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Article

Geodiversity of Las Loras UNESCO Global Geopark: Hydrogeological significance of groundwater and landscape interaction. Conceptual model of functioning

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Abstract: Las Loras UNESCO Global Geopark (UGGp) is geologically diverse, particularly in relation to water-derived features: springs, karst springs, travertine buildings, waterfalls, caves. In this work, the interactions between geology, geomorphology, structures and hydrogeology are analyzed. These four components are the fundamentals of geodiversity and their interactions provide a conceptual model of hydrogeological functioning at Las Loras UGGp. The most plausible hypothesis is that the system is formed by two superimposed aquifer systems, separated by an aquitard formed by Lower Cretaceous material. The deep lower aquifer formed by the Jurassic limestones only outcrops on the northern and southern edges of the Geopark and in a small arched band to the south of Aguilar de Campoo. It forms a basement subject to intense deformation. The upper aquifer system, formed by outcropping materials from the Upper Cretaceous, is a free aquifer. It is formed by a multilayered aquifer system that is highly compartmentalized by the very disturbed geomorphology of the landscape, constituting each moorland and each lora, an individualized recharge-discharge system. This model explains the base level of the rivers, the abundant number of existing springs and the permanent nature of some rivers, providing the keys to understand the bases of the geoconservation of a rich geological heritage linked to the active processes of the water cycle.

Keywords: Geodiversity; geosites; springs; Las Loras UNESCO Global Geopark (UGGp); hydrogeology; Ubierna Fault.

1. Introduction and objectives

Geodiversity is a complex concept describing a spectrum of geological (together with some other natural) phenomena in a given area [1]. Gray (2004) [2] defines it as 'the natural range of diversity of geological (rocks, minerals and fossils), geomorphological (landforms and processes) and soil features, including their relationships, properties, interpretations and systems'. The base concept of geodiversity is the graphic presentation of a variety of geological elements that form the surface of planet Earth [3] and provides the foundation for the biota on which human societies depend. The United Nations included geodiversity in the 2030 Sustainable Development Goals (SDGs) Agenda [4], and the International Geodiversity Day was officially proclaimed by UNESCO in 2021, with the first one celebrated on 6 October 2022 [5].

This paper describes a Geopark of relatively recent creation (2017), the Las Loras UNESCO Global Geopark (UGGp onwards). The approach presented considers the analysis of four of the components of the abiotic natural environment: (a) geology; (b) structure; (c) geomorphology and (d) hydrogeology and the relationships between them. The role of both groundwater and surface water in shaping the landscape is emphasized.

The objective of this work is to establish the elements of the geological diversity of Las Loras UGGp, and to provide a preliminary assessment of the hydrogeological processes that have led to that diversity. This understanding will identify the outstanding natural features, underpin further projects and provide the fundamentals for preservation management [6]. The scientific, cultural, and educational importance of natural springs are highlighted. Some of these sites will be proposed as a Place of Geological Interest (PGI) and their value in terms of science, education and tourism-recreation, as well as the risks of degradation will be presented.

The existing Inventory of the Las Loras UGGp (90 geosites) will be elaborated with additional data and information, although further information will be contributed by future research projects.

2. Materials and Methods

2.1. Description of the study area and the available information

The Las Loras UGGp is located in the north of the autonomous community of Castilla y León (Spain), occupying part of the NE of the province of Palencia and NW of Burgos (Fig. 1).

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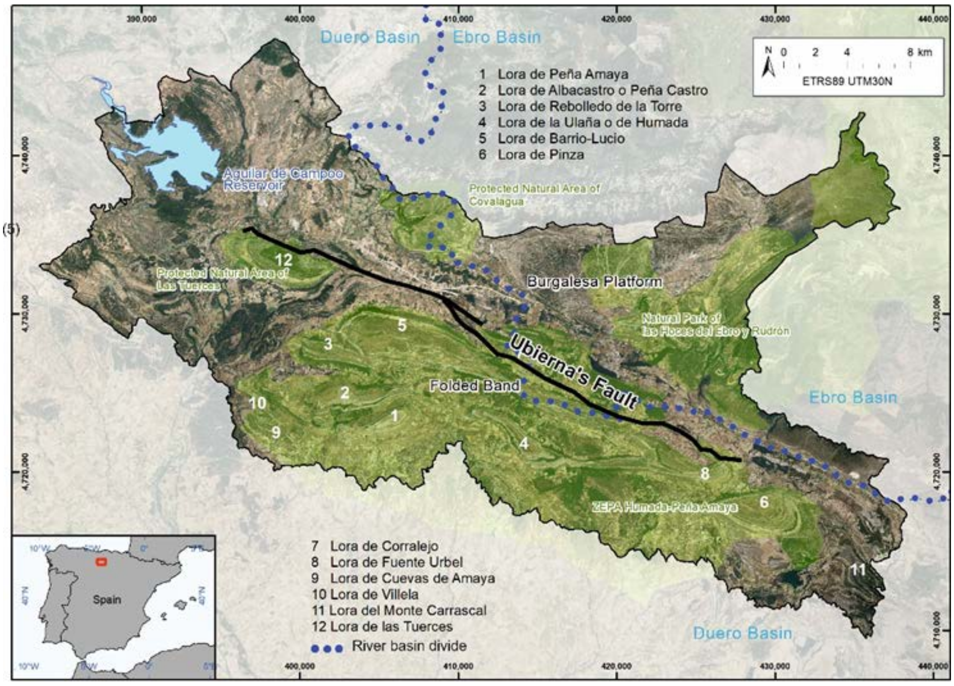

Figure 1. Location of the Las Loras UGGp in Spain, in the division of the hydrographic basins of the Duero and the Ebro. Green zones represent Protected Areas under the Spanish Legislation: Protected Natural Area of Covalagua, Protected Natural Area of Las Tuerces, Natural Park of Las Hoces del Ebro y Rudrón, and ZEPA (Zona de Especial Protección para las Aves, in Spanish, SCI) Humada Peña Amaya.

Agriculture provides the economic background of the region and includes sheep pastoralism and wheat. Other important industries include the biscuit factory in Aguilar de Campoo, the oil field of Ayoluengo (active between 1967 and 2017), the extractive forest

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industry, the production of wind energy, and the tourist activity currently concentrated in the areas of the Palentina Mountain (Aguilar de Campoo) and the Ebro Canyons (Orbaneja del Castillo and Sedano). The towns closest to the city of Burgos have been become popular as residential locations with people commuting to work in the businesses and services of the city.

The Las Loras UGGp includes 16 municipalities in the provinces of Palencia (Aguilar de Campoo, Pomar de Valdivia, Alar del Rey, Santibalez de Ecla and Berzosilla) and Burgos (Valle de Valdelucio, Basconcillos del Tozo, Sargentes de la Lora, Rebolledo de La Torre, Villadiego, Sotresgudo, Humada, Urbel del Castillo, Montorio, Huérmeces and Valle de Sedano). Aguilar de Campoo is where one of the official headquarters of the Geopark is located. It is a sparsely populated area (13,076 inhabitants), which represents a density somewhat less than 7 inhabitants/km^2. Most urban centers are widely scattered, rarely exceeding 500 inhabitants.

2.1.1. Regional Geological context

The Geopark constitutes a mountain relief, with the lowest area in the Ebro river valley, to the north with 610 m asl compared to 1,377 m by Peña Amaya [7]. The moorlands (high mountains below tree-line) and loras of Mesozoic age are the geological elements that characterize the landscape as culminating forms, and constitute the common element throughout its geography. Geologically, the Las Loras UGGp falls to the south of the Basque-Cantabrian basin (Fig. 2), bordering the Asturian Massif (located to the NW) and the Duero Cenozoic basin, which constitutes its limit to the south. The study are is a rectangle bounded in the SW by the coordinate 42.53°, -4.41° and in the NE 42.88°, -3.75° covering 950.76 km^2 [8]. In the limits there are important elements that must also be taken into account in this work because geologically they are part of the same unit: Covanera, Tubilla del Agua and Pozo Azul.

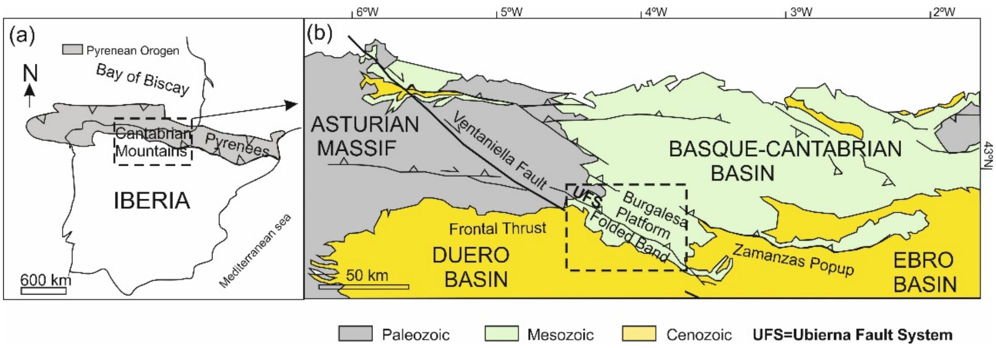

Figure 2. Geological context of Las Loras UGGp in Spain (modified from [9]).

2.1.2. Lithology and geology

The geology of Las Loras UGGp is formed predominantly by sedimentary materials (Fig. 3). The Ayoluengo-1 borehole (X= 3o 53´ 37.94´´W / Y= 42o 45´ 21.07´´N / Z= 1022 m asl) [15] is 2,397 m deep, reaching the Keuper facies of the Upper Trías at 2,375 m and is essential to understand the structure and stratigraphy of the sedimentary sequence.

There is an almost complete record from the Upper Triassic to the Paleogene with the oldest represented by the red clays and gypsum of the Keuper facies. Its areas of outcrop are associated with the main faults and thrusts (Villela, Ubierna faults, Becerril de Carpio thrust, and frontal thrust of the Duero Cenozoic basin), due to the fact that its plastic mechanical behaviour acts as a detachment layer. Overlying the Keuper, the Infralías (Rhetian), the Lías and the Dogger Formations, appear in stratigraphic sequence. These marine sediments form carniolas, dolomitic limestone on platforms, and limestone-marly rhythmites on the slopes. Upper Jurassic (Malm) and the Lower-Cretaceous (Berrasiense-Albian) continental detrital and carbonate units (Purbeck, Weald and Utrillas facies) continue the stratigraphic sequence followed by alternating limestone and loamy formations

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of the Upper Cretaceous (Cenomanian-Maastrichtian). Quaternary fluvial incision and deposition overly the consolidated sediments. The geology and geomorphology of the region give rise to the moorlands and loras that characterise the Las Loras UGGp. (Fig. 3).

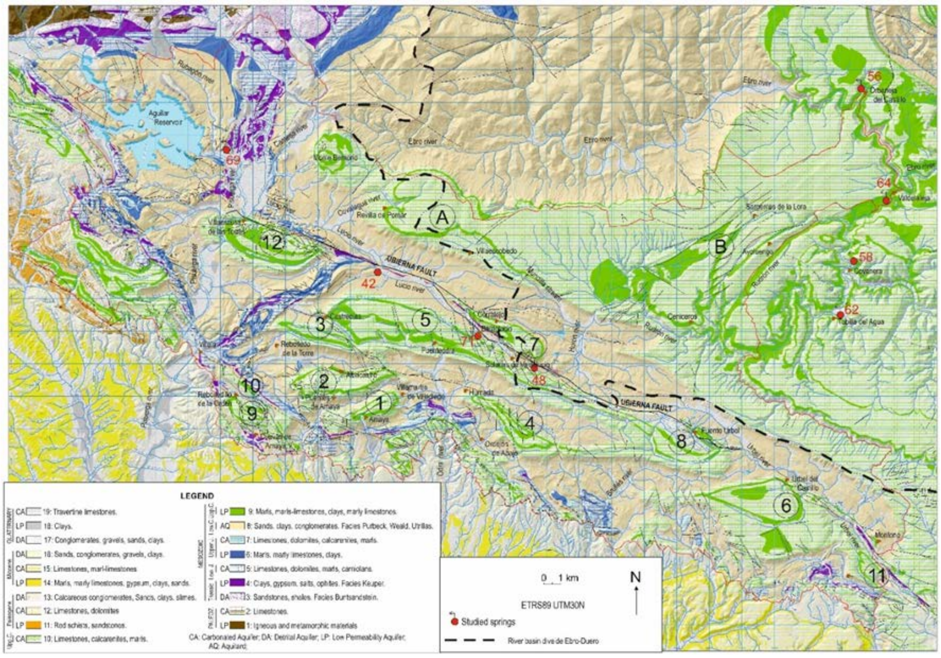

Figure 3. Hydrogeological map of Las Loras UGGp. Studied springs are in red: 69=Peñalonga spring; 42=Pisadera spring; 71 = Barriolucio water fall; 48= San Bol; 56= Orbaneja water fall; 58= Pozo Azul (Covanera); 62=Tubilla del Agua waterfall; 64=Valdelateja. The hydrogeological sectors defined by the moorlands and the loras have been differentiated and identified with numbers in circles. These sectors refer exclusively to the perched aquifers of the Upper Cretaceous: A= Moorland of Lora de Covalagua; B= Moorland of Lora de la Pata del Cid; 1= Lora de Peña Amaya; 2=Lora de Albacastro; 3= Lora de Rebolledo de la Torre; 4= Lora de Ulaña o de Humada; 5= Lora de Barriolucio; 6= Lora de Pinza; 7= Lora de Corralejo; 8= Lora de Fuente Urbel; 9= Lora de Cuevas de Amaya; 10= Lora de Villela; 11= Lora de Monte Carrascal; 12= Lora de las Tuerces (Tabla 2) Ayoluengo is the main village of the oil field. Ceniceros was a highlighted spring in the Moorland of la Pata del Cid. 58= Pozo Azul (Covanera); 82=Tubilla del Agua; 64=Valdelateja are highlighted geosites which are being studied in order to be included into the Las Loras UGGp border.

