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COPING WITH WATER SCARCITY

The International Association of Hydrogeologists

22ND - 27TH SEPTEMBER 2019

MALAGA, SPAIN

FIELD TRIP 8

Serranía de Ronda

Supported by

club del agua subterránea

A.E.H.

Mid-congress field trip to Serranía de Ronda (Malaga province, S Spain)

Key features

Departure: Wednesday 25th September 8:00 am / Arrival: Wednesday 25th September 19:00 pm approx.

Instructors: Juan Antonio Barberá Fornell and Beatriz de la Torre Martínez

Guide authors: Juan Antonio Barberá Fornell and Beatriz de la Torre Martínez

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Introduction

This field trip go into in the NW sector of the Malaga province (south of Spain), where Serranía de Ronda (Ronda mountains) is found. In this part, a great variety of natural areas having remarkable geological and hydrogeological interest are widespread:

- Sierra de las Nieves (stops* 1 and 2)
- Ronda city (stop* 3)
- Sierra de Líbar (stops* 4 and 5)
- Sierra de Carrasco (stops* 6)

The location map of figure 1 summarizes the stops planned during the circular route. The meeting and arrival locations are the same, the city centre. *Stops should be reversely numbered for the bus 2.

Location Map

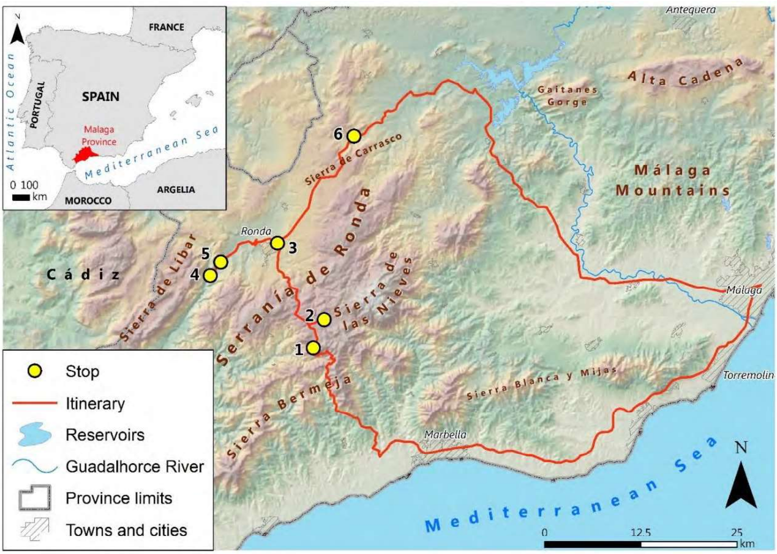

Figure 1. Planned route through Serranía de Ronda (Ronda mountains), at NW of the Malaga province.

Climate, geologic and hydrogeologic contexts

In terms of regional geology, the visited sector belongs to the Betic Cordillera, which is comprised, as it occurs with other alpine belts, of two main zones (Figure 2): the External Zone, at the N, and the Internal or Zone, at the S. The so called Campo de Gibraltar complex occupies an intermediate position between these two. Each of these zones consists of different tectono-paleogegraphic units. Thus, in the External Zone, these are the Prebetic and the Subbetic, where the most external unit. The Subbetic, its continuation towards the S, is divided into four paleogeographic domains. These are, the most external ones (Prebetic and Subbetic units), the intermediate units between them and the external, middle and internal Subbetic subunits.

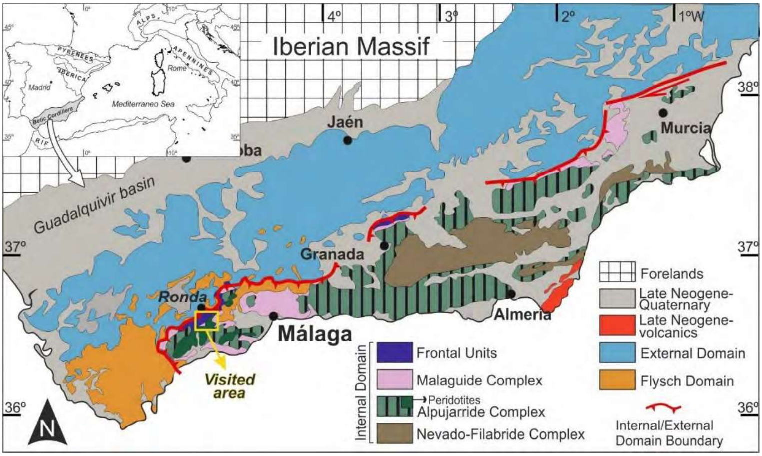

Figure 2. Regional geology of the Betic Cordillera (modified from Martin-Algarra, 1987).

