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A GEOMORPHOLOGICAL AND SPELEOLOGICAL APPROACH IN THE STUDY OF HYDROGEOLOGY OF GYPSUM KARST OF SORBAS (SE SPAIN)

ABSTRACT: SANNA L., GAZQUEZ F. & CALAFORRA J.-M., *A geomorphological and speleological approach in the study of hydrogeology of gypsum karst of Sorbas (SE Spain).* (IT ISSN 0391-9838, 2012).

The Sorbas massif (Almeria, SE Spain) is one of most karstified gypsiferous areas of the world, with hundreds of dolines and different karst features. In this massif more than 1000 caves have been discovered in an area of about 12 km^2. Its Messinian gypsum, deposited in a Neogene intramontane basin, is composed of continuous strata of very pure selenite. The purpose of this research is to identify the main karst geomorphological features and to integrate these data with hydrogeological records for better understanding the role of the karst aquifer in the groundwater recharge of the Aguas River. This study took place in the southern part of the Sorbas gypsum plateau with several steps and multiple field campaigns for geomorphological and geostructural data compilation and to record the different karst forms. Also water samples from the main springs have been collected for geochemical analysis. All field items have been inventoried with corresponding spatial position and compared with the previously existing information. Subsequently, an exhaustive data elaboration was performed leading to the definition of the karst features of the area, rendered by maps. To assess the extent of karstification, the spatial analysis of the cave entrance's distribution together with structural alignments have been studied. The cave entrances, a means of access to deep karst, are an expression of discontinuous surface karst phenomenon closely connected with underground drainage that allow to reconstruct the main direction of groundwater flow. This kind of approach can be apply in those areas where rock is exploited, to discern a possible indicator of the effects of the mining and to find the best management conditions that allow the conservation of most of the cavities, the preservation of the recharge basin of the karst system and springs, the minimum affectation to the vadose groundwater flow, the protection of nearby springs and minimizing the visual impact.

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KEY WORDS: Evaporite karst, Karst geomorphology, Karst aquifer, Almeria, Spain.

RESUMEN: SANNA L., GAZQUEZ F. & CALAFORRA J.M., *Un enfoque geomorfológico y espeleológico en el estudio de la hidrogeología del karst en yeso de Sorbas (SE España).* (IT ISSN 0391-9838, 2012).

El karst en yeso de Sorbas (Almería, SE España) es una de las zonas yesíferas más karstificadas a escala mundial, donde aparecen centenares de dolinas entre otras formaciones kársticas singulares. En este macizo, se han identificado más de 1000 entradas de cavidades distribuidas en un área aproximada de 12 km^2. Los niveles yesíferos, depositados en una depresión intramontañosa de las Cordilleras Béticas durante el Mesiniense, están constituidos principalmente por estratos continuos de yeso selenítico de alta pureza y margas interestratificadas. El objetivo de este estudio es identificar las principales características geomorfológicas del karst e integrarlas con datos hidrogeológicos para identificar la interrelación entre el acuífero kárstico y la recarga subterránea del Río Aguas. Este trabajo se ha centrado en el territorio más meridional del altiplano yesífero de Sorbas, donde se llevaron a cabo diversas campañas de muestreo y toma de datos geomorfológicos y geoestructurales. Estos elementos han sido inventariados, georeferenciados y contrastados con los existentes anteriormente. Por otro lado, se ha muestreado el agua de los manantiales principales que drenan el karst de Sorbas para su posterior análisis geoquímico. Se realizó un análisis exhaustivo de los datos recogidos, mediante el cual se definieron las características kársticas del área y que desembocó en la elaboración de mapas geomorfológicos, hidrogeológicos y de vulnerabilidad. Para evaluar la magnitud de la karstificación, se ha analizado la distribución espacial de las entradas de las distintas cavidades junto con las alineaciones estructurales de las facturas. Las entradas de las cuevas, como vía de acceso preferencial a los sistemas kársticos profundos, son una expresión superficial discontinua del fenómeno kárstico y están distribuidas en función de la red de drenaje hídrico subterráneo, lo que ha permitido inferir la dirección principal del flujo. Este estudio es aplicable a otras áreas kársticas afectadas por minería a cielo abierto, con el fin de predecir los efectos provocados por la actividades mineras sobre el medio subterráneo y orientar la explotación hacia la conservación de las cavidades, la preservación de la cuenca de recarga de los sistemas kársticos, así como atenuar la afección al flujo subterráneo de carácter vadoso, la protección de los manantiales cercanos y la minimización del impacto paisajístico.

PALABRAS CLAVES: Karst evaporítico, Geomorfología kárstica, Acuífero kárstico, Almería, España.

INTRODUCTION

Due to the widespread karst developed on limestone or dolostone rocks, the speleogenetic importance of gypsum had been relegated to the background of karst sciences. However, since the 70s, the existence of an extensive karst network formed within massive gypsum, with more of 100 km of linear development, was discovered in Ukraine (Klimchouk & Aksem, 2002) and this created a great interest from various researchers, so that nowadays, after numerous studies, the gypsum karst areas are highly regarded for their hydrogeological and environmental peculiarities (Calaforra & Pulido-Bosch, 1996).

Furthermore, the advances in scientific knowledge of karst in gypsum are still increasing and areas with higher global interest are the Tertiary evaporitic basin in the upper section of the Dniester and Prut river besins (Ukraine) and the extensive fore-Ural gypsum karst region, both in the Eastern European Platform; the Cambrian platform in eastern Siberia, the outcrop of Pinega and Kuloj region in the North of the European part of Russia, the Tertiary gypsum of Emilia Romagna (Italy), the sulfo-gypsiferous karst of Sicily (Italy), the Gypsum Plain in New Mexico (USA) and the Messinian basin of Sorbas in Almeria (Spain) (Klimchouk & *alii*, 1996, Stafford & *alii*, 2008a, b, c).

The gypsum karst of Sorbas in the South-East of Spain (fig. 1) is distinguished from other evaporite karst areas by an important geological environmental heritage (Gutierrrez & *alii*, 2008), which includes particular surface karst features such as tumuli, a high density of caves and the presence of a large variety of speleothems, some of them unique in the world (Calaforra & Pulido-Bosch, 1999; Calaforra & Forti, 1993). In this massif more than 1,000 caves have been discovered in an area of about 12 km^2 (Calaforra & Pulido-Bosch, 2003): the Agua Cave (Cueva del Agua) is the longest gypsum cave in Spain, with a development of about 8.9 km; the hollow gypsum stalagmites, mainly present in the Forest's Gallery of the Covadura Cave, are found only few places, as in Sorbas, Kugutang and Gaurdak regions (South-East Turkmenistan) and Lechuguilla (New Mexico, USA) (Forti 1996); the gypsum balls that appear on the walls of most of the caves, as in the Agua Cave, Tesoro Cave (Cueva del Tesoro), Covadura Cave, etc., are quite rare elsewhere. The existence of metric twinned gypsum with arrowhead shape, are especially important in the Tesoro Cave. Within it, in the Crystals Gallery, a twin crystal with a length of 2 m has been found. The gypsum tray speleothems found in Covadura Cave, sometimes developed as a «fir», have been seen only in Sorbas and in New Mexico (Doran & Hill, 1998). Therefore, a total of 2,375 hectares were declared Protected Natural Space of the Gypsum Karst of Sorbas in