2.1.3. Climatology

Average annual precipitation at Aguilar de Campoo (2009-2021) is 570 mm, while the temperature ranges between maximum of 27.08º C in July-2013 (Fig. 4), and a minimum of -4.66 in Dec-2009; and the average annual temperature is 9-11ºC for the 2009-2021 series.

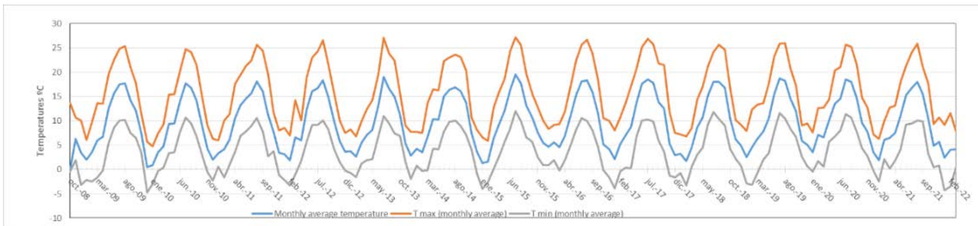

Figure 4. Evolution of temperatures in the station 2243A Aguilar de Campoo.

2.1.4. Hydrology

Las Loras UGGp includes the catchment divide between the hydrographic basins of the Ebro River flowing south-east in the Mediterranena Sea and the Duero River flowing west into the Atlantic Ocean. Within the Duero basin, the most important rivers are the Pisuerga, and its tributaries (Camesa, Lucio, Monegro and Sauquillo, on its left bank; the latter three originate in the area of the geopark). The Odra and Brullés rivers, which rise in the Geopark and flow south, the Brullés river being a tributary of the Odra river and this, in turn, of the Pisuerga river. Also the Úrbel river that runs to the east, flowing into the Arlanzón river, a tributary of the Arlanza river, and this, in turn, of the Pisuerga river. The Ebro River borders the Las Loras UGGp to the NE and E, along with the Rudrón River to the E, which rises as the Hurón River in the central area of the Geopark, and disappears into the Cueva del Agua sinkhole in Basconcillos del Tozo, to resurface 2 km to the northeast, as the Rudrón River. All of them are deeply embedded in the reliefs, sectioning geological structures and generating river canyons of considerable magnitude.

2.1.5. Aquifers and groundwater bodies

The surface topography of Las Loras UGGp overlies two adjoining groundwater bodies (GWBs): The Páramo de Sedano y Lora GWB, to the north, belonging to the Ebro River Basin District; and Quintanilla-Peñahorada-Lora, belonging to the Duero River Basin District [16], Páramo de Sedano y Lora GWB has three closed contour limits: southeast, subsidence of the Cretaceous under the continental Tertiary of La Bureba; northeast: Mesozoic-Neogene contact of the Padrones de Bureba inlet; North: Wealdic core of the Zamanzas anticline. A semi-permeable boundary to the northwest, the top of the Utrillas formation; and the only open limit is to the south, the Ebro-Duero hydrographic divide. The main direction of groundwater flow within the territorial scope of the Las Loras UGGp in this GWB is to the east, in the vicinity of the Rudrón riverbed, and to the northeast, towards the Ebro river.

The limits of the Quintanilla-Peñahorada-Loras GWB are formed by mechanical contacts towards the Tertiary detrital area of the Duero Basin on the southwest flank, towards the Valdavia, Villadiego, Castrojeriz and Burgos GWB (Fig. 5). The northwest edge corresponds to the basin boundary. Materials from the Cervera de Pisuerga GWB (to the west) form an impermeable edge in the northwest sector. The hydrogeological functioning is in a karstic regime and recharge is produced by direct infiltration of rainwater, discharged both by the drainage of the rivers that cross them and where the permeable limestone of the Quintanilla-Peñahorada-Loras GWB is in contact less permeable rocks of the Valdavia, Villadiego and Castrojeriz GWBs to the south (Fig. 5) [16].

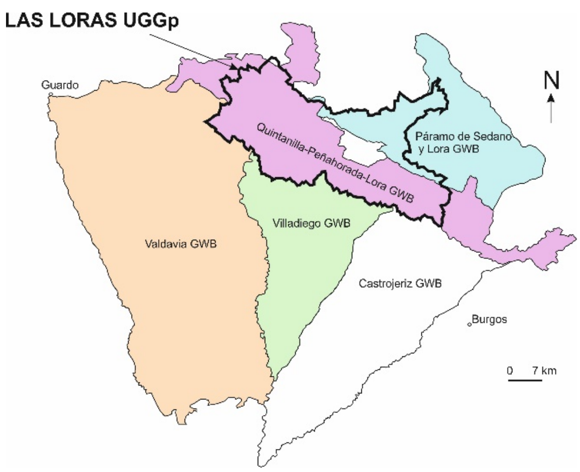

Figure 5. Hydrogeological context of Las Loras UGGp (data obtained from [17]).

Two types of aquifers are distinguished: an unconfined aquifer; and deep confined or semi-confined aquifer [18-19]. The former are made up of permeable materials from the Upper Cretaceous (dominantly limestones); and the deeper aquifer corresponds to the Jurassic sediments.

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2.2. Materials and Methods

2.2.1. Literature review

This study is based on a bibliographic review including: the institutional databases of the National Geographic Institute of springs, the institutional documentary databases (IGME, universities), as well as the IGME's own resources [20-21] and the viewers available at the Ministry of Ecological Transition. In general, the bibliography available on the study area is regional, dating back several decades. The Hydrogeological Atlas of the Province of Burgos [15] and more recently, the hydrogeological study carried out in the western sector of the Geopark for the construction of the High-Speed Train from Nogales de Pisuerga to Reinosa [22-23] stand out.

2.2.2. Field campaigns

Water sampling, measurement of unstable parameters, and field reconnaissance were conducted in August-2021, Oct-2021, Dec-2021, Apr-2022, Jun-2022 and Aug-2022. Field observations verified changes and contrast in permeability between outcropping materials and allowed the recognition of geological units that had been previously overlooked.

2.2.2.1. Water samples

The water samples were stored in new polyethylene bottles, washed with the same water that was sampled and filled to the brim to avoid interaction with atmospheric gases. No chemical preservatives were used and prior to analysis, the samples were kept refrigerated at 4º C +-2º C. Water temperature, pH, Electrical Conductivity and Redox Potential were measured in the field, in situ, at the time of sampling with a multiparameter pH/conductivity/temperature/redox potential instrument (Hanna HI 9828, Hanna Instrument, USA); and in the laboratory. Details of the 46 water samples (Figure 6) are provided in Table 1 (see supplementary material, SM files).

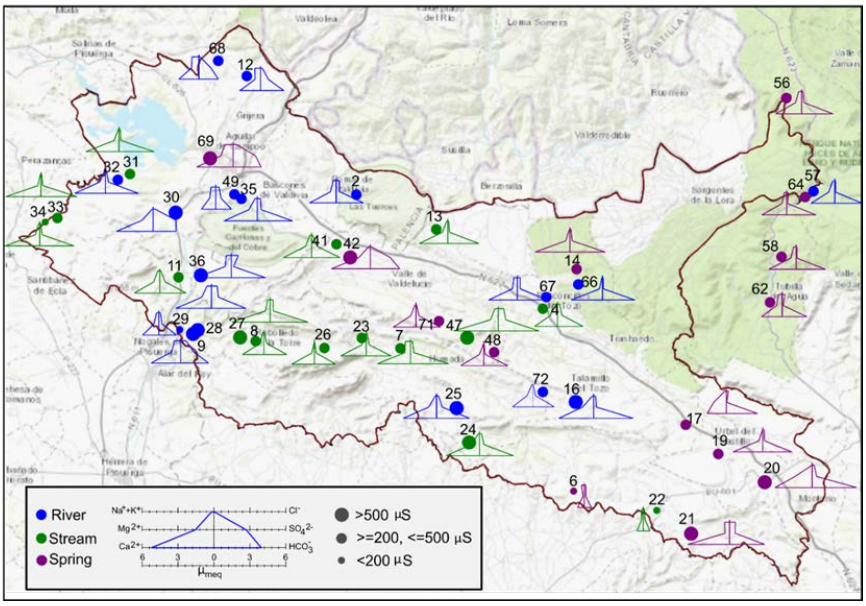

Figure 6. Location of the water samples with the hydrochemical facies and distribution of major ions represented by Stiff graphs [24] and mineralization (Electrical Conductivity) by circles. SM_Table -1 (supplementary material) shows the coordinates of each of the points represented and their identifying name.

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2.2.2.2. Physical-chemical analysis of water

Chemical analyzes were carried out in the IGME laboratories, accredited according to the requirements of ISO/IEC 17025, using validated standard methods: pH by electrometry, anions and cations by absorption spectrophotometry, heavy metals by mass spectrometry with inductively coupled plasma, excepting iron, which was determined by inductively coupled plasma atomic emission spectroscopy.

The hydrochemical information was analyzed and represented using the INAQUAS software [25].

This information has been duly reported in the results section.

2.2.3. Construction of hydrogeological profiles

Geological and hydrochemical information was integrated into profiles with a highly exaggerated vertical scale in order to better visualize the differences in elevations and the active processes. In these profiles, which are presented from Figure 15 onwards, the elevation was extracted using the digital elevation model that underpins Google Earth.

2.2.4. Analysis of springs. Comparison criteria.

The hydrogeological characterization of springs was approached in two stages of work: (1) Review of the existing inventory of springs, from the database of the National Geographic Institute (IGN) [26]. (2) Analysis of the geological, hydrogeological, geomorphological, and topographical characteristics of selected springs with well-differentiated characteristics, which have subsequently been sampled in the field. (3) Comparative analysis considering the following key criteria:

a) Upwelling level.
b) Geological formation(s) to which it is associated.
c) Hydrochemical facies, based on the results of the water analyzes carried out.
d) Electrical Conductivity as an estimator parameter of the salinity of the water.

2.2.5. Integration of results and representation in Arc Gis.

The information collected from the different sources, was integrated as a spatial database in Arc GIS Pro [27].

3. Results and discussion

3.1. Geodiversity of Las Loras UGGp

3.1.1. The Ubierna fault

The Ubierna fault is the primary feature that configures the geology, geomorphology and hydrogeology of Las Loras UGGp (Fig. 1). It constitutes a fault with quaternary and recent neotectonic activity [28-30].

This Ubierna fault, has a slightly sinuous NW-SE orientation. In reality it represents a 'fault zone' with numerous associated structures [10-14], which define what constitutes in structural terms, the "fault zone" (Fig. 7). The fault represents a tectonic event of considerable magnitude, as indicated by its considerable depth [30]. According to some authors, it has developed rooted in the plinth [31] and its subsequent evolution has followed a complex path that has led to its structural uprooting [32], although this issue is open to discussion and is outside the scope of this work. This fault has been interpreted as an extensional fault formed in relation to rifting at the end of the Jurassic and beginning of the Lower Cretaceous (controlling the sedimentation of the Campóo Group) and has undergone a strong tectonic inversion during the Tertiary. Another significant feature of the Ubierna fault is the presence of Keuper evaporite outcrops along its path [33].