Sierra de las Nieves

This relief is made up of several mountains, namely, from W to E, Sierra de las Nieves, Sierra del Pinar (Yunquera), Sierra Prieta and Sierra de Alcaparaín (Figure 3). In Sierra de las Nieves two main sectors can be differentiated: Llanos de la Nava (stop 2 or 5), at the W, and Torrecilla area, at the E part, both included in the natural park protected as Biosphere Reserve of UNESCO environmental distinctive.

The spatial distribution of precipitation in Sierra de las Nieves is strongly influenced by the SW-NE mountain alignment and their proximity to the Atlantic Ocean (Liñán, 2003). The average annual precipitation is approximately 1000 mm (1200 mm in the western area and 800 mm in the eastern area). During the autumn months, there were local stormy precipitations, which contributed to restoring the deficit of soil moisture accumulated since the previous spring. During the winter months (mainly from December to January), there were moderate to heavy continuous precipitations, which constituted the main rainfall and recharge period. Finally, in the spring and summer, precipitations were scarce or moderate, generating a very limited recharge (Liñán, 2003; Pardo-Igúzquiza *et al*., 2012).

Geologically, Sierra de las Nieves is located in the front of the Internal Zones of the Betic Cordillera. The rock exposures belong to two tectonic units, the Nieves unit and the overlying Yunquera unit, both overthrusted by a third one (Los Reales unit) made up by peridotitic rocks (Figure 2). The stratigraphic series of the Nieves Unit (Martín-Algarra, 1987) is constituted by a group of carbonate lithologies, mainly dolostones and limestones, up to 1000 m thick.

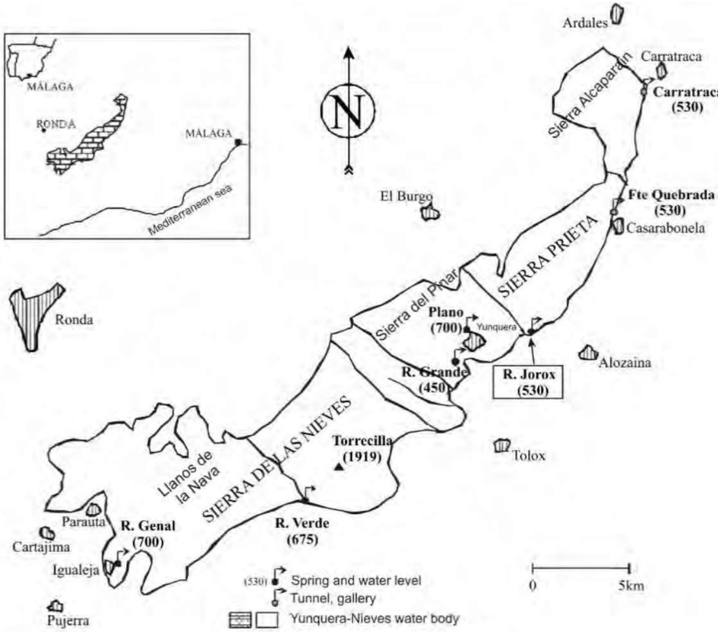

Figure 3. General hydrogeologic map of Sierra de las Nieves (Liñán, 2003).

The geological structure of the Nieves unit basically consists of a large synclinal fold verging NW with an axial direction of N40-60E (Martín-Algarra, 1987), which is overthrusted by the Yunquera unit. These structures are cut by significant N130E fractures, which provoke a horst and graben pattern and, consequently the relative uplift of some areas with respect to others (Pistre *et al.*, 2002). Thus, Torrecilla area and Sierra Prieta constitute two horsts, while the western part of Sierra de las Nieves (Llanos de la Nava) and Sierra del Pinar (Yunquera) are two grabens.

