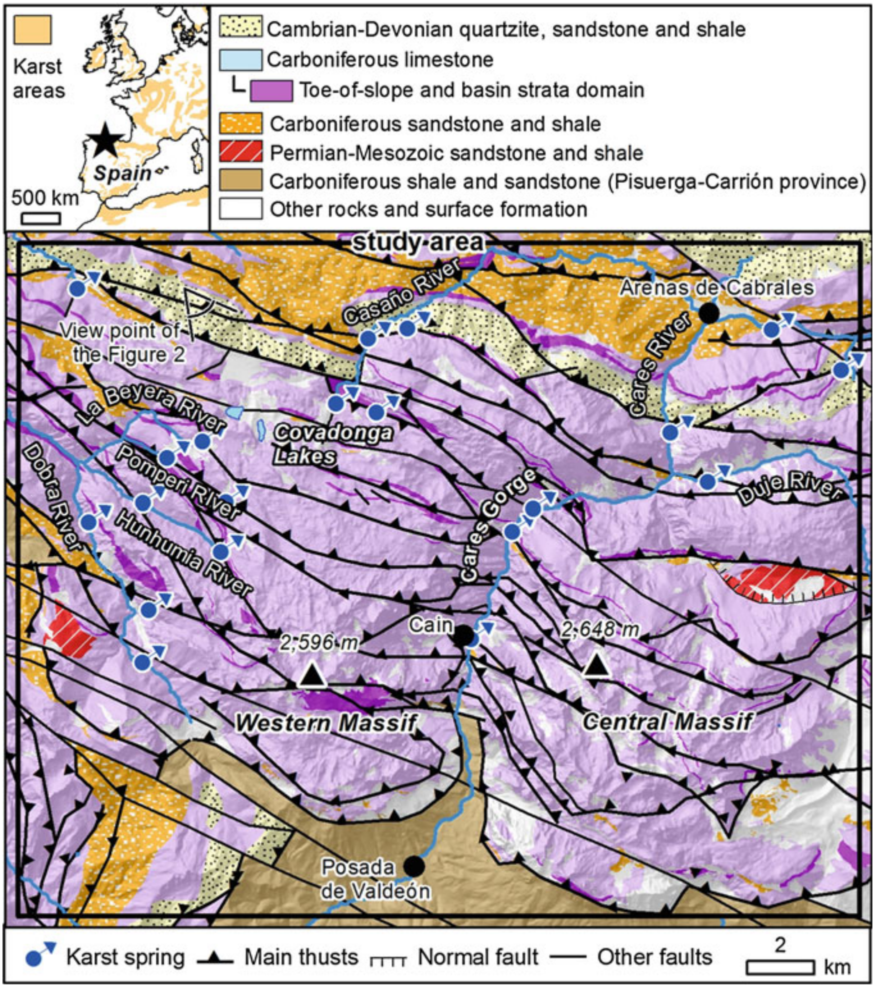

Fig. 1 Overview of the study area (after Merino-Tomé et al. 2013a, b)

and sandstone (Fig. 1). Carboniferous limestone is placed in the core of Picos de Europa and includes an interbedded strata domain named "toe-of-slope and basin" (Bahamonde et al. 2007). This strata domain comprises alternations of limestone, chert, and shale. The geological structure includes a Variscan thrusts imbricate system that was modified during the Alpine Cycle (Merino-Tomé et al. 2009). In the South of Picos de Europa, the detachment level of the Variscan system dips 30–45° to the North and is developed below the Carboniferous limestone. The footwall of the detachment level is formed by the Carboniferous sandstone and shale that crops out to the South of these mountains.

3 Methodology

The methodology includes: (1) collection of existing speleological, hydrogeological, and geological data; (2) 3D reconstruction of 214 km surveys of cave conduits; (3) inventory of 20 karst springs; (4) identification of hydrogeological units classifying them as aquifers or aquicludes (impervious rocks) based on their lithology and the presence of caves and springs; (5) elaboration of a 3D geological model; (6) elaboration of the hydrogeological 3D model at low water stage by KARSYS (Jeannin et al. 2013) combining the geological model with the position of the main karst springs and assuming a set of hydraulic principles in karst aquifers; (7) delineation of the springs systems catchments based on the hydrogeological model and their validation by previous dye-tracings; (8) grouping of the cave conduits by catchment areas and elaboration of their vertical distribution profiles with their absolute elevation (m a.s.l) (Filipponi et al. 2009); and (9) definition of cave levels and the graphical comparison of their length versus their vertical distribution.