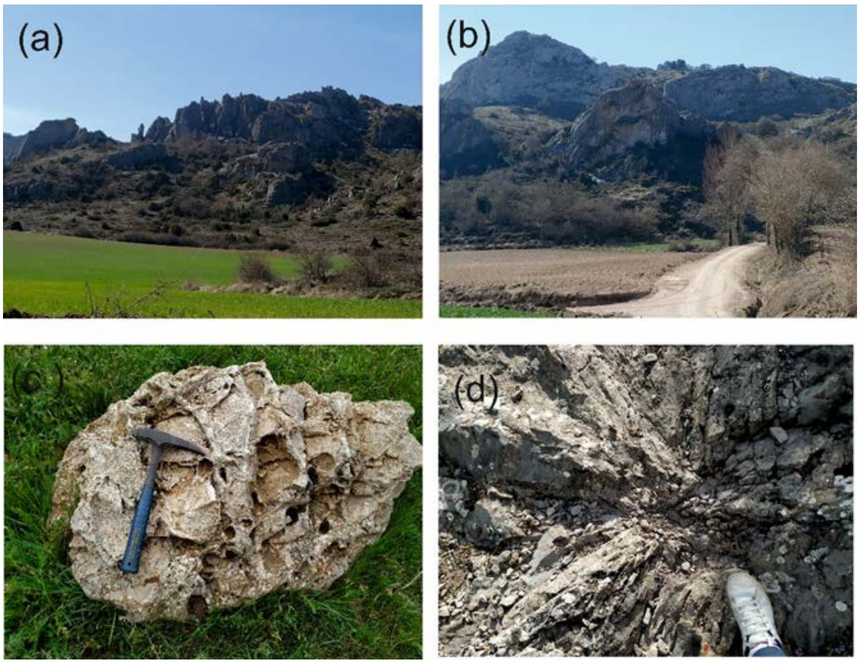

Figure 7. (a) Fault zone in the vicinity of the Ubierna fault within Las Loras UGGp. (b) Detail of the subvertical position of the carbonate outcrops near the Ubierna fault. (c) Detail of carniola found near the Ubierna fault. (d) Detail of a flower structure close to the fault plane.

The Ubierna fault divides Las Loras UGGp into two well-differentiated sectors, or types of folded relief. The first, between the Ebro river and the Ubierna fault is the Burgalesa Platform, characterized by the presence of calcareous moors made up of carbonate outcrops of extensive surface, and affected by a slight deformation presenting as horizontal or sub-horizontal platforms. The second, between the Ubierna Fault and the frontal thrust of the Cenozoic materials of the Duero basin is the so-called Folded Band, characterized by the presence of frequent folds recognized as hanging synclines that are called "Loras" (Fig. 3).

3.1.2. Caves

Nine caves associated to the karstic environment occur within Las Loras UGGp and they have been identified and described in reports published by the Edelwiss Speleological Group of the Cueva de los Franceses and the Orbaneja Water Basin [34].

They are Cueva de los Franceses, Cueva de Villaescobedo, and Cueva del Toro, in the Páramo de la Lora de Valdivia; Cueva de los Moros, on the north face of Mount Bernorio; Cueva del Agua, in Basconcillos del Tozo; Cueva de Valdegoba, in Huérmeces, at the southeastern end of the Geopark; Cueva de la Reina, in the Lora de Peña Amaya; Cueva Corazón and Cueva de Valdorao, in Lora de Las Tuerces; Cueva del Agua in Orbaneja del Castillo (Fig. 3).

The Cueva del Pozo Azul also stands out, a cavity of more than 14 km in length mapped [35] whose end has not yet been explored. It is located at the eastern end of the moorland of la Pata del Cid and at its exit is the Pozo Azul upwelling.

3.1.3. Springs

Among the geological diversity of Las Loras UGGp, the springs are of particular interest not only because they are windows to hydrogeological processes, but also because they have a long history of cultural significance for people in the region.

The Cueva del Agua (Orbaneja del Castillo), already mentioned, an important karstic spring originating from a large deposit of calcareous tuffs partly within the town of Orbaneja del Castillo. Some of the buildings within the town are impacted because of the dynamics of the landforms associated with the springs [36].

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The Pozo Azul (Covanera) consists of a concavity with a diameter between 7 and 8 m and a depth of 10 m (Fig. 8-1 and 8-2). The spring discharges from a subhorizontal conduit that follows an E-W direction (Fig. 8-3), clearly conditioned by the stratification of the karstic massif. Until now, the submerged gallery has been explored to a distance of 14 km. It has an average flow of 1 m^3/s, drains from the Upper Santonian carbonate aquifer, in which the Lower Santonian marls form the base of the karstic aquifer. The temperature of its waters is constant throughout the year varying between 9 and 11^o C [37]. It is located on the right bank of the Rudrón River, about 330 m from the main channel of the stream.

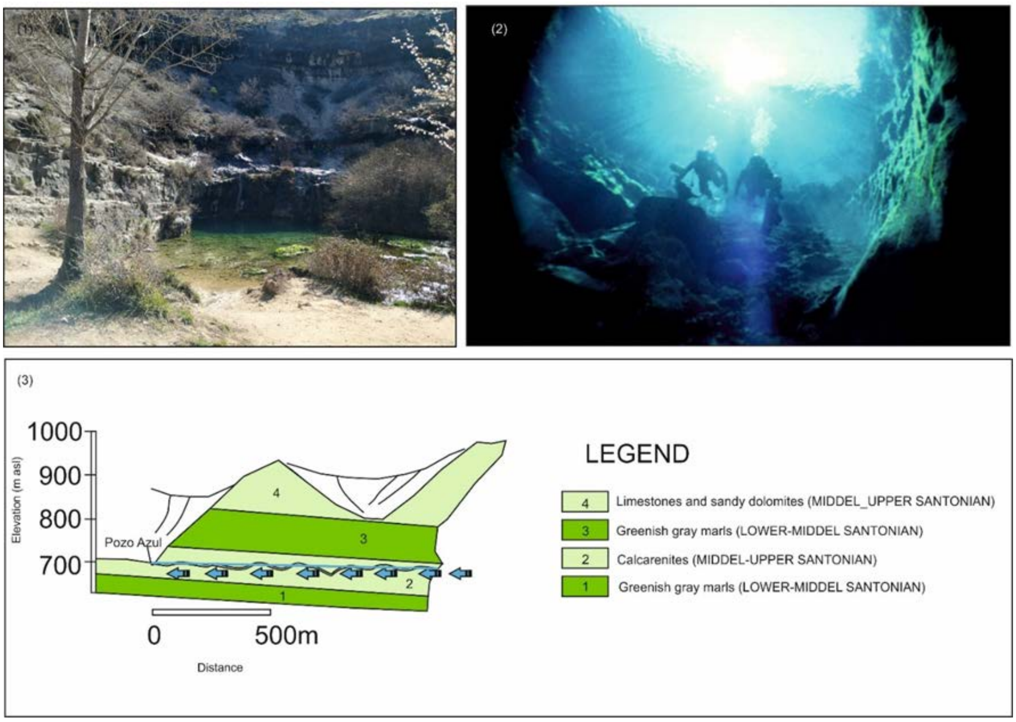

Figure 8. Pozo Azul. (1) Photograph of the Pozo Azul taken on 06-06-2022. (2) Beginning of the subemergent gallery tracing the groundwater flow [38]. (3) Diagram of hydrogeological functioning (modified from [35]).

The resurgence of the Rudrón River after crossing the Valle Ciego, in the Cueva de Los Moros, near Barrio Panizares, has been the subject of various studies [15].

3.1.4. Travertine buildings

In Las Loras UGGp there are several active springs that show the presence of a tuff/travertine building as an exceptional feature. Thirteen systems of travertine building (Table 1) and associated waterfalls are located in: Orbaneja del Castillo, Tubilla del Agua, Hoyos del Tozo, Villaescobedo, Moradillo del Castillo, within the scope of the Ebro basin; Covalagua-Revilla de Pomar, Rebolledillo de la Orden, Fuenteodra, and Barriolucio, within the scope of the Duero basin. The processes that are build these structures are not active throughout the year. The tuffs in the Upper Ebro are associated with two well-differentiated geomorphological contexts, the slope and the bottom of the valley. These positions in the landscape determine the typology of the tuffaceous accumulations and their magnitude (Table 1). The spring that gives rise to the Orbaneja del Castillo waterfall is permanent. It is located on the left bank of the Ebro River, on the northeastern edge of the Geopark. It features a waterfall several meters high, along which different types of travertine have formed: waterfall, barrier, and travertine terrace [35]. The Ebro Hydrographic Confederation have historical data on flows in the Cueva del Agua (so called, upwelling of the spring that generates the Orbaneja waterfall). The Orbaneja spring hydrograph (water point 19075 ORA according to [15] ranges between 0.1 and 1400 l/s in 1996, with the higher picks in the winter and spring months. Other waterfalls are probably only active regime only in the winter and spring months.

There is an large outcrop of inactive travertine (approximately x m^2), a few meters upstream from the Valdelateja spa, on a terrace on the left bank of the Rudrón River. Although recognized by González Amuchástegui and Serrano Cañadas (2013) [39], it is not mapped on the MAGNA50 sheets made by the IGME, probably because of its small size. It represents an inactive geological process of outstanding educational and scientific value. For this reason, and others that will be discussed related to the Valdelateja spring, this outcrop should be a new LIG to consider in the Geopark's LIG inventory.

Table 1. Travertine buildings inventoried in Las Loras UGGp.

River	Name	Geomorphological context	Altitude (m asl)	Site	Reference
Rudrón	El Tobazo	Hillslide	≈850	Tubilla del Agua	(1)
Rudrón	La Toba	Hillslide	≈850	Tubilla del Agua	(1)
Rudrón	Tubilla-La Fuentona	Valley bed	810-710	Tubilla del Agua	(1)
Rudrón	La Tobaza	Hillside	≈850	Tubilla-Covanera	(1)
Rudrón	Spa	Valley bed	670	Valdelateja	(1)
Rudrón	Valdelateja	Valley bed	660	Valdelateja	(1)
Rudrón	Ebro-Rudrón	Valley bed		Valdelateja	(1)
Ebro	Agua Cave-Orbaneja	Hillside [*]	800-720	Orbaneja	(1)
Ebro	La Tobaza	Hillside	≈730	Orbaneja	(1)
Lucio	Barriolucio	Waterfall/Hillside	≈990	Barriolucio	(2)
Covalagua	Covalagua	Waterfall/Hillside	≈1030	Revilla de Pomar	(2)
Rudrón	Moradillo del Castillo	Waterfall/Hillside	≈810	Moradillo del Castillo	(2)
Mundilla stream	Villaescobedo	Waterfall/Hillside	≈1100	Villaescobedo	(2)

[*] In the opinion of the authors, waterfall, slope and terrace.
[1] González Amuchástegui and Serrano González (2013) [39].
[2] Argeol.

Of the several waterfalls in Las Loras UGGp Yeguamea, Cascada de la Churrera is associated with vertical carbonate wall. Others are associated with the formation of travertine buildings (Orbaneja del Castillo, Tubilla del Agua, Covalagua, Barriolucio) (Fig. 9); in addition to others, such as Valdelateja, are associated with riverbeds.

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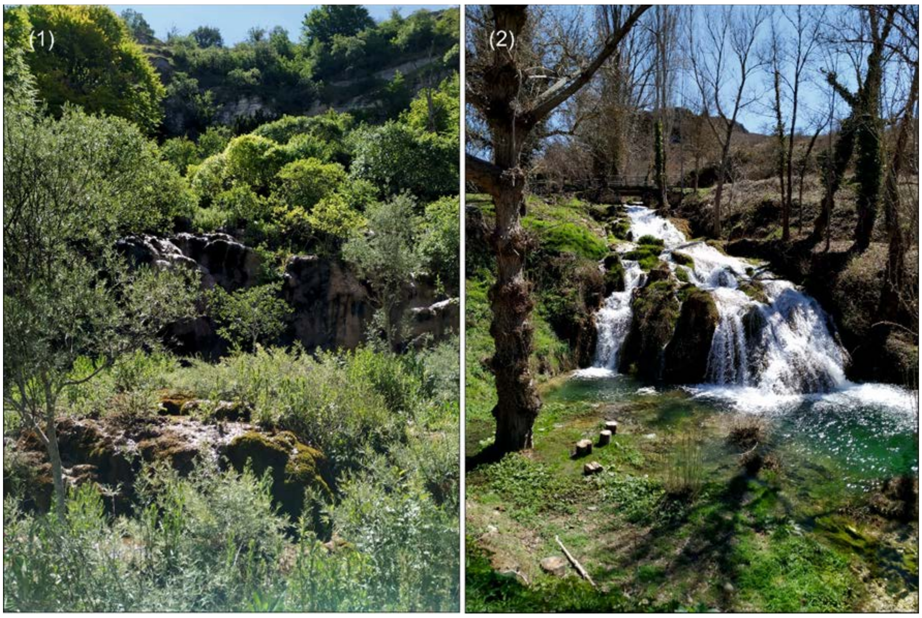

Figure 9. (1) Covalagua Waterfall taken 26-06-2021. (2) Tubilla del Agua Waterfall taken 06-04-2022.

Orbaneja is a karstic spring forming a stream which only emerges through the Cueva del Agua itself when rainfall is intense (Fig. 10). After going through part of the town and following a channel towards an old mill, it falls forms a majestic waterfall that descends rapidly towards the Ebro River. The Orbaneja del Castillo waterfall space [40] and is a product of: cascading, barrier and terrace travertines [35]. It is a distinctive and valued feature of the town but also forces the inhabitants of Orbaneja to take constructive measures to prevent flooding by the waterfall bypass.