Considering the geomorphological aspect, the massif of Sierra de las Nieves constitutes one of the best Spanish examples of mediterranean karst of intermediate altitude-mountain range. Its higher sector at the NW of the Torrecilla peak shows a plateau landscape with altitudes ranging between 1700 and 1800 m a.s.l. This high plain is bounded by hills alternating with wide U-shaped valleys, karstic depressions and V-shaped valleys in the plateau border, which go into deep and steep creeks. In this massif we can find magnificent examples of exokarstic and endokarstic forms, as well as surficial stream shapes, periglacial and polygenetic features (Delannoy, 1987). The most characteristics exokarstic landscape in Sierra de las Nieves are closed depressions (dolines) that break the bottom of the summit plateau, the semipolje of Llanos de la Nava and the sculpted karren (Delannoy and Guendon, 1986). The cavities are very abundant in the Sierra de la Nieves, especially those of vertical development. More than 100 cavities have been inventoried and mapped by the Underground Explorations Group of Malaga. Undoubtedly, the emblematic cavity of Sierra de las Nieves is the GESM shaft 1101 m deep.

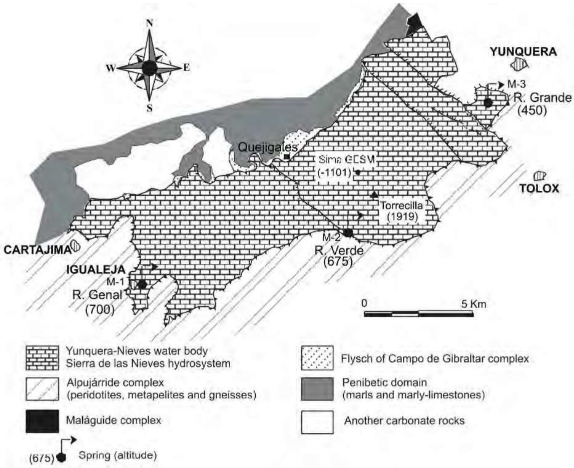

Figure 4. Yunquera-Nieves hydrogeologic unit (modified from Liñán et al., 2001).

The Yunquera-Nieves hydrogeological unit (Figure 4) is formed of rocks belonging to the thick dolomitic-limestone series of the Nieves and Yunquera units, which are bordered by low-permeability lithologies. The carbonate rocks outcrop in the Sierra de las Nieves, Sierra de Prieta and Sierra de Alcaparain, with a total extension of 170 km^2. Recharge takes place by the infiltration of rainwater and snowmelt. Groundwater discharge occurs basically through springs on the southern edge of the unit (Figure 4) and through a few pumping wells used for water supply and irrigation. The most important springs are (Figures 3 and 4): Grande, with an average discharge of 625 L/s and peak flow up to 5000 L/s; Genal, with an average flow of 375 L/s; Verde, with an average flow of 350 L/s; and Jorox, with an average flow of 110 L/s. Hydrograph analysis reveals that fast decreases in water level occur in these springs, due to the existence of a relatively highly karstified system. Groundwater is of Ca-HCO_3 and Ca-Mg HCO_3 types, low mineralized and experiment rapid chemical variations (Andreo *et al.*, 2004). All this evidences suggest that residence times are short because the calcareous rocks have developed a karstic drainage pattern (conduit flow system).

Sierra de Líbar

It is located in the northwestern edge of the Malaga province. This area basically consists of two NE-SW striking mountain ranges, which enclose a series of flat landforms between them, named Llanos de Líbar or Poljes de Líbar (Figure 5). The poljes hosted in Sierra de Líbar are situated in the altitude interval 950 - 1000 m a.s.l. At the E, land surface descends relatively steep down to less than 400 m a.s.l. in the

Guadiaro river, while at the W the high land called Llanos de Villaluenga (approximately 800 m a.s.l.) is found.

While the average temperature (14-18 ºC) is quite homogenously distributed, the annual precipitation shows larger differences. It strongly varies spatially, but also depending on the climate (dry and wet years). However, there is no clear relation between precipitation and elevation. The orientation of the main wind direction and the protection effect by mountain ranges seems to be more important.