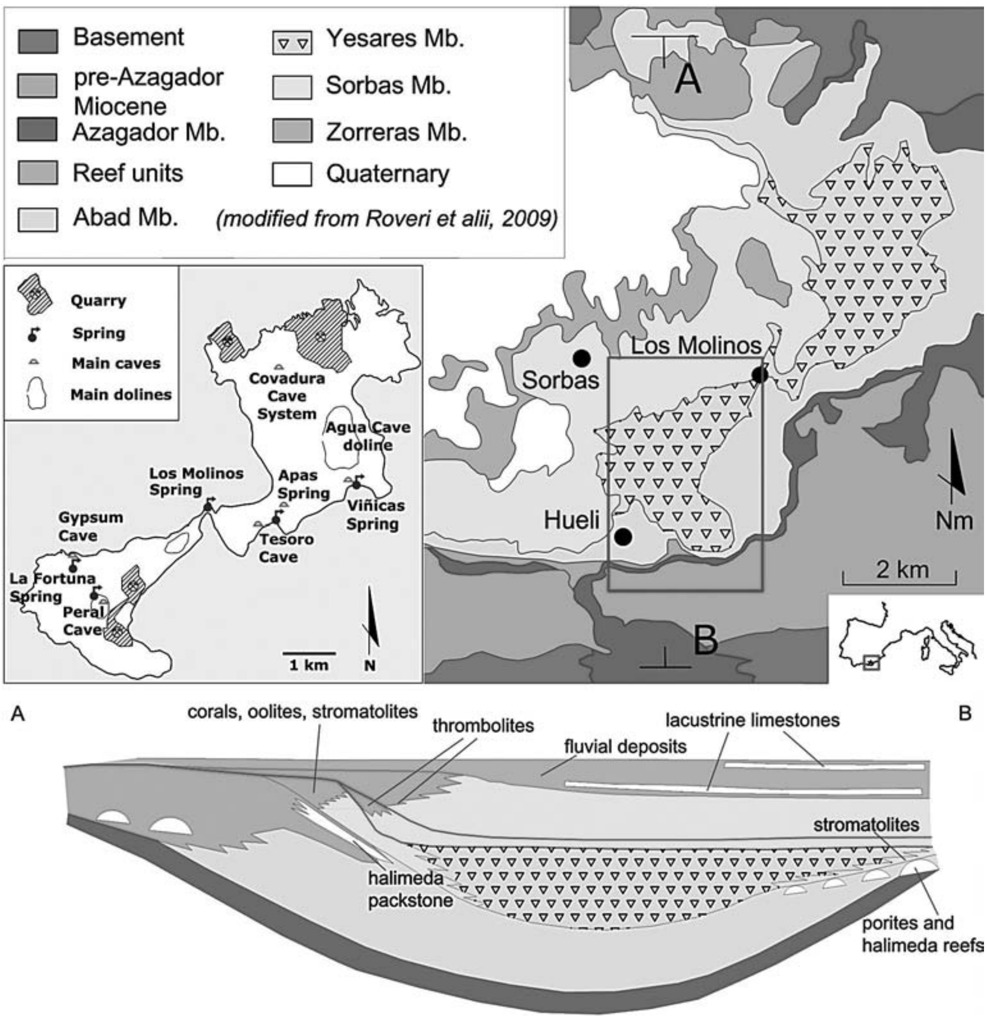

FIG. 1 - Geological sketch map of Tabernas-Sorbas Basin and study area location (red square) with the main interesting points of the Sorbas gypsum karst area.

1989 by the Andalucía Government for its caves, geomorphological and biological features (Calaforra, 2003). In addition, the area was confirmed Special Protection Area for Birds in 2002 and currently is proposed as a Site of Community Importance (Junta de Andalucía, 1988; 1989).

This region not only has geological and environmental interests, but also a great relevance due to its mining significance, since there are three gypsum quarries that support the local economy and its surroundings. Its Messinian gypsum, deposited into a Neogene intramontane basin, is composed of continuous strata of very pure selenite, which during the last 40 years has been extracted producing more than 200,000 tonnes/year of high quality gypsum (Pulido-Bosch & *alii*, 2004). The exploitation of gypsum has intensively affected the caves and the ecosystem, especially the landscape and the surface and underground water drainage. For this reason, an adaptive management of the area is essential for the coordination between protection of the karst environment and development of mining activity, before the complete destruction of such natural epigean and hypogean karst treasures occurs.

With a multidisciplinary approach that models geomorphological and speleological data together with hydrogeological ones, the aim of this research is to locate the main points of aquifer recharge, to identify potential groundwater flow divides in the sector and to understand the groundwater drainage network in the southern part of the gypsum karst massif of Sorbas, that will allow to drawing a mining guide to achieve the conservation of most of the karst features.

STUDY AREA

The gypsum karst of Sorbas is a part of the Tabernas-Sorbas Basin (SE Spain), a narrow, E-W elongated intramontane Neogene depression, within the Betic Belt, bordered by metamorphic rocks and filled by a thick, continental to marine sedimentary sequence (Dronkert, 1977) (fig. 1). From a stratigraphic point of view, the sedimentary series is represented by 5 units from Middle Miocene to Messinian in age separated by unconformities (fig. 1). Messinian evaporite units (Yesares Member) overly Upper Tortonian eroded conglomerates that pass to sandstones, silt-marly submarine fan and laterally to carbonate reef limestones (Abad's Member) (Mather & *alii*, 2001) and are capped by Pliocene to Quaternary siliciclastic coastal plain sands and alluvial fan conglomerates that mark the final stage of basin infill, before the continued uplift caused a change from aggradation to erosion, producing deep river incisions during Pleistocene (Roep & *alii*, 1979; Mather & Harvey, 1995).

Primary selenite gypsum deposits crop out on top of the Abad's Member marls over an area of about 25 km^2 for a maximum thickness of 130 metres, occurring as 16 cycles of banks up to 30 metres thick of vertically arranged twinned crystals separated (fig. 2A) by salt-marl laminated interbeds up to 3 metres thick (Roveri & *alii*, 2009). Despite their compact appearance, the gypsum layers are composed of large crystals deposited in shallow water that can be up to about 2 metres in length. The structure is poorly-deformed tabular and stratification varies from slightly inclined (from 10° to 20°) to sub-horizontal, with beds affected by some northward tilting and faulting (fig. 2B).

In the study area, three main gypsum strata occur separated by marly discontinuities. These unconformities are marked by gypsum sedimentation hiatuses and among them 10-20 cm thick sandstone levels with carbonate matrix or dark marl are present as well. This piling upward structure plays an important role in the development of the surface and underground drainage network (Calaforra & Pulido-Bosch, 2003). Above the impermeable silty level of the Abad's Member, a thick macrocrystalline layer of gypsum with tree structures in growth position and large spatial continuity appears, easy to use as a guide stratum. Locally river terraces and other alluvial fan deposits rest unconformably on the gypsum. In the highest hill, microbial carbonates also crop out (Roveri & *alii*, 2009).

From a karstological point of view the area was studied since 1982 by researchers from the University of Granada and Almeria (Pulido-Bosch, 1986). Currently, the gradual increase on the karst knowledge has led to unique findings (Calaforra & Pulido-Bosch, 1999). There are more than 1,000 inventoried dolines, most of collapse origin (formed by the failure of the gypsum surface layer). In some areas the doline concentration is extremely high with tens of kilometres of underground conduits, the number of which increases each year with the discovery of new cavities. In the eastern part of the gypsum plateau, the catchment area of the Agua Cave counts more than 100 dolines in 1 km^2, which represents the highest doline density in Spain. All infiltrated waters flow towards different springs: Los Molinos (the main outlet of the whole region with a discharge of about 26 L/s, with a maximum of 120 L/s) (Cano Medina, 2005), Las Viñicas, Tesoro, Peral, Los Apas, Infierno and La Fortuna, (all of them mainly with a mean discharge of less than 1 L/s). In the main structure, cut from the valley of the Aguas River, on the base of underground water flow direction, two different drainage zones can be distinguished: in the NE zone groundwater flows South, with springs at an altitude comprised between 300 to 360 m asl, while in the SW zone drainage is northwards with outlets at 410, 390 and 340 m asl. Los Molinos spring is located at the connection between these two zones.