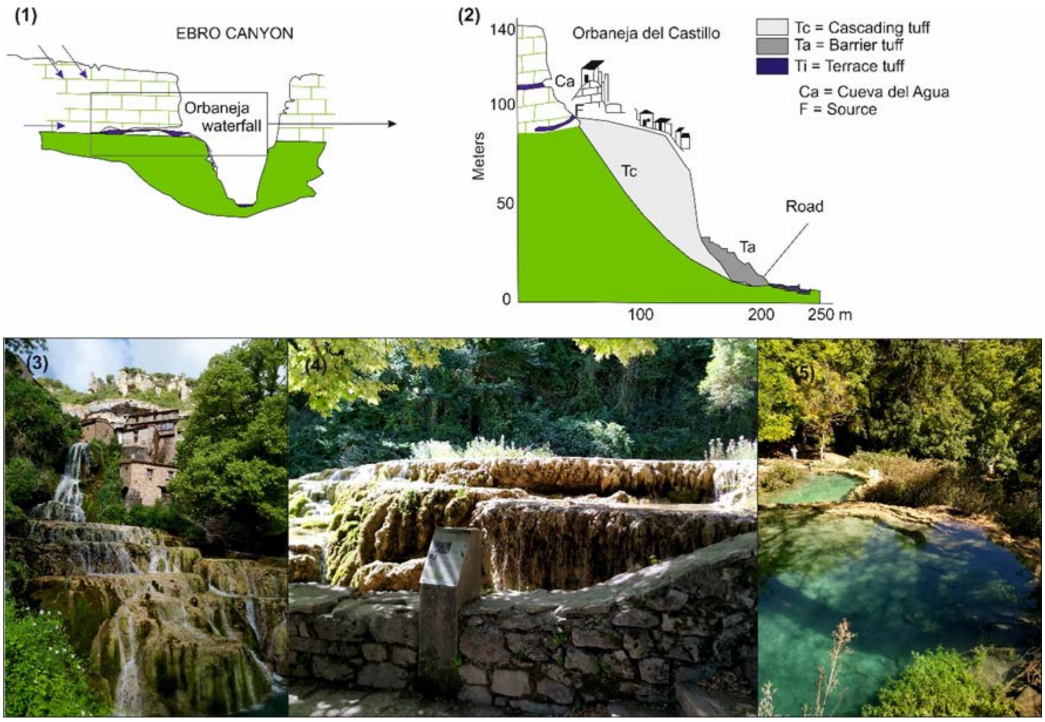

Figure 10. (1) Cross-sectional profile of the Ebro riverbed at Orbaneja del Castillo. (2) Detail of the waterfall in the section between the Cueva del Agua, point of upwelling, to the travertine terraces downstream of the BU-643 road (modified from Edelwiss, 2009 [35])). (3) Orbaneja del Castillo waterfall taken from the road on 07-06-2022. (4) Detail of the barrier travertines; picture taken 21-08-2022; (5) Image of the travertine terraces that generate the so-called "Pozas de la Turquesa", waters below the road indicated in the profile diagram taken 07-06-2022.

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3.1.5. Peat bogs

Peat bogs are located in: La Piedra, Urbel del Castillo, Humada, Fuencaliente de Puerta, Corralejo del Valdelucio. There are alos peat farms in Basconcillos del Tozo and another restored after its exploitation in Villanueva de Puerta. The processes that have allowed ofr the development of peat bogs in this área are poorly known.

3.1.6. Canyons and sickles

In the northeastern end of the Geopark, the canyons and gorges of the Ebro (Fig. 11a) are the spectacular elements of the landscape. There are also, the Rudrón gorges in the center of the Geopark, and in the western sector of the Geopark, the Horadada canyon in Mave (Fig. 11b).

Figure 11. (a) Sickles of the Alto Ebro in the surroundings of Orbaneja del Castillo. (b) La Horadada Canyon (Pisuerga River) north of Mave (Source: Las Loras Geopark).

3.1.7. Sinkholes

There is a sinkhole of the Hurón River in the Cueva del Agua, located in Basconcillos del Tozo.

3.2. Geomorphology: Loras and moolands

3.2.1. The moorlands

Moorlands have formed on extensive slightly deformed carbonated platforms [7]. They are located in the northern half of Las Loras UGGp at Páramo de la Lora de Valdivia and la Pata del Cid.

The moorlands are much more extensive than the loras which occupy the flat-tops of individual hills (Fig. 12).

The Ubierna fault configures the arrangement of the geological formations, the geomorphology and conditions the hydraulic connection relationships between them. Other geological elements to highlight are moorlands, loras, caves, springs, travertine buildings and waterfalls associated with them, canyons and gorges, karst sinkholes, upwellings and resurgences, all of them associated with the karst landscape. Many of them are identified as PGI, however, specific data are not yet available to define their characterization, and that constitute the starting point for their monitoring and functional evaluation, aspects that are key for the conservation and management of the geological heritage.

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Figure 12. (a) Loras de Peña Castro and Peña Amaya from the La Lorilla viewpoint; the valley zone corresponds to the warping of the synclines. (b) Moorland of la Pata del Cid.

3.2.2. The loras

The loras are hanging synclines in a landscape undergoing compression that have been subsequently eroded by Quaternary fluvial incision. The result is a hanging folded relief that gives a distinctive morphology to the landscape. The formation of the parrots dates back to the Jurassic (Fig. 13). The medium-large radius folds are of variable length between 5 and 20 km, with separation between hinges of 1 to 2.5 km and weak dips on the flanks [7].

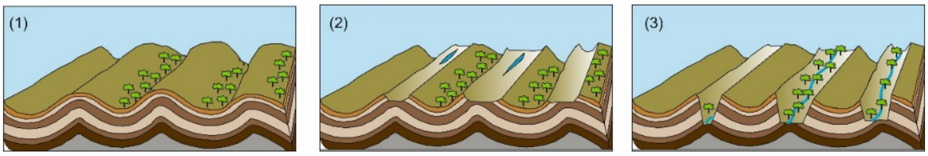

Figure 13. Formation process of a lora. 65 million years ago, the collision between Iberia and Europe caused marine sediments to emerge, and the formation of large folds and fractures, forming the mountain ranges of the Pyrenees and the Cantabrian Mountains. The relief is a result of different erosive processes that are still active: erosion by rain and wind. Limestone, more resistant to wear, is part of the highest areas of the Loras, with sandstone and marl, prone to erosion, in the valleys.

Martínez Arnáiz, 2013 [7] distinguishes a total of 12 loras (Fig. 1).

The vast mesas and moors, the plains interspersed between the tabular culminations, or narrow valleys cutting off the moorland, or the rugged relief of mountains provides a landscape of great contrasts. The Ebro and Rudrón rivers chamfer the high Moorland of la Pata del Cid into narrow and deep valleys several hundred meters deep. The Rudrón has maximum relief between San Felices and Valdelateja, less than 3 km from its mouth in the Ebro, where its valley is at 660 m and the peaks on the right bank are at 1,040 m. There are 380 meters of unevenness in a distance of 500 m on the plane, which causes an average slope of 37° (76%). The relief represents the sequence of Cretaceous floors. Those of the Upper Cretaceous build the mountainous profiles of the Loras and the wide moorland, while the Lower Cretaceous is widely represented in the valleys. Some facies of the Cretaceous are in abnormal contact and outcrop discontinuously and irregularly. The Lower Cretaceous sediments are have little exposure but have a great role in the relief [7].

The differentiation between moorlands and loras is given by three of their characteristics: altitude, extension and deformation. In general terms, the loras reach higher altitudes than the moorlands (Table 2), with the exception of the highest point in the Moorland of la Pata del Cid, which exceeds the heights reached by the loras.

Table 2. Characteristics of the loras and moorlands in the Las Loras UGGp (Fig. 3). The source of springs is Iberpix (IGN) [41]. It is indicated in the rows in white, the moorlands; and in the rows in gray, the loras identified in the area of Las Loras UGGp.

No	Name	Maximum altitude (m asl)	Length (km)	Width (km)	Nearest villages	Springs
A	Moorland of la Lora de Valdivia	1222	6,85	4,92	Revilla de Pomar-Villescobedo	Covalagua, Villaescobedo
B	Moorland of la Lora de la Pata del Cid	1063	22,20	14,14	Villaescobedo, Orbaneja, Valdelateja	Upwelling of Rudrón river, Ceniceros, Valdelateja
1	Lora de Peña Amaya	1370	5,3	2,7	Amaya-Villamartín de Villadiego	Fuente Prabal, Manantial de las Quintanas, Fuente de Oncejuelo
2	Lora de Albacastro	1349	6,78	2,7	Albacastro, Puentes de Amaya	Manantial de la Ceña, Manantial de Hoya Redonda, Fuente de la Legaña, Fuente de la Turquilla
3	Lora de Rebolledo de la Torre	1243	7,96	2,55	Rebolledo-Castrecias	Manantial de la Raposa, Fuente de San Roque
4	Lora de Ulaña o de Humada	1206	7,09	1,4	Humada-Ordejón de Abajo	Fuente de San Pedro, Manantiales de Vallejo, Fuente del Carril
5	Lora de Barriolucio	1193	25,5	2,99	Barriolucio-Fuenteodra	Barriolucio, Manantial de la Magdalena
6	Lora de Pinza	1107	7,38	6,6	Urbel del Castillo	Manantial de la Recova, Manantial del Pradal, Manantial de Tarancón, Manantiales del Olmo, Manantial de las Matas, Manantial de los Pradillos, Manantial de la Pedrosa, Manantial de los Milagros
7	Lora de Corralejo	1161	6,7	1,65	Corralejo-Solanas de Valdelucio	Fuente Cuevas, Fuente de Ostra
8	Lora de Fuente Urbel	1085	5,15	3,05	S de Fuente Urbel	Fuente Urbel, MAnantial de Valledrías, Manantial de Trescuevas, Manantial de Valdehayas
9	Lora de Cuevas de Amaya	1150	3,65	1,57	Rebolledillo-Cuevas de Amaya	Fuente del Obispo, Fuente Ritoba, Fuente Junquera
10	Lora de Villela	1077	2,38	3,16	Villela-Rebolledillo de la Orden	Fuente Gatón, Fuente Mijo
11	Lora de Monte Carrascal	1035	4,26	1,61	San Pantaleón del Páramo-Montorio	Manantial de Valdemudo
12	Lora de Las Tuerces	1087	6,85	2,63	Villaescusa de las Torres	-

[1] Expressed in km.

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3.3. Interpretation and hydrogeological significance

The oldest rocks correspond to the Upper Triassic Keuper facies. These are marls and clays variegated with salts and gypsum, highlighting the presence of clear and orange bipyramidal quartz (hyacinths from Compostela). Its presence is limited to narrow strips of a few hectometers wide and a few km long, or to eyelets that do not exceed one kilometer in axis. Spatially they are restricted to the S (Quintanilla Pedro Abarca, San Pantaleón del Páramo and NW of Castrillo de Rucios) and to the W (around Los Ordejones, Amaya and Villela). Small elongated enclaves are also found along the Lomilla-Castrillo dislocation line, between the Corralejo and Valdelucio loras. However, despite its little superficial significance, its importance in relief is remarkable. The very plastic behavior of the Keuper materials has allowed them, during the compressive phases of the Alpine Orogeny, to move laterally, inject, perforate and disjoin the overlying strata as diapirs, causing very interesting nuances in the relief.

Pushed by the Keuper, other materials stratigraphically located on top of said unit were dragged in the ascent. Accompanying the perforations appear small and unconnected outcrops of rhetian and liasic okerous carnioles (Fig. 7c), which form crestoncillos and small ridges. Subjected to strong compressions, the fracture of these dolomitic limestones (Fig. 7d), lacking plasticity, is pronounced. The intense fracturing together with their ocherous nature makes them very vulnerable to karstic dissolution; the high content of magnesium carbonate and iron minerals results in abundant terra rosa, which is the basis of soils suitable for cultivation or pasture [7].

The Keuper materials constitute the detachment level of the thrust that is mapped in the Becerril area, and also appears as extrusive material associated with some sectors of the Ubierna fault, as can be seen in the MAGNA 133 sheets [11] and 134 [10]. The permeability of this predominantly clayey formation is very low. There is only a certain permeability through fractures and discontinuities that can favor the entry of water and produce a certain dissolution of the gypsum in their surroundings. This formation constitutes an impermeable barrier to underground flow.

The Jurassic materials, formed by limestone and ocherous dolomite, are linked either to the Becerril thrust, or to the Ubierna fault in its westernmost sector, between Aguilar de Campoo and Fuencaliente de Lucio. They are stratigraphically disposed over the previous Keuper materials. Its power is very variable depending on the characteristics of the outcrops, but it is estimated between 150-200 m, and can reach 400 m. They present significant karstification, due to the presence of porous carniolar levels and an intense degree of tectonization, which gives them high or very high permeability. Karst development increases permeability, generating preferential underground flow paths.

The alternation of marl limestone and marl from the Jurassic presents average permeabilities of 0.0089 m/d and 0.0031 m/d [22].