From the geological standpoint, Sierra de Líbar is located in the Penibetic unit, in the western part of the Internal Subbetic one (Figure 2). In this area the rocks cropping out are of carbonate nature and Jurassic age, which are underlayed by Triassic clays with evaporites (Keuper formation) and overlayed by marls and marly-limestones of Cretaceous age (Figure 6). The Jurassic rock sequence may be up to 600 m thick (Martin-Algarra, 1987).

The geological structure of Sierra de Líbar (Figure 6) is characterised by a series of NE-SW oriented anticlines and synclines, which are several kilometres long and slightly plunge to the NE. Longitudinal faults associated with a syncline in the centre of the box-fold delimit a series of flat and low lands, in which the Cretaceous sediments are hosted. An intense tectonic deformation (reverse and normal faults) affecting folded rocks can be observed especially in the Jurassic materials.

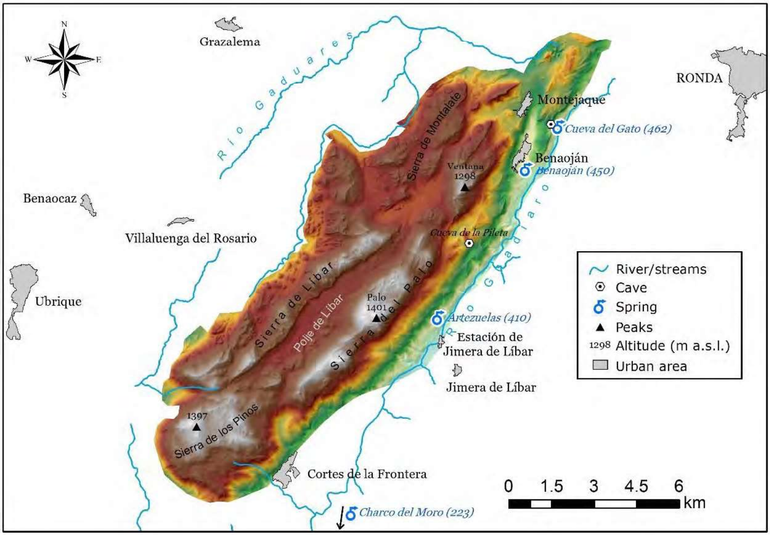

Figure 5. Physiographic features of Sierra de Líbar.

The lithological and geological structure determine the existence of a relief characterised by steep slopes and the plateau in the central sector, where there are abundant karstic landforms (Delannoy, 1987), including karren, sinkholes and poljes with swallow holes, while at the northern edge there are even some streams that infiltrate directly into the limestones, as well as abundant karstic caves. Vast areas of the Sierra de Líbar are covered by karren fields of different types. In many places the extensive karstification already created ruin-like karren features (Delannoy, 1998) which are sometimes hard to distinguish of rockfall blocks. Thus, in Jurassic limestones exposures some spectacular features (e.g. screw-shaped pinnacles) can be observed.

Dolines are also very abundant in the outcrops of the Jurassic rocks. Some of them are filled with sediment or residual red clays (*terra rossa*), the larger ones often containing smaller dolines, acting as swallow holes. Several poljes exist in this area, the most important is the polje de Líbar, 4'3 km long and 1'5 km wide. It is linked to a tectonic semigraben, situated in the axis of the box fold. This polje is drained by a stream which infiltrates into several ponors. They sink in very deep shafts or simas -the Spanish word-. Many of these shafts, some still active during the rainy season, others not active anymore, have been explored by speleologists. A more spectacular case is the sinking stream of the Gaduares river. This river, collecting the surface runoff of the north-western slopes of the Sierra de Líbar and (to a larger part) of the flysch areas north-west of studied area, totally sinks into the karst aquifer in the N of the Sierra de Líbar (Hundidero). Two well-explored cave systems were developed within Sierra de Líbar: the Hundidero-Gato system and the Pileta Cave.