Sorbas is a semi-arid zone in the eastern part of Almeria Province (SE-Spain), with an average annual temperature of approximately 19.5 ºC, with a minimum in January (11 ºC) and a maximum in July (30 ºC), and a mean annual rainfall of 210 mm yr^{-1} (minima mean values in July and in November), 80% of which is distributed in low-frequency rainstorm events (Esteban-Parra & *alii*, 1998; Calaforra & *alii*, 1993). On average, there are 30 rainy days per year (Pulido Bosch & Calaforra, 1993) and this situation allows the formation of epigenic karst morphologies that are well developed thanks to the high gypsum solubility. Several types of dissolution features common in other similar karst terrains are found. The presence of a consider-

FIG. 2 - Major karst features of gypsum massif of Sorbas. A: twinned gypsum with arrowhead shape. B: evaporite series (left) stands up to the other lithologies (white line marks gypsum-marl contact and the arrow indicate a small house). C: sharp rillenkarren on bare surface. D: large tumulus. E: two cave entrances of the Urra System. F: Infierno Canyon develops along a N-S oriented fracture. (Photos L. Sanna).

able gypsum escarpment, several tens of metres high, on the edge of the karst outcrop is worth mentioning. Bulges with hemispherical morphologies (tumuli), affecting most superficial layers of the gypsum are among the most interesting surface forms (Calaforra & Pulido-Bosch, 1999). They can reach a few metres in diameter (fig. 2D).

Concerning the wide variety of karst forms and their quite homogeneous distribution, this study focuses on an area of 16.7 km^2 located in the south-western part of the gypsum karst massif, on the right side of the Aguas River (fig. 1).

METHODOLOGY

As mentioned above the objective of this research focuses on a detailed study of the south-western part of the gypsum massif of Sorbas, with the aim to understand the underground drainage network, locating the main points of aquifer recharge and identifying potential groundwater flow divides in this sector.

The work was carried out gradually with multiple field trips for data collection. Using standard geological survey techniques, in each outcrop the direction and dip of fractures was measured, the inventory of different forms such as karst sinkholes, caves, potholes, gullies, meandering, depressions, conduits, large tumuli and outcrops of different nature were recorded. All of them were catalogued at their corresponding spatial position (UTM) measured using GPS Garmin e Trex H (3 meters accuracy with DGPS corrections).

Field data processing lead to the creation of a database in ArcGIS 9 environment, which allowed to carry out an exhaustive analysis of the karst features of the area, its geomorphology, the main fracture directions, the major lineations and to compare the new cave entrances with the previously known ones (supplied by Speleo Club Almeria caving club). Surface watersheds were delimitated using 1:20000 PNOA 2008 aerial photographs (no Digital Elevation Models was available) and these data have been integrated with three monthly hydrochemical parameters of the main springs. Temperature, pH and conductivity were collected with a Multi 340 WTW instrument (pH measuring ranges between –2 to +19, resolution 0.01, precision ±0.01; temperature range between –5.0 and +105.0 °C, resolution 0.1 °C, precision ± 0.1 °C; conductivity sensor ranges between 0.00 and 19.99 mS/cm, resolution 0.01 mS/cm, precision ± 0.01 mS/cm). Bicarbonate concentration was determined in field by titration with methyl orange indicator. Water for $\delta^{18}O$ and δD measurements were taken in glass bottles and refrigerated until analyzed. Also 1 mL of HgCl has been added to the samples to avoid contamination from biological CO_2. Isotopic composition have been simultaneously analyzed with a laser spectroscope (Los Gatos Research Instruments: reproducibility of ±0.1‰ and ±0.8‰, respectively) at the Davis Stable Isotope Laboratory of California University.

To assess the extent of karstification, the spatial analysis of the distribution of cave entrances as main surface evidence of karst development, has been studied. There is a discontinuous expression of the karst process that is a function of geostructural conditions, vegetation cover and the degree of speleological knowledge of an area. For these reasons, it is difficult to draw a detailed map of this regional variable. Due to the high density of dolines, and especially their structural alignment, a geostatistical analysis of the spatial variation of the network of underground tunnels permits to describe the distribution of the karst features of Sorbas karst area (i.e. where it is more likely to find karst cavities).

First, a statistical analysis of the variability in the distribution of the entrances has been carried out with a variogram. The cave entrances represent a regionalized variable and are also random functions describing a phenomenon (karstification) distributed in space with an autocorrelation structure where the value of the variable depends on the point of measurement. The variogram is a tool to estimate and simulate this variable, and indicates how the correlation between the data from the experimental points increases or decreases when the distance among them advances. Using the results of the variogram analysis, a spatial interpolation has been applied to create the contours (areas delineated with equal input concentration) by linear kriging using Surfer 8 software. This technique consists in finding the best possible estimate of a feature given the available information; the particularity of this type of model is to use a stationary random function of unknown expression. Later, through analysis of the data collected, a map has been produced by rendering (fig. 5) that provide a density of the karst features.

KARST GEOMORPHOLOGY

The depression of Sorbas is characterized by an arid gypsiferous isolated plateau that dips slightly to the NW, shaped by Pleistocene intense erosion and karstification. The current Sorbas landscape is affected by tectonic factors, mainly related to still active movements. During the last geomorphological evolution phases, several transgressive cycles occurred, interspersed with periods of stability marked by several erosion surfaces at different altitudes above the present sea level. In the highest zone of the massif, these uplifts are corroborated by the deep incision of valleys and perched alluvial terraces on which complex karst morphology is superimposed. This uplift was contemporary to intense surface erosion that has resulted in a significant reduction of the thickness of the sedimentary formations, and of the gypsum beds, which originally must have been much more extensive.

Currently, the structure of the gypsum massif is a monocline plateau whose inclination is still approximately 10° NW. The intersection of the topographical surface with the bedding planes produces a oriented gypsum relief, especially in the area of Los Molinos, or a landscape organized in smooth rounded hills (Hueli and El Peral). In some sectors (Cerron of Hueli), the morphological slopes have lithological character as in the case of carbonated and conglomeratic outcrops found adjacent (or overlapping) to the gypsum strata.

A special geomorphology of the gypsum karst of Sorbas is associated with the strong contrast of the lithologies and structures between gypsum itself and the surrounding rocks. This landscape, located at a mean altitude of about 400 m asl, consists of a large flat area, topographically high, and elongated towards the North-East (fig. 2B). In the southern part of the massif, steep cliffs of at least 20 metres in height, open in front of badlanded valleys excavated on highly erodible marls and clays. This escarpment characterizes the southern and eastern limit of gypsum outcrop, whereas to the North and West the strata disappear beneath more recent sediments (fig. 3).

From a morphological point of view, the area is characterized by two contrasting morphological types. A setting related to the weak clay-marly lithology, with an erosive surface, flattened at the same height in the peak (between 450 and 500 m asl) and then reworked by fluvial incisions.