The fluvial base levels are constituted by the channels of the Pisuerga rivers (in the western sector), with levels between 897 and 892 meters above sea level; Lucio, in the central sector, with elevations between 980 and 875 meters above sea level; and Urbel (eastern sector), with levels between 1010 and 900 meters above sea level.

Three types of sediments have been considered in the analysis: aquifers themselves (which according to their dominant lithology can be carbonated or detrital), aquitards and aquifuges (Table 3).

Table 3. Classification of the formations ordered chronologically according to their hydrogeological behavior. Note: The Neogene/Paleogene is not present within Las Loras UGGp. Its presence is representative within the Duero detrital Tertiary, outside the southern limit of the Geopark.

Formation	Aquifer	Aquitard	Aquifuge
Quaternary	X		
Maastrichtiense			X
Campaniense	X		
Campaniense		X	

Upper Santoniense	X		
Lower Santoniense		X	
Coniaciense/Turoniense	X		
Cenomaniense-Albiense (Utrillas)		X	
Apt-Albiense		X	
Valong. Barremiense		X	
Portlandiense-Upper Kimmeridgiense (Purbeck)		X	
Dogger	X		
Dogger Batho.			X
Dogger Bajo.	X		
Upper Lias-Alb.		X	
Lower Lias-Alb.	X		
Trias			X

The upper aquifer in the Las Loras UGGp encompasse materials between the Lower Cretaceous and the Quaternary. A second deep regional aquifer is predominantly represented by marine Jurassic sediments. In the first case, most are free-type aquifers, whose discharge points are above the level of the river valleys. In the second case, these are confined aquifers that in some cases discharge at a level higher than the river valleys or at the same level as these, with a certain pressure.

There is no evidence of a connection between the two aquifer systems described; the materials from the Lower Cretaceous provide an aquitard that isolates both aquifer systems.

a) Upper multilayer aquifer

The aquifer-aquitard overlapping sequence in the upper reaches of the Cretaceous (Table 4), is the reason why fluvial erosion has isolated certain structures (mainly "loras" in favor of semi-permeable materials, generating well-configured isolated aquifers such as: The Valdivia Lora, the Barrio-Panizares Lora, or the Barriolucio Lora.

Table 4. Stratigraphic series of the Cretaceous that makes up the sequence of free-type aquifers in the different types of loras.

Code	Geological age	Description
C-7	Upper Santoniense-Lower Campaniense	Calcareous sandstones, dolomites and limestones with rudists and foraminifera
C-6	Upper Santoniense	Glauconitic marls and limestones
C-5	Medium Santoniense	Calcarenites with "Lacazina Elongata"
C-4	Lower Santoniense	Calcareous marls and marly limestones
C-3	Medium Turoniense –Upper Coniaciense	Sandy limestones, oolitic limestones and limestones with rudists
C-2	Medium Turoniense	Sandy loams
C-1	Cenomamiense	Sands, microconglomeratic sandstones
C-0	Utrillas Facies	Sands, microconglomeratic sandstones and clays

a) Deep aquifer

It constitutes a barely known aquifer. The available data is scarce and comes largely from the hydrogeological studies carried out in Sargentes de la Lora as a result of the oil drilling carried out in that area. It is made up of Jurassic limestone and dolomite that rest on Triassic clay and gypsum that acts as an aquitard (cf. Table 3).

Considering the previously commented results in an integrated manner, sectors with different hydrogeological functioning within the Geopark have been identified. These sectors correspond to the loras and moors divided by rivers and streams that collect the diffuse discharges of underground flows, coexisting with various springs that occur at levels higher than said channels, as a result of the permeability contrast between geological formations in contact (Fig. 3).

The Barriolucio lora is separated from the Fuente Urbel lora by a complex system of sigmoidal faults in relief that displace the continuity of the outcrops by a few metres, being easily visualized in aerial photography.

As a synthesis of the results obtained, the conceptual hydrogeological model of the system has been built. In Las Loras UGGp there are different superimposed aquifers that form a multilayer system in the geological formations of the Upper Cretaceous. The configuration of the outcrops determines that the phreatic surface reaches certain levels in the loras and parameras, discharging in areas with contrasting permeabilities, generating springs frequently installed on the edge of the paramos and loras, or as diffuse discharges in the riverbeds that surround them. To visualize this model, Fig. 23 shows a section of the geopark that begins at the Peñalonga spring, crossing the Las Tuerces, Rebolledo de la Torre and Peña Amaya loras, to end at the Odra riverbed, within the geological domain. detrital Tertiary of the Duero basin. In this profile the springs and riverbeds have been reflected at the upwelling level based on a detailed topography.

Due to the absence of groundwater exploitation, there are no data available that allow locating the piezometric level of the regional Jurassic aquifer. This aquifer can function in a free regime, as in the outcrop generated by the Peñalonga spring, or in a confined or semi-confined regime at depth.

3.4. Analytical results

The analytical results and the parameters calculated for the hydrochemical characterization of the Las Loras samples are collected in three tables that are attached as complementary material. SM_Table-1 contains the analytical results, SM_Table-2 the descriptive statistics and SM_Table-3 the result of the calculation of various indices and hydrochemical parameters.

The waters present throughout the sampled area have very similar hydrochemical facies (see Figure 14 and SM_Table-3), mostly of the calcium bicarbonate type. Points 30, 42, 68 and 69 are an exception as their facies are sulfated bicarbonated. Among these, point 42 (Manantial de la Pisadera) whose rSO_4^{2-}/rCl^- ratio is 95.2 and point 30 (Riotobas) whose rSO_4^{2-}/rCl^- ratio is 12.14 stand out for their anomalous sulfate content (SM_Table-1). This group could include the Peñalonga spring, whose sulfate ion content is very high, although the rSO_4^{2-}/rCl^- ratio (6.64) remains within the typical values of the area. The high proportion of sulphate in these points corroborates the idea that they are fed by waters that travel longer and are deeper than the rest, in contact with detrital materials from the Keuper, with the presence of clay and gypsum in their composition, sometimes located outside the park boundary. In Figure 6, through the Stiff diagrams, the spatial distribution of the facies in the study area has been represented. You can see the uniformity of the spatial distribution of the facies and of the total mineralization (represented as electrical conductivity). However, to the west, a north-south strip can be seen that includes all points between 68 and 12 to the north and 9 to the south. The points of this strip differ slightly from the rest due to their small but appreciable content of Cl^- and Na^+ ions. It is possible that there is a structural reason that explains this difference, since this strip approximately coincides with the Becerril de Carpio thrust.

The analysis of the Piper, Chadha and Durov diagrams presented in Figure 14 shows that the facies and ionic relationships in streams is notably more homogeneous than in rivers and springs, for example in the Chadha diagram all are located in the sub-field 5 (alkaline-earth metals and anions of weak acids both exceed alkali metals and anions of strong acids, respectively), it is therefore a water that presents temporary hardness characteristic of the dissolution of carbonate rocks without contact with highly soluble evaporites. This homogeneity is probably due to the fact that the main contribution of water to

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the streams comes directly from surface and sub-surface runoff (hypodermic flow), which drains the most superficial carbonate outcrops, giving rise to hydrochemically very homogeneous waters with low mineralization.

The pH values are consistent with the calcium bicarbonate nature of the waters, they are always above neutrality, in the range between 7.13 and 8.18 pH units, thus they are waters without dissolved carbon dioxide, even the pH of some of the samples (23, 26, 42, 32 and 21) reaches relatively high values, between 8.17 and 8.18, very close to the alkalinity by CO_3. They are also low mineralization waters, from a minimum of 125 µS/cm in sample 6 to a maximum of 693 µS/cm in Peñalonga Spring. In Figure 6 the spatial distribution of the total mineralization of the water has been represented and, as was the case with the facies, a north-south stripe can be seen to the west in which none of the samples is found in the group with the lowest electrical conductivity.

All the calculated ionic ratios (see SM_Table-3) again indicate that the mineralization of water comes from contact with carbonate materials and that of the salts more soluble than carbonates, sulfates prevail over chlorides in most cases. In this sense, as has already been explained in previous paragraphs, samples 30 and 42 constitute a particular case.

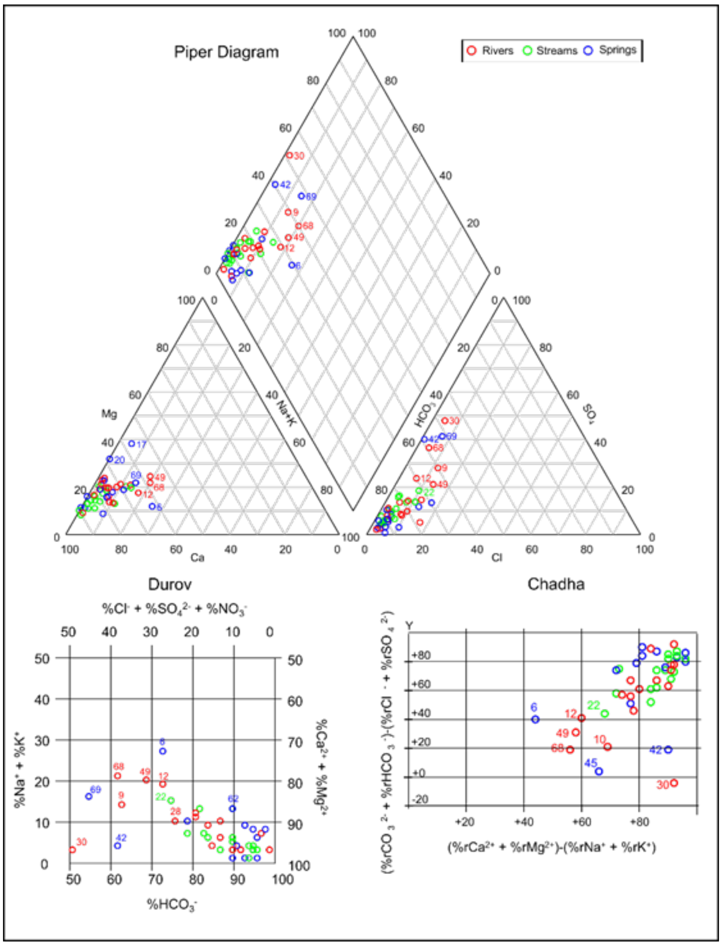

Figure 14. Representation of the water samples taken in Las Loras UGGp using Graphs of Piper [42], Durov [43] and Chadha [44]. In the case of the Durov and Chadha plots, only the portion of the plot in which the samples are grouped is shown.

The content of nitrogenous species and phosphorus, which in this type of water can be used as indicators of agricultural pollution, is very irregular. Detectable phosphate levels have been measured in eight of the analyzed samples, between 0.1 and 0.8 mg/L, high amounts given the carbonate nature of the soil matrix that tends to remove phosphate in the form of apatite precipitates and insoluble hydroxyapatite. On the other hand, ten of the samples present NO_3 values above 10 mg/L and of these four above 20 mg/L (points

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58, 20, 21 and 47), the first three being springs and the fourth being a stream. . These values, together with the low agricultural activity in the area, demonstrate the great vulnerability of the system to contamination and how fast the response must be given that both springs and surface channels are affected.

Except for sample 47 (Arroyo de las Solanas) whose content of nitrites, ammonium and phosphorus suggests that they are affected by some type of organic contamination, all are waters of excellent quality for any use, including human consumption.

No indication or hydrochemical mark of thermalism has been observed except in samples 64 and 6 (Valdelateja spa and Manantial de la Cárcava respectively), the temperature values predicted by the geothermometers (SM_Table-2) are above 99.73 % of the samples studied. In the case of Valdelateja, this data is consistent with its proven thermal nature, since its upwelling temperature is 20º C, nine degrees above the annual atmospheric average. However, in the case of the Cárcava Spring, it seems that the high silica content, caused by contact with siliceous materials, makes the geothermometers predict temperatures well above the typical values of the rest of the samples. This idea is supported by the low mineralization of the water of this spring that with 115 μS/cm is the lowest of all those analyzed. Note that the Pisadera Spring (number 42), which was once described as thermal [41] as it presents an upwelling temperature of 18º C, currently does not show a temperature above the annual average or any other sign of thermalism.

3.5. Hydrogeological characterization of springs

Springs are the natural discharge points of aquifers and therefore their analysis provides information of great interest for understanding the dynamics of groundwater.

Within the limits of Las Loras UGGp there are 212 inventoried springs [26], many of them unnamed. Most of them are located in the Fold Band, revealing the consequences of compartmentalization and the evidence of changes in permeability between the geological formations in lithological contact. A series of springs that have different characteristics have been selected, based on the criteria discussed in the methodology.

3.5.1. Peñalonga spring

It is located in Aguilar de Campoo. Known since the 9th century because it was the origin of the construction of a monastery by the Premonstratensian monks. The monastery has undergone changes throughout history, being known as a Romanesque monastery built for the most part between the 12th and 13th centuries, later abandoned in the 19th century, at the end of the 20th century it was rebuilt, currently housing a teaching institute secondary (Fig. 15). The spring is still active and due to its upwelling temperature, 12º C, it was used for air conditioning in the classrooms in the winter months (verbal communication from the monastery guides).