4 Results

A zoom from the elaborated hydrogeological model at low water stage is displayed in Fig. 2, showing the defined five hydrogeological units. The units 1, 4, and 5 are formed by quartzite, shale, and compact and clayey sandstone and are considered as aquicludes due to their low permeability; the unit 2 entails limestone and forms the main karst aquifer; the unit 3, formed by limestone, chert, and shale, is interpreted in this work as an aquiclude due to the presence of springs along the contact with the unit 2. The karst aquifer is strongly divided into, at least, 19 groundwater bodies (phreatic zones) laying lie as terraces from 140 to 1,425 m a.s.l. These groundwater bodies are compartmentalized by the units 1, 3, 4, and 5 and their elevation decreases step by step toward the North and to the position of the Cares River, displaying a geometry in “terraces”. The units 1, 3, and 4 represent the lateral and lower boundaries of the groundwater bodies, whereas the unit 5 usually marks their lower limit. Most of the groundwater bodies are unconfined, with flow directions to the NW, SE, and sometimes, to the North. The hydrogeological model includes 42 cave siphons documented by speleological works which are sited where the conduits appear saturated by water. The siphons are usually perched between 100 and 200 m over the supposed level of groundwater bodies. In some areas placed in the core of the massifs, groups of neighbor siphons of different caves are placed at the same altitude and perched up to 650 m above the inferred groundwater bodies. This data suggests that the geometry of the aquifer in these areas could present more compartments than the divisions that can be recognized.