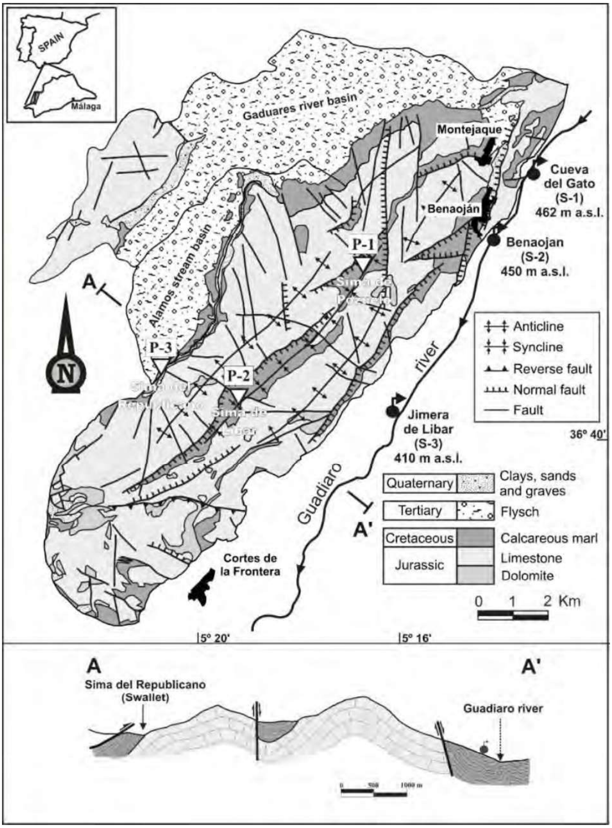

Figure 6. Geologic map and aquifer geometry of Sierra de Líbar (Andreo et al., 2006).

Sierra de Líbar aquifer is built up mainly by Jurassic limestones, and is limited by the clayey materials of the Keuper at the basement and the Cretaceous marls at the top (Figure 6). The Keuper clays as well as the materials of the Tertiary formations are impermeable. The recharge of the aquifer is done by direct percolation of the rainfall and the infiltration of important volumes of surface runoff from outside the area (Gaduares river and Álamos stream). The most important springs are all situated in the east of the Sierra de Líbar (Figure 6), near the river Guadiaro, Cueva del Gato spring (stop 5 or 2), with an average flow of 1'5 m^3/s, although during flood periods it can surpass 20 m^3/s, Benaoján, with an average flow of 0'88 m^3/s, Charco del Moro, with an aproximated average flow of 2 m^3/s and Jimera de Líbar, with an average flow of 0'15 m^3/s. Apart from the Charco del Moro spring they concentrate on the northern half of the area.

The mentioned springs increase rapidly in flow, from null discharge to several m^3/s of flow after rainfall events. Hydrograph analysis reveals that fast decreases in flow occur in these springs, due to the existence of karstification (Benavente y Mangin, 1984). The chemical type of groundwater in Sierra de Líbar is of calcium-bicarbonate. It is characterised by low mineralization and rapid chemical variations; the frequency curves of hydrochemical data show a wide variation range and are predominantly plurimodal (Carrasco *et al.*, 2001).

Stop 1: Peridotites (Sierra de las Nieves)

Peridotites are plutonic rocks whit a deep origin, rich in olivine and ferromagnesian materials. These rocks come from fragments of the upper terrestrial mantle, located under the continental and oceanic crust, at depths between 70 and 700 km. Around 450 km^2 of extension make it the largest outcrop in Europe. Today, there is controversy regarding the origin of this mass of magmatic rocks. On one hand, it is understood that its location has been the result of a stage of crustal thinning, expansion and opening of the Atlantic, followed by the rise of viscous and heavy magma from the superior mantle of the Earth. Loomis (1972) states that peridotites intruded diapiric way into the Earth's crust whit temperature conditions between 1000 and 1200 ° C, which caused an extensive halo of contact metamorphism in the adjacent rocks. Magma could be aware of transform faults, perpendicular to the Atlantic dorsal locks, and whose traces are currently limited to the African and Iberian plates.