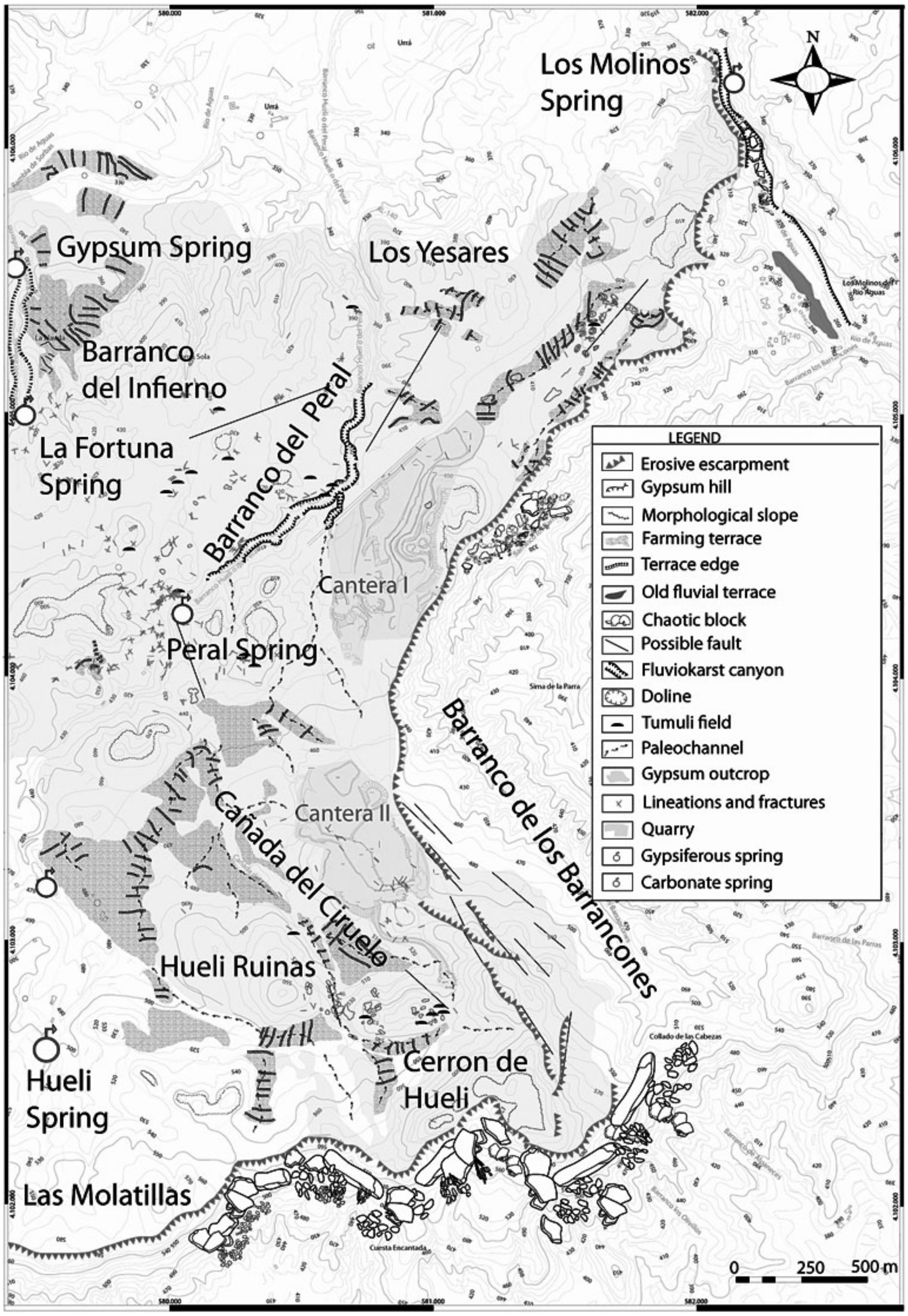

FIG. 3 - Prominent geomorphological features of the study area.

In the western area, the predominant forms in this lithology are more rounded.

On the other hand, the landscape associated to the resistant Messinian succession is more uniform and in the South and East of Sorbas is always observed topographically higher than the other lithology, with elevation above 600 m asl. The gypsum beds gradually dip northwards under the continental deposits.

The semi-arid climate, characterized by mild and relatively dry winters alternated with long dry summers (mostly exposed to south-western quadrant winds which produce heavy summer night condensation phenomena), limits the development of vegetation and accelerates the degradation of the slopes with rapid transport of soils, especially where plant cover is lacking. Throughout the area alluvial fans and terraces have a rather well developed soil produced under different climatic conditions, now more or less used for farming. Furthermore, slope deposits consisting in a set of chaotic blocks of large size are deposited at the base of the escarpment.

The external karst surface is characterized by a large number of dolines, different forms of karren and wide fields of tumuli. Most of these karst features are related to underground water drainage network presents in the arid desert of Sorbas. In fact, the dolines and the sinkholes are located in correspondence of the endokarst as a result of the capture of the surface hydrographic system. They collect the runoff and allow its infiltration contributing to the further supply of the aquifer coming from the slow seepage among the sulphate crystals, following their cleavage planes and inter-crystalline surfaces.

The most abundant surface karst forms are represented by the dolines, with different amplitudes, distributed along the main lineations. As previously mentioned, these are located in large outcrops particularly characterized by intense fracturing and upstream at the head of the valleys. The most important example is seen in Los Molinos sector, where in an area of approximately 1.2 km^2 the highest doline density is aligned along a NE-SW direction (fig. 2E).

Other important geomorphological forms are karst gorges with deep narrow profiles, such as the Barranco del Peral and Barranco del Infierno canyons (fig. 2F). Where the bottom of these canyons is not filled with sediments, a series of fluvial-like morphologies can be recognized (waterfalls, rapids, potholes, and ponds) although usually dry and only rarely occupied by water. On the other hand, when the canyons cut the local water table, perennial springs appear in the talweg. The Peral and La Fortuna outlets are good examples and testify the interconnection between the surface runoff network and the karst aquifer. A common phenomenon in these fluviokarstic canyons is the presence of hanging valleys on the river bed of the main streams, related to a different erosion rate of the main river compared to its smaller tributaries. Another type of hanging valley is generated by regressive erosion that produces the interception of a nearby stream catchment area and leaves a dry relict palaeo-hydrography (palaeo-channels).

An important aspect to consider in the highest hill of Cerrón of Hueli is that epigean features are subordinate to the tectonic lineations. The karst nature of the area, in addition to the almost total absence of surface runoff, is underlined by intense erosion of the rock surface and by the lack of karst mesoforms (dolines), represented only by furrows of variable length and depth in the order of several meters, which represent fractures with vertical development and ending in underlying strata or with the tendency to close gradually towards depth.

Among the epigean features karren (or solution flutes, also known as lapiaz) are very abundant. On slightly dipped structural surfaces (fracture plain and stratification), ruin-like forms and, particularly in tectonized areas, karren of great length and depth that evolve in karren fields are found. Some of these forms are the result of dissolution processes that occurred on the bare rock (solution flutes) whereas other features are related to phenomena developed under soil and plant cover (rounded karren). Among the solution flutes, rillenkarren are common, normally found in isolated rock surfaces of step pavement (fig. 2C), and rinnenkarren (grooves of width and depth of a centimetre to metric scale) with meandering direction on slightly inclined surfaces and straight on steeper ones. Slopes characterized by the presence of stepkarren are also observed.

Also rounded karren (rundkarren) can be distinguished consisting of sub parallel channels with a concave bottom separated by rounded ridges. Finally, the most unique superficial feature on the gypsum karst of Sorbas is the tumulus, which occurs on bare rock when a clear horizontal stratification or lamination is present. These features mainly occur in macrocrystalline gypsum, as in the North side of Peral and in the Cerron of Hueli sectors. Lithological and textural discontinuities play an important role in tumulus genesis (Calaforra & Pulido-Bosch, 1999; Ferrarese & *alii*, 2002). These forms represent a preferential way for the surface water to infiltrate.

FRACTURES AND LINEATIONS

The uplifting of the Sorbas Basin, and the stress of the post-Miocene tectonics, led to the formation of some very vertical normal faults with slight displacement, associated to an intricate network of fractures and joints, traceable on the land surface as discontinuity. Predominant directions are NE-SW (which is the axis of the basin), NW-SE and N-S. One of the main tectonic lineations runs parallel to the Barranco de los Barrancones valley with a length of over 2 km. This fault controls the river path. Most of the ledges and cliff walls are also the result of tectonics, as evidenced by the presence of intense fractures associated with strain on the edge of gypsum cliffs.