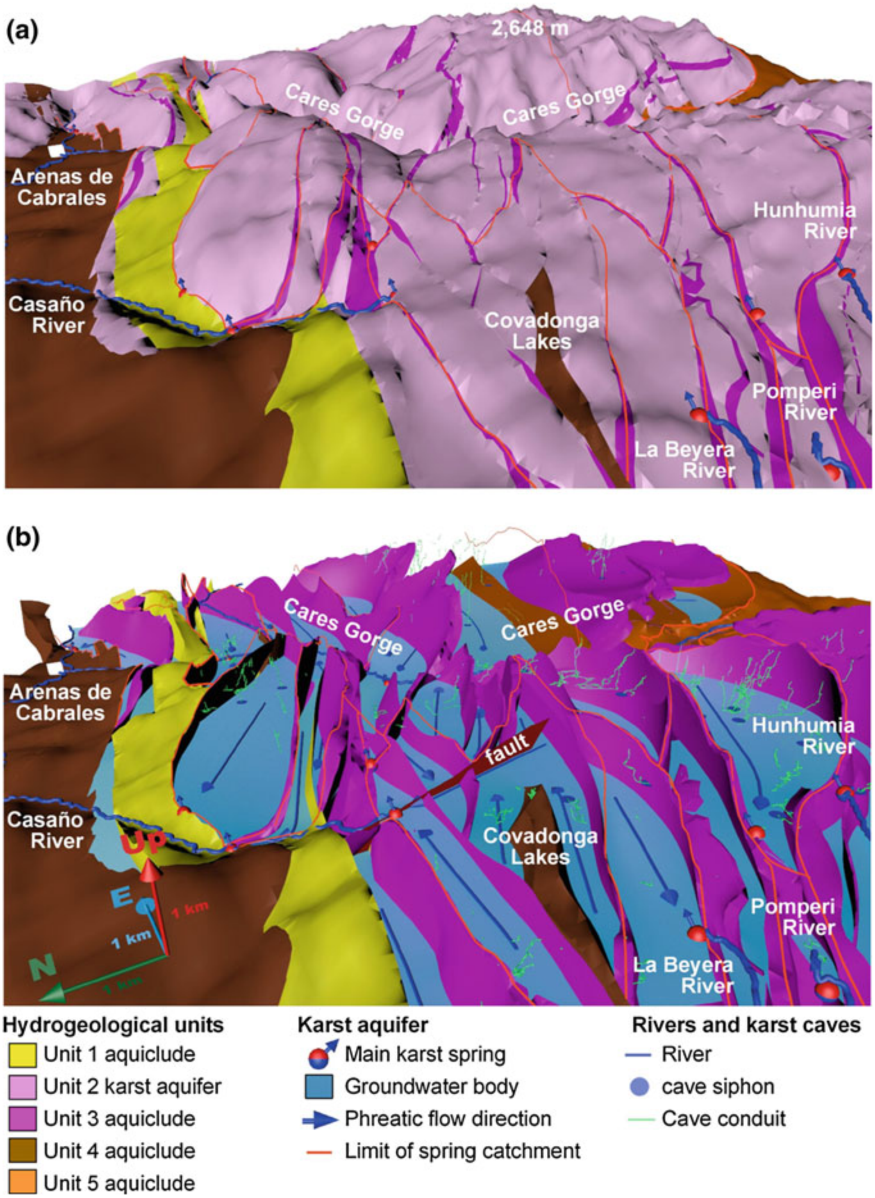

Fig. 2 **a** Zoom on the hydrogeological model showing the limits of the main karst springs catchment. The position of the point of view is displayed in Fig. 1. **b** Same view excluding the volumes of limestone (karst aquifer) in order to display the groundwater bodies (saturated aquifer), phreatic flow directions, and documented caves conduits and siphons

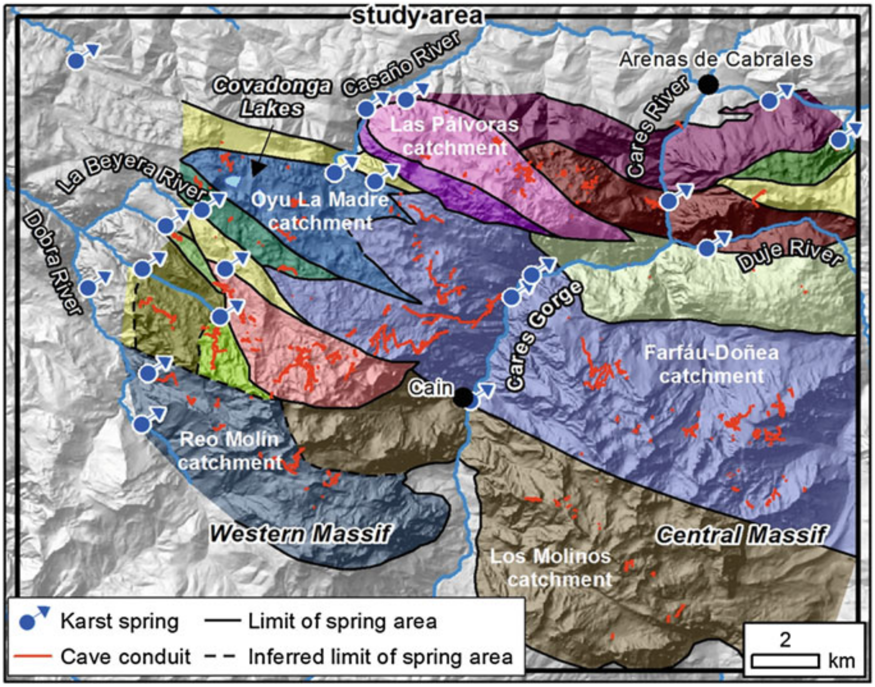

Fig. 3 Cave conduits and spring catchments delineated on the basis of the hydrogeological model, showing the name of the biggest areas. Cave data are provided from speleologists

The hydrogeological model allows us to delineate 17 catchment areas of springs (named "spring catchment" in this work) which limits are shown in Fig. 3. The geometry of the spring catchment is designed for low-flow conditions and is conform to tracer-tests results performed for low water stage. Their extension ranges from 1 to 86 km^2 and their geometry presents high differences from one area to another. Eight spring catchments (the bigger ones) are drained by springs related with the Cares Basin and seven of them flow to the Sella Basin. The base levels of the spring catchments are marked by the altitude of the main permanent springs, although some conduits can be placed under the base level. The base levels of the spring catchments associated to the Dobra basin are sited varying from 1,050 to 1,450 m a.s.l. and the base levels related to the Cares basin are located between 140 and 440 m a.s.l., although one of them, Oyu La Madre spring, lies at 835 m a.s.l.