Previous hydrogeological studies (Vadillo *et al.*, 2015) have allowed to distinguish surface, subsurface and deep flow system and to establish a conceptual scheme of hydrogeological functioning system. Most of springs studied show hydrodynamic inertia with constant discharge (1-2 L/s) during the hydrological year. However, there is a hydrochemical evolution with two great extremes (Figure 7): (1) springs with waters low to medium electrical conductivities (200-700 μS/cm) and pH less than 9. In this case, the flows are "epiperidotytic" (surface and subsurface) and hydrogeochemical reactions are characterized by low solubility of minerals, the contribution of CO_2 and active serpentinization reactions.

They are waters with bicarbonated-magnesium or magnesium-sodium facies: and (2) springs with waters more mineralized (EC > 700 μS/cm) and a pH greater than 9 (up to 12). The discharge of this springs is related to deep flows favored by the tectonic (overthrust, faults, etc.), this entails a longer contact time with the rock and the evolution towards a closed system (CO_2 and O_2), which causes reduced waters, very old (thousands of years), thermal and Cl-Na or Ca-OH facies.

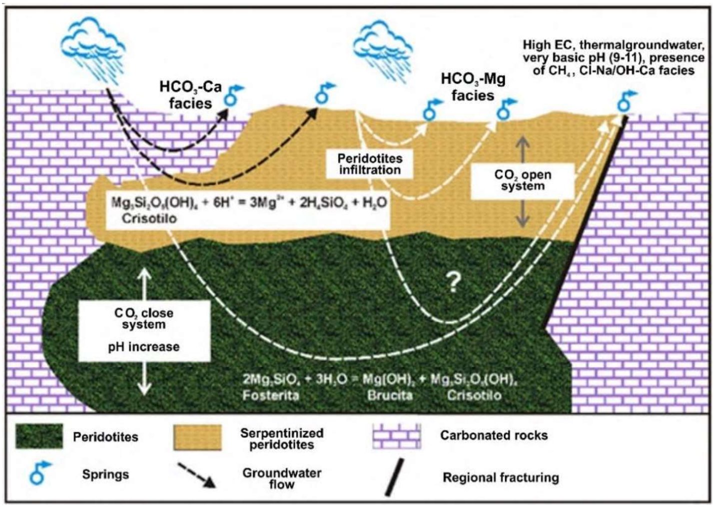

Figure 7. Hydrogeological conceptual model of the peridotites of Ronda system (Modified from Marques et al., 2008).

Stop 2: La Nava de Ronda (Sierra de las Nieves)

This a flat karstic landform situated in the western part of Sierra de las Nieves (Figure 8), 4'5 km length and 1'5 km width (Lhénaff, 1998). This polje has developed in the axis of the synclinal structure, in which extensively crops out Brecha de la Nava. Nowadays, this polje is drained by two streams, but also there are some swallow holes and dolines, whose bottom can be flooded in the rainy periods. From the hydrogeological point of view, this area is very important due it constitutes a preferential area of infiltration and recharge.

Figure 8. Overview of the Nava polje and Alcojona hill, Sierra de las Nieves (Author: Francisco Portillo).

Stop 3: Ronda city

The Tajo de Ronda (Figure 9) allows a magnificent observation of the sediments deposited in the meridional margin of the Miocene basin of Ronda. It is constituted by conglomerates in the lowest part and calcareous sandstones towards the top, deposited in shallow coastal environments. In the Tajo de Ronda sediments are arranged horizontally, which indicates that they have not suffered valuable deformations. As soon as the region emerged, the stream erosion acted intensely in the area of Ronda, largely favoured by the elevation of the region. This has given place to the formation of the Tajo and the deep canyon of the Guadalcobacín River.

Figure 9. The sculpted gorge of Tajo de Ronda (Author: Luis Marín).

Stop 4: Molino del Santo spring

The spring of Benaoján or Molino del Santo drains the NE sector of the Sierra de Líbar (Figures 6 and 10.A). The hydrographs of these discharge points (Figure 10.B) show rapid and marked peak flows, with important differences between the end of depletion and the discharge peak. Normally, hydrodynamic responses occur one day after the significant rain event (Jiménez, 2010).