It is also possible to determine the chronological order of the succession of deformation events that led to the fracture field. The ENE-WSW direction is the oldest detectable and emphasizes the orientation of the basin. Currently, the water of Aguas River flows along this lineation, especially upstream respect to the Los Molinos spring. Also, the southern border of the massif is developed along this direction. Besides this main lineation, another NW-SE fracture system is overprinted, well marked by the eastern escarpment and the associated river network. Also the reach of Aguas River close to the Los Molinos spring (a possible area of river capture) has the same direction. The most recent lineations are oriented NE-SW, and subordinately N-S, as testified by the narrow canyons that cross the karst plateau.

In general, the study area is characterized by a dense system of fractures and lineations. Fractures are basically vertical (with a few exceptions) and predominantly orientated towards 320° N. Only Los Molinos sector differs considerably, with a main fracture direction of 30° N. In each sector some differences are also found (fig. 4):

Los Yesares. By measuring a total of 110 fractures, a multiple lineations system has been observed. At the remarkable

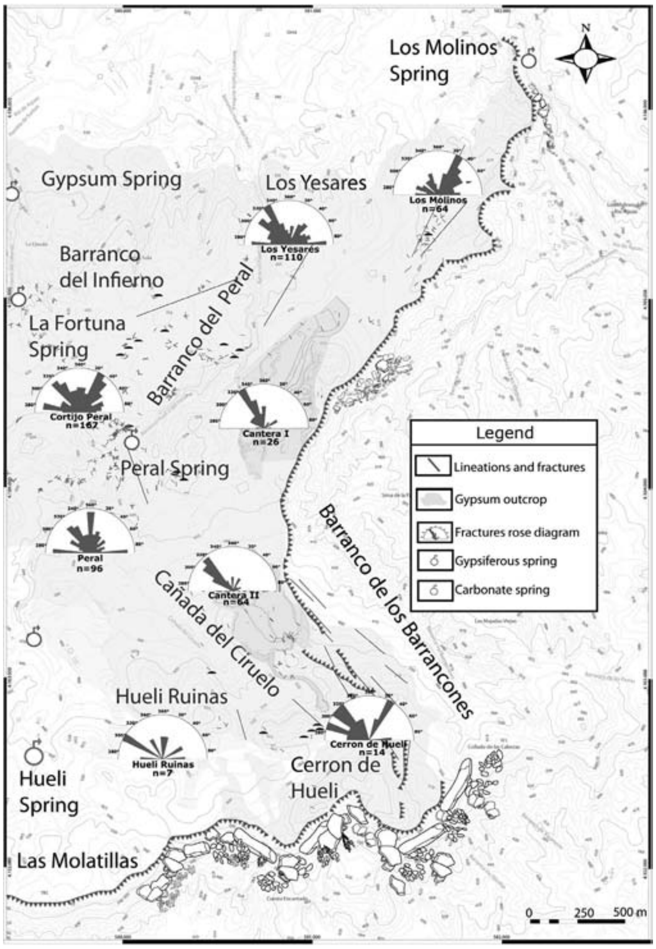

FIG. 4 - Rose diagrams of the fractures and lineations measured in each sector (n).

predominant 330° N-directed fractures are conjugated those with the direction 310° N. Also noteworthy is the presence of a large number of fractures EW in the direction.

Los Molinos. In this sector there are three main groups of fractures, one of them with ranging from 20° N and 40° N, with predominance of the first direction. In the second fracture system varies between 280° N and 300° N and a third group is oriented from 310° N to 340° N. In any case, most of the measures correspond to the direction 30° N, so this shows a fracture zone different from the other sectors, as discussed above.

Cortijo Peral. In this sector many fractures have been surveyed (167 items were specifically localized), with widely range of directions. The main ones are oriented NS, 30°-60° N, 320° N, EW-340° N, dominated by directions 30° N and 320° N.

Cantera I. The measurements made inside the quarry mainly consist of data from the currently mine slopes. There is a prevalent fracture direction: 330° N. Also the system NS (360° N) has to be note.

Peral. Most of the information about this sector correspond to the hills located in the southern part of the valley, due to two reasons: first, the valley is upset by breeded terrace; on the other hand, the wild vegetation, makes difficult, or even impossible, observation access to the measurement area. In this sector three predominant directions of fracturing (NS, EW and 320° N) are detected.

Cantera II. The measurements have been taken both on the quarry slopes and in the surrounding area. Fractures range mainly between 300° N and 320° N in direction.

Hueli ruinas. There is a wide range of fractures, being abundant in NS, 60° N, 340° N and EW, but mainly 300° N oriented.

Cerrón del Hueli. In this sector the direction of fracturing varies from 290° N to 320° N, the most abundant corresponding to 320° N. In addition, some measurements indicate an EW direction and several fractures are 30° N oriented.

CAVES

Speleogenesis of most of the cavities is mainly controlled by the tectonic discontinuities and by the stratigraphic surfaces, and subordinately the heterogeneity of the rock. Caves usually develop in any type of gypsum facies, but especially in the macrocrystalline levels.

In this study, a total of 208 relevant karst items (shafts, caves, closed sinkholes, etc.) have been inventoried, 154 of which were already catalogued by the Caving Club of Almeria, while 54 have been discovered in the course of this project. An ID number has been assigned to the cavities that have been taken from the gypsum karst catalogue. A total of 58 cavities, 4 of them described for the first time, have been listed in the sector of Los Molinos. Almost all of them are on the South side of the road AL-140 and located in dolines of various sizes. The main surface karst feature is an elliptic doline, probably anthropically-retouched, about 30 m in diameter, into which 6 shafts open their entrance. It is also important to note that in this sector the Paso Cave, the Mud Cave and the Urra System are present. The rest of the cavities remain virtually unexplored and still lack any survey.

In the sector of Hueli a total of 87 cavities (the most dense of the three described sectors) have been found, 18 of which are inventoried for the first time. The greatest concentration of cave entrances is observed in the southeastern part of the sector; almost all of them show signs of having been formed favoured by the high degree of fracture concentration (fig. 4).

It should be noted that most of the inventoried but uncatalogued caves in this area are located in Cañada del Ciruelo plain. This sector is strongly modified by terraced fields and dense vegetation that hinder in many zones the observation of possible sinks or gullies, so it is very possible that there are more cavities than those presented in this study.

In the sector of Peral, a total of 63 cavities has been detected, 31 of which are new in the cave catalogue of Sorbas. The area presents a high difficulty of exploration, especially on both banks of the Peral stream. The large num-