The hydrogeological model involves 214 km of cave passages, usually showing cavities with length ranging from 1 to 4 km and depth exceeding 100 m. The caves are formed by horizontal and vertical conduits. Previous works (Ballesteros et al. 2011; Smart 1984) evidence that vertical conduits are vadose shafts while horizontal conduits correspond to vadose canyons or phreatic and epiphreatic conduits. The vertical distribution of the conduits density highlights 24 altitudes where the

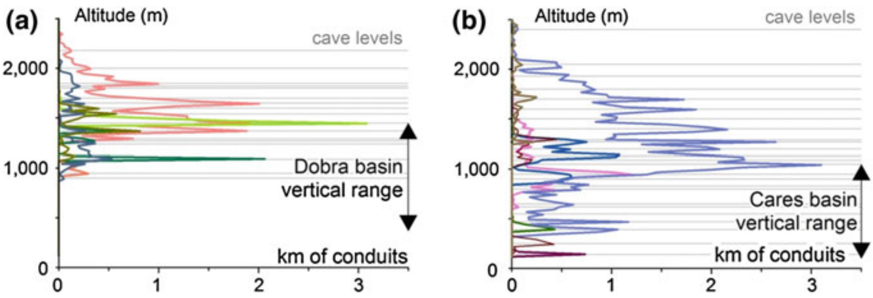

Fig. 4 **a** Vertical distribution of conduits density of the spring catchments related to Dobra basin. **b** Vertical distribution of conduits density of the spring catchments related to Cares basin

abundance of conduits is higher and where phreatic and epiphreatic morphologies are identified by previous works (Ballesteros et al. 2011; Smart 1984; Senior 1987 and others) and by the author. These altitudes define 24 cave levels in the entire area of study ranging from 140 to 2,400 m a.s.l. Most of the cave levels can be correlated in several spring catchments although the abundance of conduits is different from one level to another. Phreatic and epiphreatic features were identified in most of these cave levels in previous works or by the authors.

The comparison of the altimetric distribution profiles of the spring catchments related to Dobra and Cares basins are shown in Fig. 4. The cave levels of both basins are similar over the 1,090 m a.s.l., but below this elevation spring catchments of the Dobra basin do not present cavities in the study area. In this way, two sequences of cave levels can be established. The first sequence includes 13 cave levels defined over 1,090 m a.s.l. and the second sequence involves 11 cave levels, only in the Cares basin, at less than 1,090 m altitude.

5 Discussion and Conclusions

The hydrogeological model shows that the karst aquifer is strongly compartmentalized in, at least, 19 groundwater bodies related to caves with few kilometers length. These data evidence that the cave evolution should be related to the evolution of the aquifer, controlled by the fluvial network. The idea is supported by the three points: (1) the geometry of the spring catchments and the position of the rivers suggest that small western and northern spring catchments and their caves are being captured by the Cares River, increasing those areas of Farfáu-Doñea and Los Molinos springs; (2) the cave level sequence is related to the two fluvial basin and the lowering of the base level, allowing us to define two phases of caves evolution; and (3) fluvial network acts as regional base level of the karst systems, the organization of the caves reflects the evolution of the fluvial network. In the first phase, the first sequence of cave levels (2,400–1,090 m a.s.l.) was developed at a regional scale during the incision of the Cares and Dobra Rivers. In the second phase, a second sequence of caves levels (1,090–140 m a.s.l.) was originated in the Central Massif and the West and North of the Western Massif related to the incision of the Cares River. During this second phase, the incision of Dobra River was continuous, and probably, unknown cave levels and spring areas from the Western Massif were captured by the Cares River and deep shafts were developed intercepting previous cave levels in both massifs. The differences in the evolution of the Cares and Dobra basins are unknown and, perhaps, can be related to different erosion rates, differences about the lithology of the bedrock, the effects of the glaciations, or other reasons that must be considered for future research in the area.

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