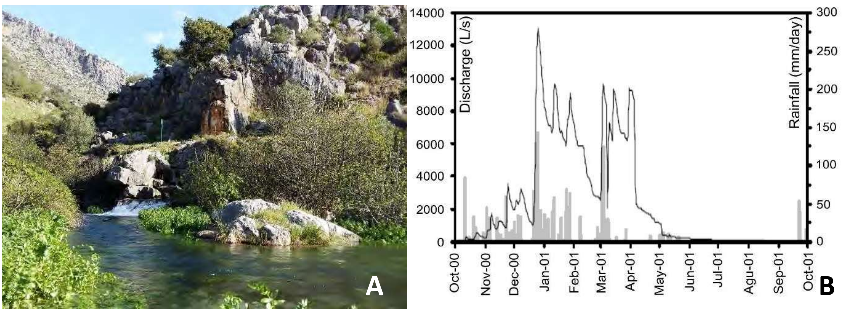

Figure 10. (A) Benaoján spring or Molino del Santo spring in Benaoján village (Author: Beatriz de la Torre) and (B) hydrograph of this spring from daily data for the hydrologic year 2000-2001 (Jiménez, 2010). Rainfall recorded in the meteorological station of the Sierra de Líbar (Cueva de la Pileta).

Stop 5: Cueva del gato

This karst spring is situated in the homonymous cave (Cueva del Gato), about 25 metres above the talweg of the Guadiaro river (Figure 5, 6 and 12). It is fed by the underground continuation of the Gaduares river as well as other karst water inflows. It shows a fast and strong reaction to rainfall events and the typical fluctuations of karst water springs (Figure 11). The maximum outflow can reach more than 20 m^3/s (DGOHCA, 1997) while minimum outflows as low as 0'02 m^3/s were measured in September of 2000 (Jiménez, 2010). The average outflow is approximately 1'5 m^3/s, the annual discharge between 60 and 65 hm^3. The spring itself is not captured for water supply.

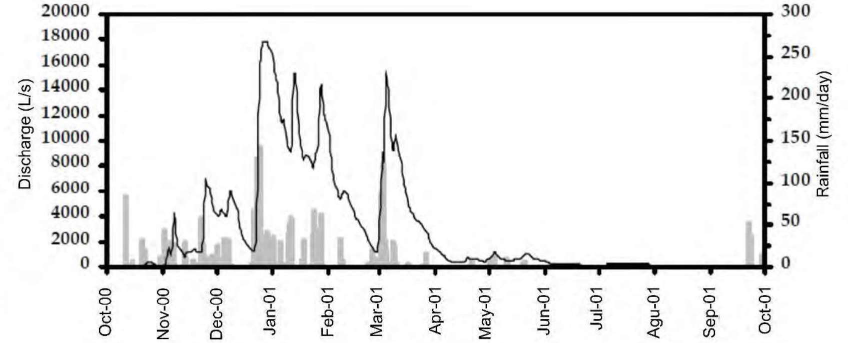

Figure 11. Hydrograph of the Cueva del Gato spring from daily data for the hydrologic year 2000-2001 (Jiménez, 2010). Rainfall recorded in the meteorological station of the Sierra de Líbar (Cueva de la Pileta).

Figure 12. (A) Cueva del Gato spring and (B) cave entrance of Hundidero dam as the main recharge point of the Cueva del Gato spring. (Author: Beatriz de la Torre).

Stop 6: Travertine in the town of Cuevas del Becerro

The rural town of Cuevas del Becerro has been built over a travertine platform (Figure 13) that resulted from the precipitation of carbonate minerals dissolved in groundwater flowing through Sierra de Carrasco. This recently formed carbonate platform (725 m a.s.l.) has an elliptical shape and it is bordered at the N by the Cuevas river (680 m a.s.l.) and at the SW by the Castillón carbonate mountain of Jurassic age. In the latter border, the Carrizal spring (735 m a.s.l.), whose discharge is responsible of the travertine formation, emerges in the contact between the Jurassic carbonate rocks and the travertine platform (Barberá, 2014). The thickness of the travertine deposit is about 45-50 m and the absolute age, measured from the application of radiogenic techniques, is around 25-27 ky (Cruz-Sanjulián, 1981). This author also estimated the precipitation rate from of this travertine providing a rough value of 1-2 mm/year.

Figure 13. Panoramic view of the town of Cuevas del Becerro and the travertine formation underlaying it. (Author: Juan Antonio Barberá).

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