Figure 15. Peñalonga spring. (1) View of the Romanesque Monastery of Santa María la Real (Aguilar de Campoo) with the carbonate massif that houses the aquifer in the background. (2) Courtyard of the springs, where the spring is located, located at the foot of the massif; and (3) sampling point (Coordinates: -4,272; 42,796) in the current entrance courtyard to the monastery.

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The spring emerges at the foot of a carbonate massif in its contact with the Keuper materials that act as a wall of the aquifer (Fig. 16). The Keuper outcrop in this area is due to the existence of several thrust scales that force its outcrop in this sector. The upwelling elevation is 905 m above sea level. The waters of this spring present calcic bicarbonate facies with an electrical conductivity of 909 µS/cm measured in situ on 08/19/2022.

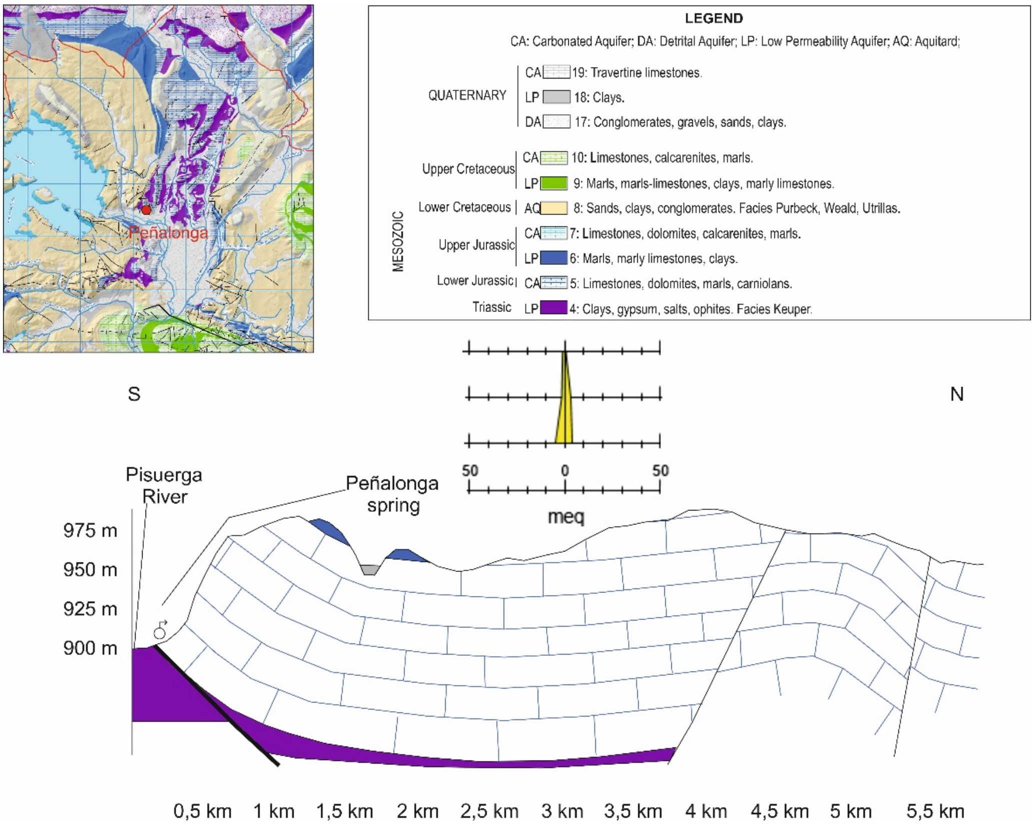

Figure 16. Location and hydrogeological cross-section of the Peñalonga spring with Stiff diagram of hydrochemical facies included.

3.5.2. Spring of La Pisadera

This spring is of a structural type, due to the upwelling that occurs in the contact of the Ubierna fault with the less permeable materials of the Lower Cretaceous (Fig. 17). However, the presence of the Jurassic aquifer at a relatively shallow depth would justify the spring feeding through the fault plane.

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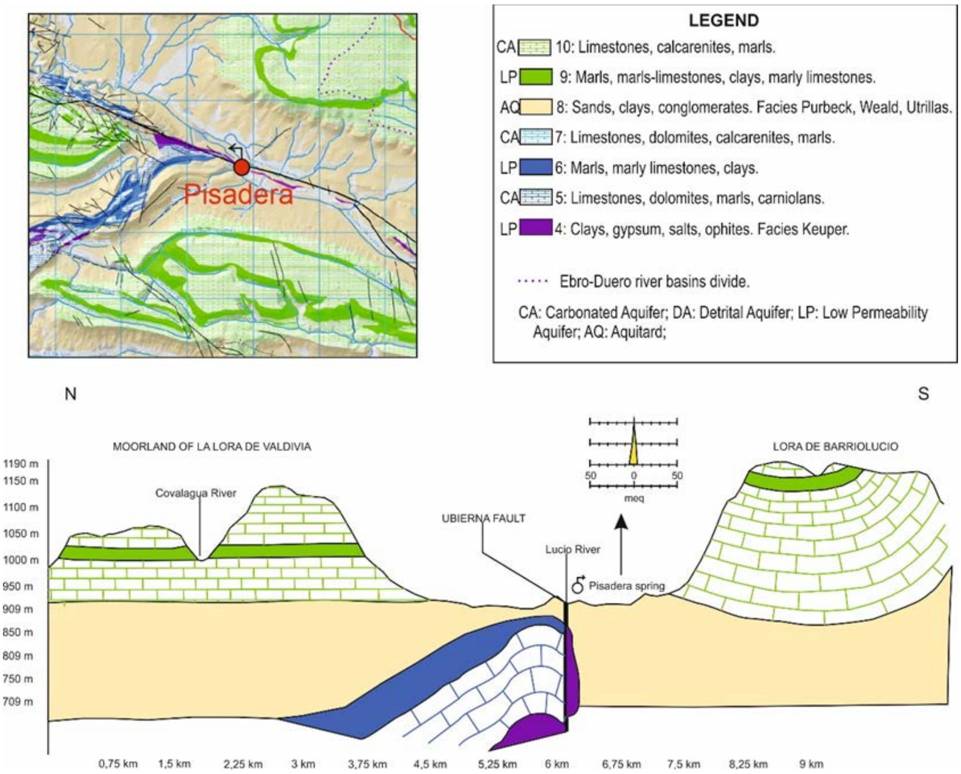

Figure 17. Location and hydrogeological cross-section of La Pisadera spring with Stiff diagram of hydrochemical facies included.

According to some bibliographical sources (Cidad, 1986) [45]), it is a thermal spring with a stable upwelling temperature of 18º C all year round. A measurement quantified its flow of 10 l/s. Currently no thermalism is detected, measurements in the field give an upwelling temperature of 13º C, both in the April-2022 campaign and in June 2022, while in the August 2022 campaign it was dry (Fig. 18). Thus, field observations do not support the hypothesis of potential hydrothermalism, neither current nor historical, at this point of upwelling. In addition, there are no mining signs or mineral paragenesis associated with metallogenetic deposits that indicate the existence of hydrothermalism in this fault zone [46].

Figure 18. Spring of La Pisadera. (a) Photograph taken on 04-04-2022; (b) Photograph taken on 08-19-2022.

The physical-chemical characteristics of the water reveal a certain variation in the underground circulation pattern. However, these indications do not allow to define its thermal character. This observation is consistent with the fact that the literature review shows that no low enthalpy geothermal reservoirs have been found within the Las Loras UGGp.

The factors that may have participated in the evolution of the Pisadera spring would require a more in-depth investigation than that developed here, including climatic and hydrogeological aspects, in particular, the evolution of groundwater levels in recent decades, which this is complicated given the scarcity of available data.

3.5.3. Fuentehoz spring in Barriolucio

The Lucio river rises in what is known as the Lucio River cave or the Hoz cave located just below the BU-621 road, between Km 25 and 26, below the Upper Santonian limestone cut (number 16 of lithological legend in MAGNA50-134 [10]) that crosses the trench of road. A stream of water emerges from its entrance, active most of the year, next to her, between the space that separates the Turonian-Coniacian-Santonian limestones (14), from the Upper Santonian limestones (16), there is a narrow band, affected by faults, of calcareous marls and sandy limestones with glaucinite from the Middle Santonian (15). The permanent upwelling of Fuentehoz appears, from which the town of La Riba de Valdelucio is supplied, the water fills the deposit located on the tuff platform, on the right side of the river, pouring the surplus once it has passed the active front of the tuff building. The water that comes out of these suggestions is the one that runs through the surface and precipitates from the top of the tuff formation, originating the Barriolucio waterfall.

It is a permanent spring and according to verbal testimony of an inhabitant close to this spring, it has only stopped flowing in extremely dry years. In the visits of 07-21-2022 and 08-19-2022 it can be seen that not only has the flow not reduced, which would be expected given that 2021/2022 is being a dry year, but that the flow has increased considerably, generating a second pool to the E of the main one through which a somewhat smaller flow of water circulates, also in a cascade (Fig. 19).

This enclave constitutes a somewhat inhospitable place, in which the pristine conditions in which this spring is preserved are especially noteworthy, despite the anthropic activity of the environment, with cultivated fields downstream, close to the location of the spring.

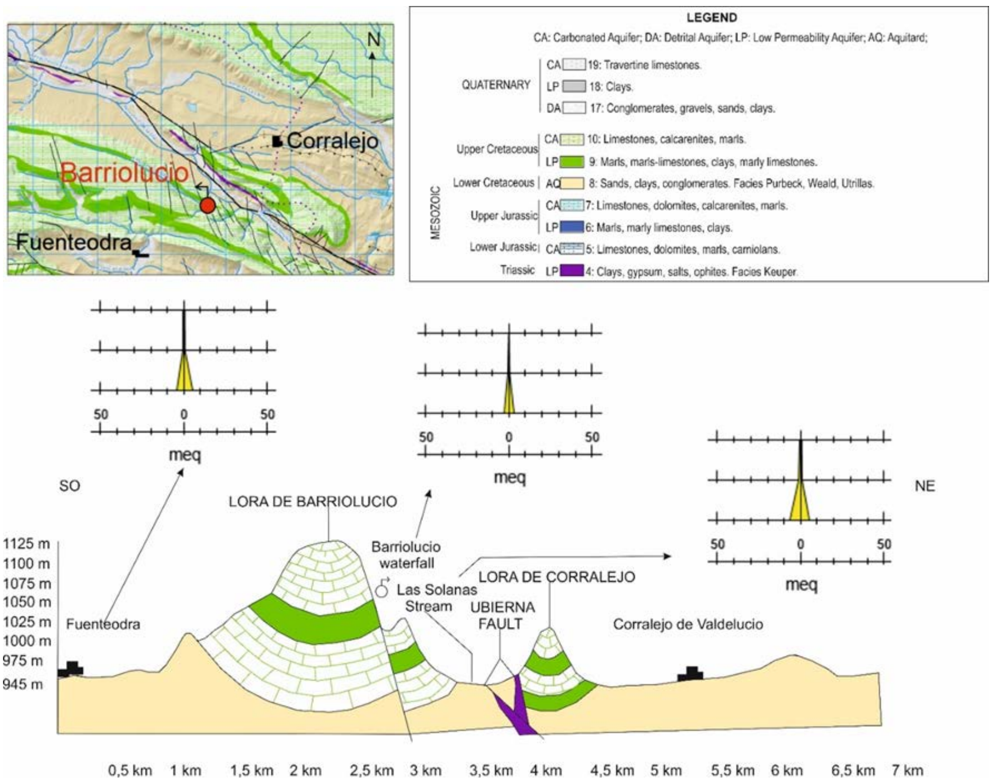

Figure 19. Location and geological cross-section of the Loras de Barriolucio and Corralejo transversal to the Barriolucio waterfall according to a Fuenteodra-Corralejo direction. The water sample of this waterfall is called Manantial de Barriolucio, no. 71 in our analyses of SM_Table-1 and SM_Table-3.

The Barriolucio upwelling is located on the northern flank of the Lora de Barriolucio syncline, at the lithological contact between the Turonian-Coniacian-Santonian (14) limestones and the Cenomanian (12) sands and clays. This interpretation differs from the cartographic representation of Sheet MAGNA50 no. 134 [10] (where it is indicated that the spring is located near the intersection of the two faults that put the Upper Santonian limestones (16) in contact with the Turonian-Coniacian-Santonian limestones (14). The presence at a local scale of Cenomanian loams (13) is not ruled out, which is not incompatible with the MAGNA50 cartography due to the different work scale, however, due to the abundant vegetation and the upholstery generated by the travertine building, it has not been possible to verify it in the field.

As indicated in Sheet MAGNA50 no. 134 [10], the Cueva and Fuentehoz springs appear near the intersection of two faults that are part of a series of oblique faults associated with the Ubierna fault, which affect the northern flank of the Lora de Barriolucio syncline, forming a duplex in echelon between the towns of Escuderos and Solanas de Valdelucio.