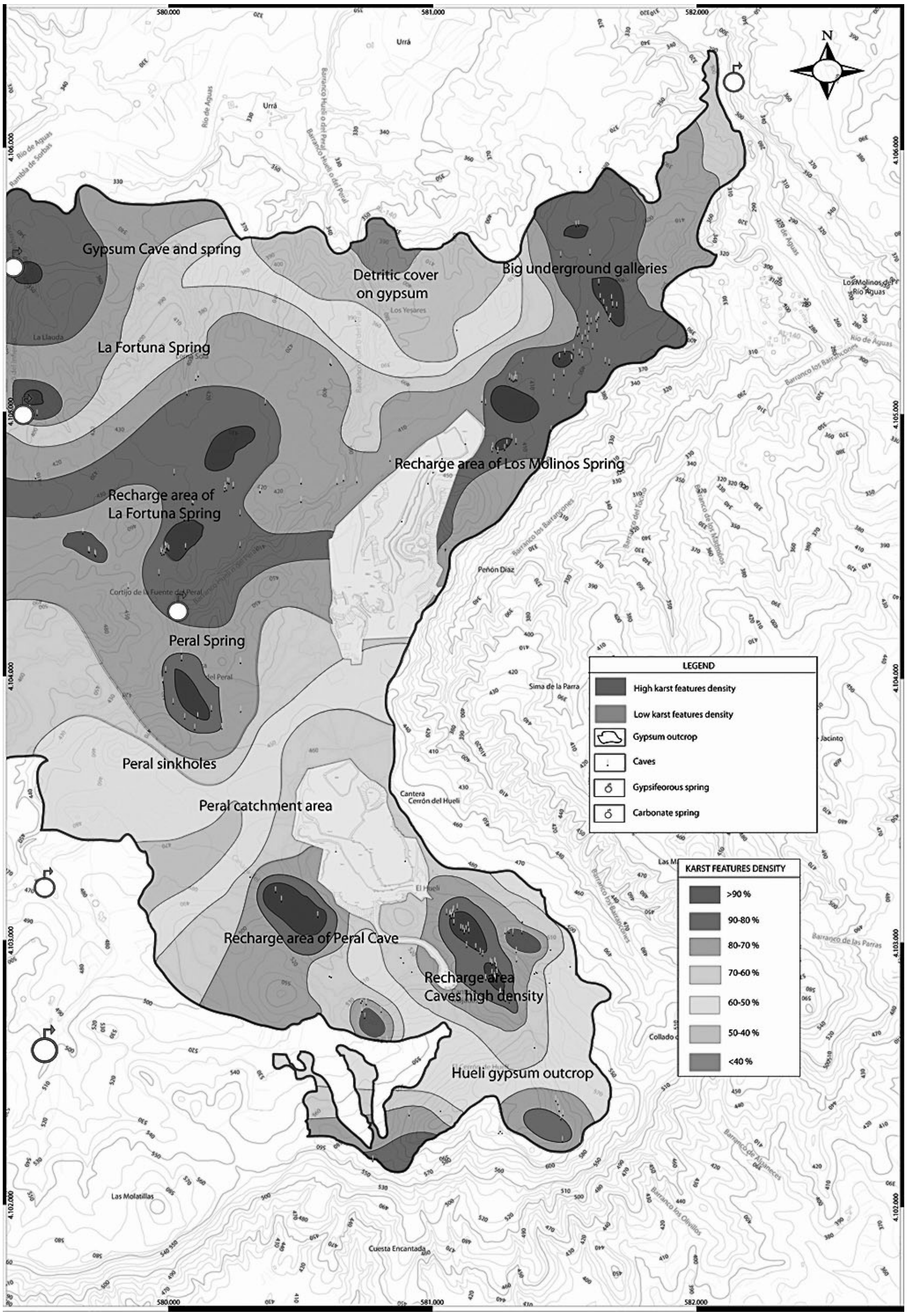

FIG. 5 - Density map of cave entrances. Contour lines resulting from spatial interpolation, reflect some of the most sensitive district (red areas) to the mining impact on the gypsum karst systems.

ber of sinkholes plays a very important role in the hydrology of this area, and the existence of two large depressions (one with 7 entrances, while the other one with a total of 10) and several vertical feeder shafts are worth mentioning.

The main karst system of this sector is the Peral Cave (Cueva del Peral). This 2 km-long cave can be considered as the main drainage system. It is located on the right bank of the Barranco del Peral canyon and has 8 entrances. Only a pit is isolated from the system by an impenetrable conduit, while the others communicate directly with the two main galleries. The great importance of this cave is due to the presence of a perennial underground water flow giving rise to the spring of Peral. The average flow from this spring barely exceeds 1 L/s (usually 0.2 L/s in drought condition), although during periods of heavy rainfall, the discharge can reach 1 m^3/s. Another important cave, known as Gypsum Cave (Cueva del Yeso), is located in the Infierno sector between the blind gorge of the homonymous canyon, at the confluence with a hanging captured gully, and the pocket valley that from the downstream cave entrance reaches the Aguas River. It is a typical fluviokarstic cavity developed in N-S direction with large interbedded galleries for a total length of more than 1,000 metres and 40 metres of depth. Upstream a huge doline testifies a past sinkhole that drained surface water into underground pathways, when the watertable was higher than today. Currently, Gypsum Cave hosts a perennial rivulet fed by La Fortuna spring, a 20 m long phreatic karst conduit cut by the Infierno Canyon, 200 metres upstream.

In the North of the study area, three zones reach the highest cave density in a large region corresponding to the Los Molinos (NE), Peral and Gypsum (NW) cave systems. These high values match with the recharge areas and preferential infiltration of the main springs. In the areas where the gypsum is covered by the presence of a soil, by other lithologies and farming terraces, the effects of the deep karstification is not detectable at the surface. It is therefore necessary to note that this cave density evaluation method also has a limiting factor imposed by the difficulties of speleological explorations, and so the results of the geostatistical analysis also reflect the knowledge about the direct access to the cavities and their entrances.

WATERSHEDS

Aguas River watershed covers an area of approximately 590 km^2 and belongs to the sub-basin V-I (Upper Aguas River hydrographic unit) of the National Hydrological Plan Andalucía. Much of its course is ephemeral and temporary. Only about 3 km are permanent and fed by karst springs coming from the gypsum massif of Sorbas. The most important source is Los Molinos spring, at an altitude of 290 m asl, with a catchment area of 240 km^2 and an average discharge of 26 L/s. The other karst outlets have a lower recharge depending on the (poor) rainfall and on the occult rain contributions (condensation waters) of the karst systems. Among these water sources, the most significant are: the Peral (410 m asl), La Fortuna (390 m asl), Viñicas (355 m asl), Tesoro (315 m asl), Gypsum (340 m asl) and Los Apas (300 m asl), all of them related to known karst systems. Also a small intermittent carbonate resurgence is present near the ruins of Hueli village (Calaforra, 1986).

The surface hydrographic system is essentially ephemeral and losing, so that most of the rain contributions reach the karst aquifer quickly. The drainage network is hierarchical and mainly depends on the tectonic control and, secondarily, on the geometry of the strata. The river system is well organized on weak marly-clay lithologies, while on the evaporite rocks it tends to disappear due to rapid infiltration, developing an underground water flow. The main river channels are N-S and NE-SW oriented, while the tributaries are located in transverse directions with respect to the main reach. Where small streams flow directly on gypsum beds, without any deposit, sinkholes form easily. The most important are located in the endorheic basin of the Peral.

The study area grid is divided into 5 major surface catchment basins, all of them represent a sub-basin of Aguas River (fig. 6).

The Infierno watershed is located in the north-western side of the study area. Its northern boundary is the talweg of the Aguas River, while to the East and South this watershed is adjacent to that of the Peral. In this study an area of only 1.11 km^2, where gypsum outcrops are present, is considered. The main contribution comes from outcrops located to the East and South-East of the Infierno gorge, which acts as boundary between this watershed and the Peral. Preferential infiltration occurs in two sinkholes very close to the canyon, on its eastern flank.

The Peral watershed is the largest detected in the study area with a surface of about 4 km^2. It is bounded to the North by the Aguas River; it borders to the West with the Infierno catchment basin; its South-East limit is defined by the gypsum escarpment, whereas to the South the drainage divide corresponds to the hills of «The Molatillas». In this watershed no particular points of infiltration have been highlighted but there are several sinkholes, especially at the North-West side of the Peral Cave and at the Cortijo Peral farm.

The Los Molinos watershed covers an area of about 1.25 km^2 and is located in the far North-West of the study area. Its northern and north-eastern boundaries are defined by the Aguas River. The orographic escarpment between the gypsum and marl rocks acts as south-eastern boundary. It is limited to the South by the Peñón Diaz watershed and to the West by the Peral catchment basin. The current water contribution comes mainly from the drainage divide from the south-western part of the basin, bordering the Peral watershed, although it is possible that before the quarry activity started, a drainage from the currently exploited hills was present. The surface contributions of this sector feed the Aguas River. Most of the rain infiltration occurs at the South side of the highway AL-140, which gives access to the mine area.