Perhaps it would be possible to find two levels of surges; one between the Upper Santonian limestones (16) and the glauconite marls and limestones (15); and another between the limestones of the Turonian-Coniacian-Santonian (14) and the sands and clays of the Cenomanian

The structural configuration of the Barriolucio spring responds to a complex system of limestone outcrops in relief, whose specific hydrogeological connection requires a more detailed hydrogeological study outside the objectives of this work, with the application of specific techniques (tracers, isotopic analysis) in order to determine the provenance and origin of the water.

The outcrop of these limestones is formed by a series of blocks in relief that owe their reason for being to a series of sigmoidal faults associated with the Ubierna Fault. The block in which this spring is located is the southernmost in the series.

Although there is no continuity of the Turonian-Coniacian-Santonian limestone outcrop (14), since there is a structure in relief of this outcrop, there may be a hydraulic connection, which explains the permanent feeding of the waterfall. However, it is not possible to define the recharge zone with the data we have. The parameters measured in situ at the spring are presented in Table 5 and Fig. 19.

Table 5. Measurements of unstable parameters in situ in the Barriolucio Waterfall.

Parameter	06-06-2022	19-08-2022
EC (µS/cm)	-	612
pH	7,15	6,47
T (º C)	10,76	14,8
Redox Potential (mV)	-	25,5

Figure 20. (a) Photograph taken at the Barriolucio waterfall on 07-21-2022 with two of the co-authors. (b) Barriolucio Waterfall on 08-19-2022. The rocky level at the foot of the rock located to the right of the photograph is flooded and behind said rock there is another pool similar to the one seen in the photograph.

Fig. 20a contrasts with the image taken on 07-21-2022 (Fig. 20b) in which it can be seen that said step was dry. This may be due to an increase in the discharge flow as a result of possible recent rains, or to a modification in the construction of the travertine building that has produced a new waterfall from behind the rock located on the right of the photograph. In any case, the new volume of water is excessive to assume that it is the result of the low rainfall that occurred in the area on previous dates.

The Barriolucio spring appears in the lithological contact of the limestones (14) with the sands and clays of the Middle Cenomanian (12). The presence at a local scale of Cenomanian loams (13) is not ruled out, which is not incompatible with the MAGNA50 cartography [10] due to the different work scale, however, due to the abundant vegetation and the upholstery generated by the travertine building, it has not been possible to verify it in the field.

The structural configuration of the Barriolucio spring responds to a complex system of limestone outcrops in relief, whose specific hydrogeological connection requires a more detailed hydrogeological study outside the objectives of this work, with the application of specific techniques (tracers, isotopic analysis) in order to determine the provenance and origin of the water.

3.5.3. San Bol spring

The San Bol spring is located in the easternmost sector of the northern flank of the Barriolucio syncline (Lora de Barriolucio). It is located at the foot of a carbonated hill (Fig. 21). This spring, located in Sheet MAGNA50 134 [10], corresponds to an upwelling associated with lithological contact between the Upper Santonian limestones (16) and the Lower-Middle Santonian marls (15).

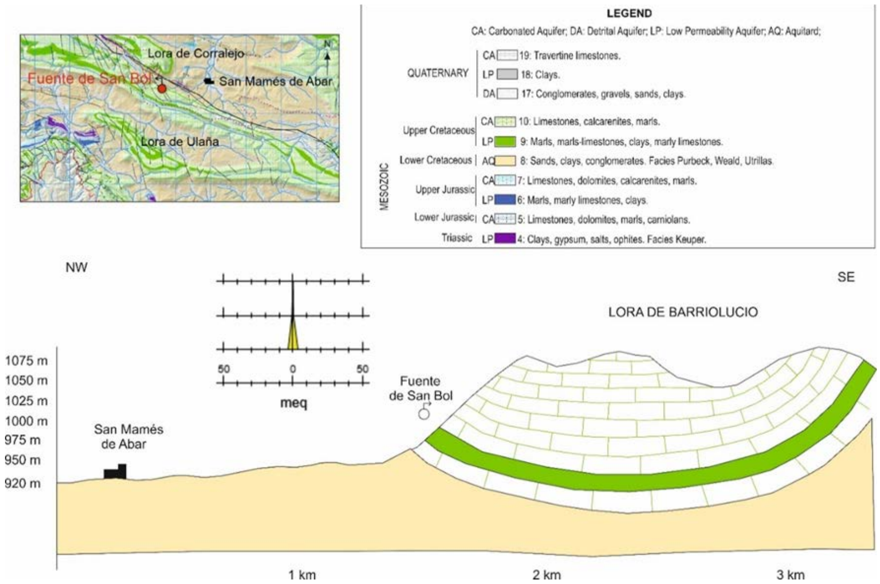

Figure 21. Location and geological cross-section of the Fuente de San Bol. The Fuente de San Bol is the sample no. 48 in the Table 1 and Table 3 of the CM files.

The chemical analysis of the sample taken on 04/04/2022 (Table 6) reveals that it is calcium bicarbonated water with an electrical conductivity of 339 μS/cm. The chloride content shows that it is continental water with very little travel within the aquifer.

Table 6. Chemical results of the water samples taken at Fuente de San Bol spring on April 4th, 2022. Concentrations are expressed in mg/L. CE in μS/cm.

Cl	SO_4	CO_3H	CO_3	NO_3	Na	Mg	Ca	K	pH	CE	NO_2	NH_4	PO_4	SiO_2
1	10	197	0	0	0	7	62	0	7.63	330	0	0	0	2.8

3.5.5. Valdelateja springs

The thermal springs of Valdelateja are located on the left bank of the Rudrón river, before its mouth in the Ebro river (nº 64 in Fig. 3). Less than a kilometer upstream from the town center is the old Valdelateja spa, closed since 2008.

There are several springs with thermal characteristics in its surroundings. Several samples have been taken (see SM_Table-1 row 64) on different dates. However, all of them show that the water temperature does not change throughout the year, presenting a temperature of 20º C. The level of the sampled upwelling is at the same level as the Rudrón riverbed, from which it is some 10 m apart.

The origin of this spring is not well known. According to IGME-SIEMCALSA (2008)[49], the origin of its waters is related to materials from the Cenomanian (Upper Cretaceous). Field observations confirm this, however, we disagree with the conceptual model of operation presented in said source, due to the fact that in the schematic geological section the marls of the Upper Cretaceous appear represented immediately below the Rudrón river bed at the height of the Spa, acting as a confining aquitard of the Lower Cenomanian sands and calcarenites. This is inconsistent with the evidence of the sample taken at the point of emergence, with the presence of calcarenite, which shows that the emergence flows in these materials. The confined Lower Cretaceous calcarenite aquifer therefore outcrops at this point through some unmapped punctual structural discontinuity. The presence of this fault (Fig. 22) is also revealed by the appearance of degassing phenomena in the Rudrón riverbed itself at the height of the river, and only at that point in the spa, where a faint and periodic bubbling is observed, ascending with bubbles of size between 1 and 7 mm.

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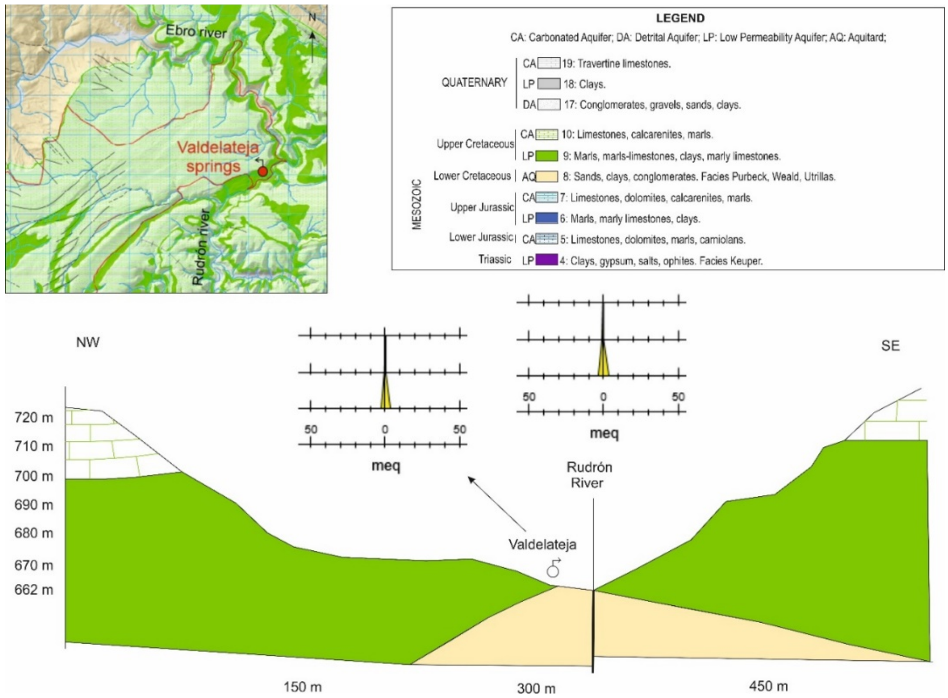

Figure 22. Location and geological cross-section of the Valdelateja spring in a transversal section to the Rudrón River at the height of the spa of the same name.

3.5.6. Springs of Orbaneja, Pozo Azul and Tubilla del Agua

These three locations are located in Fig. 3 with the numbers 56, 58 and 62 respectively.

The three sites present calcic bicarbonated waters, with low mineralization, and electrical conductivities between 403-462 µS/cm for the samples taken on April 6th, 2022 (Table-1 and 3 of SM files).

3.5.7. Summary of spring characterization

The most abundant are in the lithological contact between the Turonian limestones and the Cenomanian marls. Some examples of this typology are the springs of Covalagua, Villaescobedo (nº 2 and 13 in SM_Table-1), in the Páramo de la Lora de Valdivia (A in Fig. 3). This type of springs present waters belonging to calcium bicarbonate hydrochemical facies with electrical conductivities of the order of 400-460 µS/cm.

Secondly, the existence of springs with more mineralized water than the previous ones is observed, whose springs appear at lower topographical levels. Examples of them are the springs of Peñalonga and La Pisadera (No. 69 and 42 respectively in SM_Table-1). They present bicarbonated calcium facies waters with electrical conductivities of the order of 595-695 µS/cm.

Thirdly, there are springs located at intermediate topographic levels between the previous ones, with electrical conductivities of 595-695 µS/cm.

A summary of these typologies is shown in Table 7.

Table 7. Summary of the groups of identified springs.

Discharge level (m asl)	Geological formation	Hydrochemical Facies	EC (µS/cm)	Examples
970-1200	Upper Cretaceous	$CaCO_3H^-$	400-500	Covalagua, Barriolucio
940-960	Paleogene	$CaCO_3H^-$	350	Fuente Urbel
900-920	Jurassic	$CaCO_3H^-$	595-695	Peñalonga, Pisadera

3.6. Rivers

The main river is the Pisuerga River (number 29 in tables CM-1 and CM_3), which rises in Fuente Cobre, in the Sierra de Peña Labra, about 40 km NW of the Geopark to the Aguilar Reservoir. Along its route within the limits of the Geopark, it receives the waters of the rivers Camesa (nº 49 in tables CM-1 and CM-3), Lucio (nº 35 in SM_Tables-1 and 3), and other less important streams, on its right bank and several streams on its left bank (Ritobas (nº 30), Constana, Sudría, Bustillo). All these channels are permanent, as reported in local studies. The MIRAME-CHD Information System [17] confirms this for the Rubagón, Camesa, Lucio and Pisuerga rivers.

Within the scope of the Geopark, the rivers Lucio, Odra, Urbel (the Duero basin) and Hurón (nº 67 in SM_Tables-1 and 3)-Rudrón (nº 66 in the SM_Tables-1 and 3) (Ebro basin) are born, which are also rivers permanent according to official sources.

In turn, the Lucio River receives the waters of the Covalagua River (No. 2 in SM_Table-1 and 3) on its right bank.

The Urbel river rises in the place called "las Fuentes" in the town of Fuente Urbel (No. 72 in SM_Table-1 and 3), from which the urban nucleus where it is located takes its name. This spring has its origin in an upwelling in the contact of the limestones of the Middle Santonian (Upper Cretaceous) with the sands and clays of the Facies Weald (Lower Cretaceous).

The chemical analysis of the water samples taken at Fuente Urbel (nº 72 in Table CM_1 and CM_3) shows that it is bicarbonated calcium water, with an electrical conductivity of 361 µS/cm, without any difference being observed with respect to the waters of the river Lucio.

All the streams and rivers sampled present bicarbonated calcium waters without great differences between them. However, the high concentration of salts in the Arroyo de las Solanas (no. 47 in SM_Tables-1 and 3) stands out, admitting two possible causes: (a) contribution of more saline materials from the Lower Cretaceous at its source; (b) anthropogenic contamination;

3.7. Hydrogeological conceptual model

Hydrogeological information has been synthesized in the two most relevant sectors of Las Loras Geopark: Burgalesa Platform (Fig. 23) and Folded Band (Fig. 24).