The Peñón Díaz basin is the smallest catchment area with 0.5 km^2 and is most affected by the gypsum exploitation. Its North and West borders are with Los Molinos and Peral watersheds, respectively; its limit to the South is with the Peral Cave drainage basin and at the East with the gypsum escarpment. Its main runoff recharge comes from the South, and probably before the quarry has been opened, it had a contribution also from the North-East. The main water drainage almost completely infiltrates before reaching the Peral Canyon, due to several sinkholes situated at the West side of the quarry.

The Peral Cave watershed is bounded by Peñón Díaz catchment basin to the North-East, whereas Peral watershed makes up the North-West, South and West borders. The eastern boundary is formed by a drainage divide constituted by the ridge that from the Cerrón of Hueli hill extends towards the quarry, with an area of about 1.13 km^2.

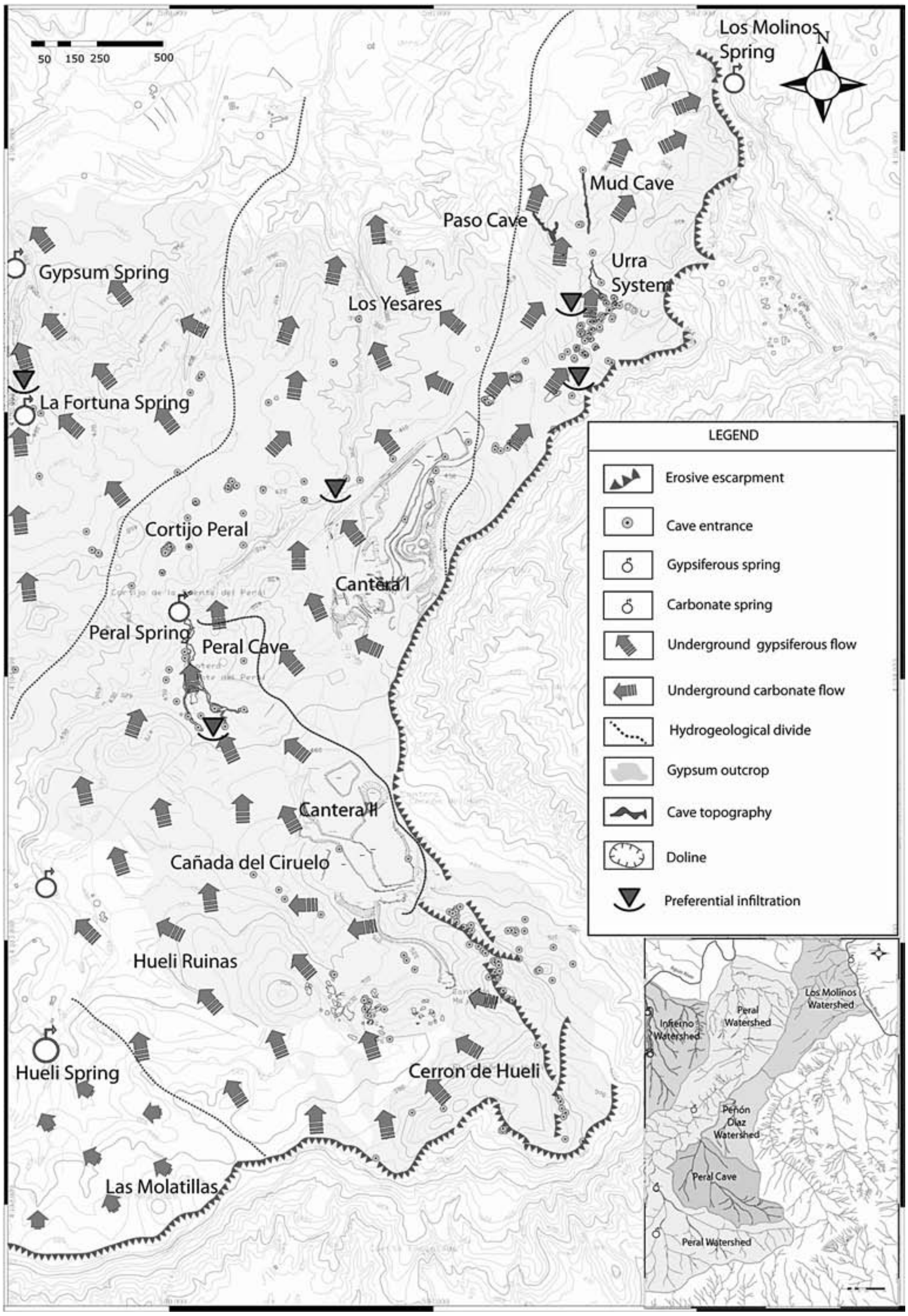

FIG. 6 - Vadose drainage map and major surface catchment basins.

The surface contribution comes mostly from the relief to the South, which defines the boundary with the Peral basin, as well as from the hills at the East of the quarry. It is possible that before the gypsum exploitation began, runoff had an additional recharge from the place where now the quarry of Cerron Hueli is present. Most of the runoff infiltrates through several existing sinkholes in the area of the Peral Cave.

VADOSE DRAINAGE

The study area is part of the Aguas River groundwater basin which boundary extends westward contributing with deeper phreatic waters to the discharge of the Los Molinos spring. All other karst springs in the district have a surface recharge dependent on rainfall and from the occult rain contributions of the karst systems, provided by condensation of water vapour inside caves and fractures (Pulido-Bosch, 1986).

The hydrogeological behaviour is controlled by the presence of two different physiographic units. On one side, the gypsum rock that constitutes the main aquifer and on the other hand the marly-clay levels of Abad's Member that work as a very low permeability layer. From a hydrogeological point of view, the described structural and stratigraphic aspects involve the definition of a multi-layered gypsum aquifer, highly permeable due to fracturing and dissolution. Nevertheless, it appears that the karstification is marked by the orientation of the palaeo-catchment drainage, which sometimes follows the direction of fractures, joints and faults.

The speleogenetic evolution of the cave systems is closely related to the hydrogeological history of the area. After an initial phreatic phase, where the water flowed through meandering proto-conduits formed within gypsum beds at the contact with marly strata, often without any preferential direction, a progressive lowering of the water table of the basin led to the activation of vadose conditions, producing mechanical erosion of interbedded marls and enlargement of underground galleries along the main discontinuities (bedding planes and fractures). Once the basal less permeable rocks were reached, water discharge variations partially filled the conduits with clastic material coming from the surface. Also the formation of the speleothems occurred in this phase (Calaforra, 1998).

While in some caves the underground water course is known and observable, in others there are only more or less hypotheses, based on direct and indirect observations and on the direction of galleries, fractures, clastic fills, flow traces, etc.... The edge of the massif and the talweg of the canyons are characterized by the presence of several springs connected to major caves that drain water from this karst area and currently are independent of allogenic contribution, except the spring of Los Molinos (Calaforra, 1998).

Inside the karst system, the water flows essentially along the gypsum and marl contact with a large discharge variation as a function of precipitation. The low water discharge of all these perennial karst springs seems guaranteed by condensation processes of humid air within the karst fractures. This condensation is more significant in summer, when the largest temperature difference between the subterranean karst systems and the external superficial environment is registered. This process is called «occult rain» (Badino, 2004). In this sense, the fracturing and the karstification of the rock play an important role in the aquifer recharge.

The groundwater flow is strongly related to geological and structural items. First, the north-eastward tilted monocline structure of the Messinian formation often forces groundwater to flow along the dip of the strata. Fractures and faults are other structural elements that determine the hydrogeology. They cross the Sorbas massif with three main directions (NW-SE, NE-SW and N-S), dividing the karst area in two main hydrogeological systems, whose underground divide is not directly detectable at the surface.

In the eastern hydrogeological system, the drainage of the groundwater basin confluences towards the spring of Los Molinos (290 m asl) (fig. 6). The water yield of this system is influenced by two components: autogenic and allogenic drainage. The first derives from direct precipitation on the massif (the underground network in the recharge area develops between 400 and 300 m asl), while the allogenic is perennial and comes from contributions related to the Tabernas Basin. The underground water flow in this sector goes to the North-East and the hydrogeological divide is oriented N-S.

The western system constitutes the largest hydrogeological unit of the study area and is bounded at the South by the escarpment of Cerron de Hueli. This system is compartmentalized by two N-S oriented hydrogeological divides in a series of small groundwater basins, one of which joins the La Fortuna springs and then, through Gypsum cave, reaches Aguas River with a N-S flow. One of these small underground water streams coming from the infiltration area of Cerron de Hueli feeds the Peral karst system.

In the south-western part of the study area the hydrogeology is a little bit different. In this sector the reef platform emerges and the permanent carbonate spring of Hueli is related to this lithology, hydraulically detached from the gypsiferous outcrops.

Cave development direction and physico-chemical parameters of the water of the springs confirm the underground pathway towards Los Molinos (table 1). For in-

TABLE 1 - Water parameters of the main karst springs

Spring	Date	pH	Cond. (mS/cm)	T (°C)	HCO_3 (mg/L)
Los Molinos	09/06/2011	7.17	3.31	21.5	228.8
	10/08/2011	7.43	3.28	21.8	245.2
	09/11/2011	7.92	3.24	21.4	225.7
	01/03/2012	7.65	3.29	21.5	231.8
Peral	11/05/2011	7.93	2.40	17.7	140.3
	10/08/2011	8.46	2.50	17.7	145.2
	09/11/2011	8.78	2.42	15.8	117.7
	01/03/2012	8.52	2.42	15.6	134.2
La Fortuna	11/05/2011	7.95	2.68	17.7	186.1
	10/08/2011	7.83	2.86	21.0	231.8
	09/11/2011	8.38	2.79	13.3	251.3
	01/03/2012	8.81	2.68	9.2	212.3
Viñicas	11/05/2011	7.97	2.40	14.4	158.6
	09/06/2011	8.03	2.41	16.4	115.9
	29/07/2011	7.99	3.02	17.0	115.9
	09/11/2011	8.20	2.37	15.7	124.4
	01/03/2012	8.60	2.38	14.4	135.4
Apas	11/05/2011	8.11	2.40	14.4	134.2
	10/08/2011	8.07	2.39	15.7	139.7
	09/11/2011	8.50	2.40	14.2	134.2
	01/03/2012	8.76	2.37	10.6	122.0

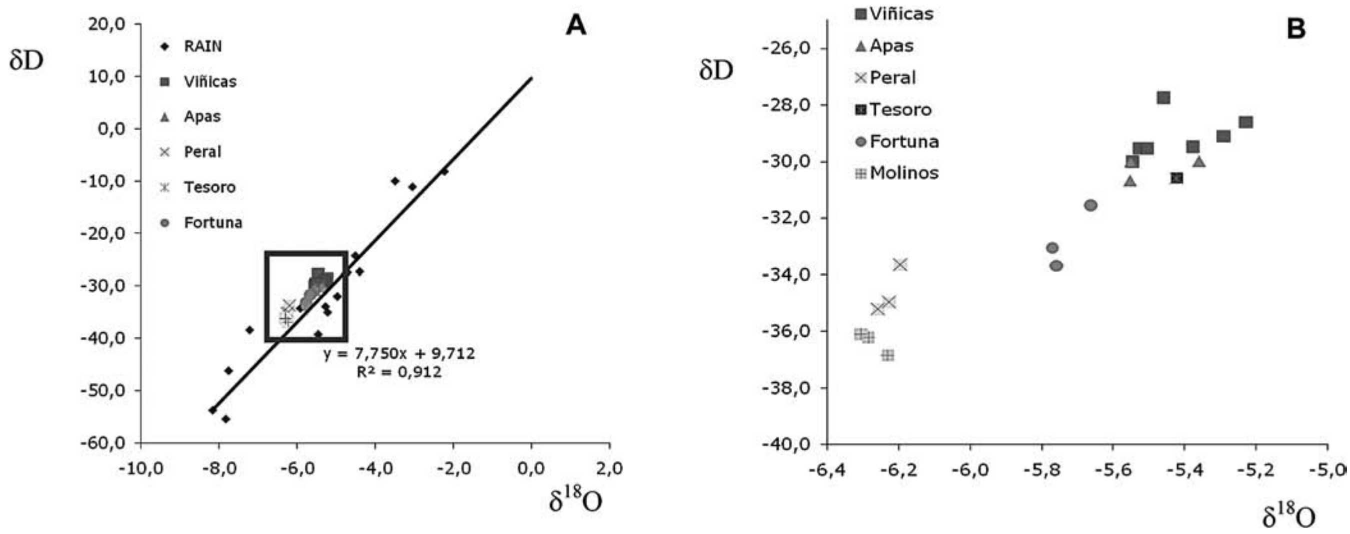

FIG. 7 - δ^2H *vs* δ^{18}O isotopic composition (in V-SMOW). A: spring water compared to rain. B: detailed plot of the karst springs; two main groups have been distinguished.

stance, specific conductivity and bicarbonate content of the main springs show a generally increasing pattern from the recharge areas (with values around 2.4 mS/cm) to the emergence (mean of 3.3 mS/cm at Los Molinos). Also the stable isotopic signature of the rain, surface and phreatic water generally shows a decrease of δ^2H (from an average of –34.6‰ to –36.4‰) and a single and constant δ^{18}O value (around –6.3‰) in the same flow direction as response to the mixing of water in secondary pathways (fig. 7A). Geochemical data from water of the outlets in the north-eastern part of Sorbas massif clearly highlight the heterogeneity among the different drainage systems (fig. 7B). A deeper groundwater flow is hypothesized, located in the lowest gypsum strata, and drains directly towards the North (Aguas River), through speleologically unknown karst systems.

CONCLUSIONS

Besides evaluating some geomorphological and speleological characteristics of the gypsum karst of Sorbas, the hydrogeological aspects of the southern part of this massif have been taking into account to determine its recharge basin and subsurface water drainage system. For this purpose particular emphasis is given to the position in the evaporitic basin, stratification and fractures (geological criteria), new discovered caves, known cave density, large and well developed karst systems (karst or speleological criteria), the presence of nearby springs, water table depth, and presence of natural recharge areas by infiltration (hydrogeological criteria).

The results of this work show that the directions of fracturing and major lineations, together with the bedding planes, play an important role in the drainage of underground and surface waters. The main points of potential groundwater recharge are in the south-western part of the karst area and groundwater flow divides do not correspond to surface drainage divides. The extensive karst topography serves as a major input area and the recharge occurs through the doline fields and air vapour condensation in fractures and caves. So near-surface structure is of great importance in this process.

Sinkholes, conduits and fracturing systems form secondary pathways for the subsurface flow.

Geomorphological, speleological and hydrochemical analyses have been successfully used to delineate the geochemical evolution of the water and to determine its provenance at Los Molinos spring which is the major emergence for the subsurface flow system. A dye trace test will allow to confirm this approach.

Taking into account the European Water Framework Directive (2000/60/EC) which provides that all Countries should protect inland water resources and their quality, and the special characteristics of the Protected Natural Space of the Gypsum Karst of Sorbas (Junta de Andalucía, 1989), in which both mining activity and karst environmental protection and water resources interests are present, it should be noted that this kind of study could attempt to discern a possible indicator of the effects of gypsum mining, and to estimate the useful conditions of rock exploitation, enabling the preservation of the recharge basin of the karst system and springs, and minimizing the impact to the vadose groundwater flow. In the case of the south-western part of the gypsum karst massif, contour lines resulting from spatial interpolation suggest those districts with minimum affectation of the mine activity on the underground gypsum karst system. This approach could be useful applied in other karst area important rock exploitation resources are present.

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