In the Burgalesa Platform sector, the flows present a southwest-northeast direction, and towards the Rudrón riverbed, which acts as the main drainage axis; the Rudrón river constitutes the base level. The springs appear in the peripheral fringe (old Ceniceros spring), associated with old terraces (Orbaneja del Castillo), or with small hanging aquifer levels, or appear in the Rudrón riverbed related to specific tectonic accidents (Valdelateja thermal springs).

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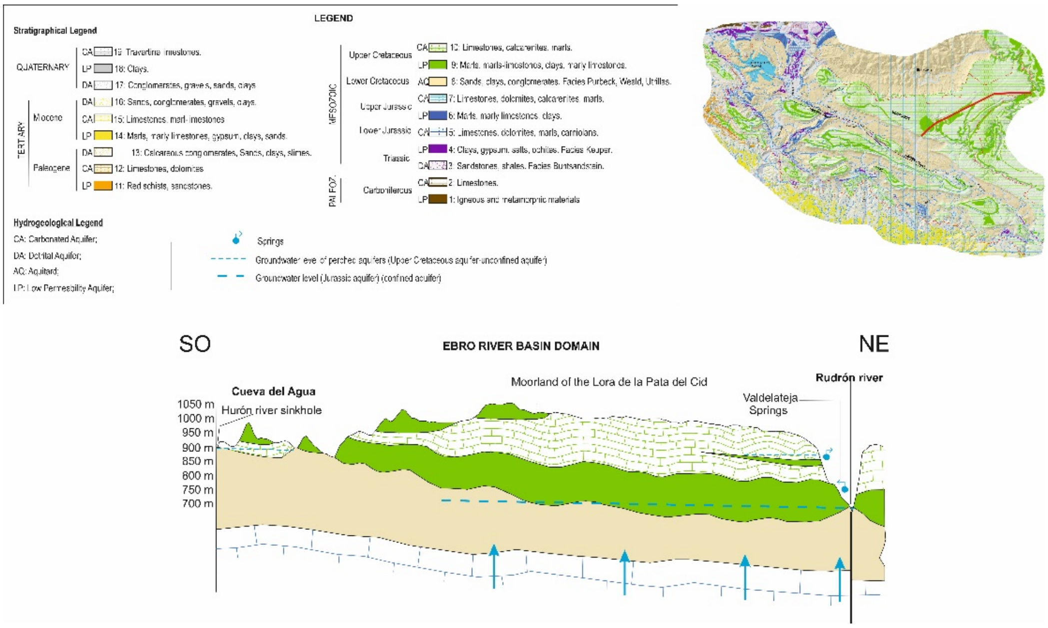

Figure 23. Hydrogeological section of the Burgalesa Platform in Las Loras UGGp.

In the Folded Band sector (Fig. 24), the compartmentalization of the loras individualizes the hanging synclines, with springs appearing on the peripheral edge of the limestone contact with the marl, which act as an aquitard, impeding the downward flows of the upper materials (Upper Cretaceous). The base level is determined by the Lucio River, which is at a lower level than many of the springs that appear in the Upper Cretaceous, with upwelling levels above 1000 meters above sea level (Fig. 24).

The results presented in the preceding sections allow us to explain the conceptual model of Las Loras UGGp consisting of two superimposed aquifer systems: a lower aquifer, formed by Jurassic limestone, whose lithological continuity in depth is assumed given the results achieved by the ALGECO project [30], despite the intense fracturing that exists, especially in the fault zone (central zone of the Las Loras UGGp). And an upper multilayer aquifer system, formed by the alternation of permeable and slightly permeable materials outcropping in most of the extension of the Las Loras UGGp, which make up the moorlands and loras.

The fact that the Lucio and Rudrón rivers constitute permanent rivers, whose channels are located at a lower level than the outcrops of the Upper Cretaceous, supports our hypothesis that these rivers receive an underground supply from the deep Jurassic aquifer.

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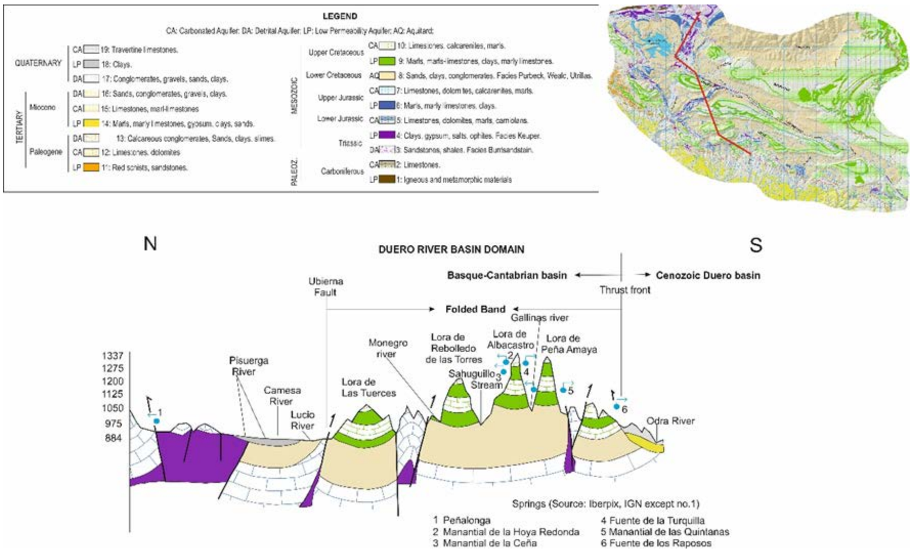

Figure 24. Hydrogeological section of the Folded Band in Las Loras UGGp.

4. Conclusions

The Ubierna Fault drives the geological, geomorphological, structural and hydrogeological characterization of the region and conditions the hydrogeological behavior of the existing aquifers within the Las Loras UGGp. The hydrogeological and hydrochemical characterization of the rivers and springs has made it possible to define the flow systems within the framework of the regional hydrodynamic behavior.

The waters in Las Loras show homogeneous hydrochemical facies, bicarbonated calcium, concordant with water of low residence time and fast flow that flow over carbonate materials. This means that almost all samples have low mineralization and suitable for any use. On the other hand, the groundwater and surface water system of Las Loras is very sensitive to contamination, so that in some of the points analyzed it is possible to speak of an incipient condition in an environment that is very little impacted by human activity.

There are, however, some exceptions to the rule, with representatives of sulphated waters (Riotobas, La Pisadera, Peñalonga) in an eminently bicarbonated environment, or thermal waters (springs in the Balneario de Valdelateja). These points contribute to the hydrodiversity of the system and to the richness of the associated biotopes, which are extremely fragile as they depend on singular points.

The conceptual hydrogeological model reveals that it is a multilayer aquifer system in which the main aquifer is the deep Jurassic aquifer, which must have continuity with outcrops of the same age to the N and NW of the Las Loras UGGp. Materials from the Upper Cretaceous that host the upper aquifers configure the outcrops of the moorlands (to the north of the Ubierna fault) and the loras (to the south of it), giving rise to independent aquifers in which the springs are frequently located in the peripheral border defined by the lithological contact between limestone and marl, or less frequently, in the mechanical contact due to structural discontinuities. The carbonated materials of the Jurassic make up the deep, confined aquifer, whose piezometric level may be responsible for an upward flow that discharges into the riverbeds, explaining its permanent regime.

The hydrogeological functioning described in this work corresponds to the central area of Las Loras UGGp, located between the left bank of the Pisuerga River and the left bank of the Rudrón River. The hydrogeological functioning of the moors located on the right bank of the Rudrón river (which includes Tubilla del Agua and Covanera-Pozo Azul) and the Bricia moorland (where Orbaneja del Castillo is located) correspond to other hydrogeological sectors not included in the current limits of the geopark, but with a view to the protection of these sites, it will be of interest to include them into the geopark limits.

Similarly, the right bank of the Pisuerga River presents geological, structural and geomorphological conditions different from those described here.

The analysis of the data presented shows, on the one hand, the abundant findings found, and along with this, the knowledge gaps that justify the need to propose future work: The role of the Ubierna fault and its structure in depth constitute matters slopes. Existing works to date still leave open questions regarding how deep the fault reaches, what materials make up the subsurface architecture and what hydraulic relationship exists between them.

The characterization of the paramos versus the parrots allows one to clearly differentiate between them. However, the confusion persists in cartography and toponymy, where both terms are used interchangeably, for example, Páramo de la Lora de Valdivia.

The definition of the hydraulic behavior of the materials that make up the Lower Cretaceous, which isolates the two aquifer systems identified in Las Loras UGGp (upper aquifer: Upper Cretaceous; lower aquifer: Jurassic), remains unresolved. It has been mentioned that in this work they have been interpreted as aquitard but the ascending or descending direction of the underground flows through it is unknown.

At the territorial scale of Las Loras UGGp, horizontally, the Upper Cretaceous outcrops do not present continuity with other Cretaceous outcrops in the environment (the closest ones are found on the north coast within the province of Cantabria), but they form separate blocks with an individualized hydrogeological behavior. However, their relationship with other aquifers in depth is unknown and it is not ruled out that they may be fed by them due to the permanent nature of some of these springs, and the reduced surface area of the materials that house them.

An individualized cartography is necessary that collects the characteristics of each of the sites identified as a Site of Geological Interest in Las Loras Geopark. In this way, it will be possible to register, through a data-based methodology, the peculiarities of each LIG and each type of element that integrates it.

A plausible hydraulic relationship, of influence or effluence, between the Jurassic limestone and the colluvial outcrop associated with the riverbeds, can be admitted.

Preserving this water heritage, its quality and integrity is only possible if (1) the integrity of the Las Loras system is preserved, (2) the use of the land is controlled and (3) the prohibition of activities or discharges that directly or indirectly could cause its pollution is guaranteed. This is especially relevant in a scenario of climate change and reduction in the amount of precipitation in which the self-purification and dilution processes will be seriously compromised.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, SM_Table-1: Location of the sampled points and chemical analysis; SM_Table-2: Descriptive statistics of the chemical analysis of the waters of Las Loras; SM_Table-3: Geothermometers and hydrochemical facies.

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Data Availability Statement: In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Please refer to suggested Data Availability Statements in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics. If the study did not report any data, you might add "Not applicable" here.

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References

1. Ruban, D.A.; Yashalova, N.N. Geodiversity meanings in global geoparks: an empirical study. *Environmental Earth Sciences* **2018,** *77*, 771. Available online: https://doi.org/10.1007/s12665-018-7962-9 (accessed on 04-02-2022).
2. Gray, M. *Geodiversity. Valuing and conserving abiotic nature.* John Wiley & Sons. West Sussex. 2004; 434 pp.
3. Carcavilla Urquí, L.; López Martínez, J.; Durán Valsero, J.J. (Eds.) *Patrimonio geológico y geodiversidad: investigación, conservación, gestión y relación con los espacios naturales protegidos*. Publicaciones del IGME, Serie Cuadernos del Museo Geominero 7. Madrid, Instituto Geológico y Minero de España. 2007. 360 pp.
4. Pereira, P.; Brilha, J.; Gray, M.; Pereira, D.I. Rephrasing the geodiversity concept under the Ecosystem Services approach and the UN Sustainable Development Goals. In Proceedings of the Conference: EGU General Assembly 2019, Vienna, Austria, 7–12 April 2019; Volume 21.
5. Sisto, M.; Di Lisio, A.; Russo, F. Geosite Assessment as a Tool for the Promotion and Conservation of Irpinia Landscape Geo-heritage (Southern Italy). *Resources* **2022**, *11*, 97. Available online: https://doi.org/10.3390/resources11100097 (accessed on 26-10-2022).
6. Guillén-Mondéjar, F.; Díaz Martínez, E.; de Santisteban, C.; Herrero, N.; Mata, J.M.; Meléndez, G. Protección, uso y gestión de la diversidad geológica (geodiversidad) y su patrimonio geológico de España. Propuestas de la Sociedad Geológica de España para los partidos políticos, legislatura 2011-2015. *Geotemas*, **2012,** *13*, pp. 1276-1279.
7. Martínez Arnáiz, M. Loras y paramera de la Lora en Burgos. El incierto horizonte del desarrollo rural en un espacio de montaña media en recesión demográfica. Universidad de Valladolid. Faculta de Filosofía y Letras. Tesis Doctoral dirigida por Fernando Molinero Hernando. Departamento de Geografía, Universidad de Valladolid, 2013. 762 pp. https://uva-doc.uva.es/handle/10324/4223 (accessed online on 01-10-2022).
8. Salman Monte, K.; Sánchez Fabián, J.A.; García García, F.; Basconcillos Arce, J.; Rodríguez García, A.; Gallego Rojas, N. (Eds.) Application dossier to be a UNESCO Global Geopark. Proyecto Geoparque Las Loras. Diputación de Palencia, Diputación de Burgos y Junta de Castilla y León. 50 pp.
9. Ramos, A.; Mediato, J.F.; Pérez-López, R.; Rodríguez-Pascua, M.A. Miocene to present-day tectonic control on the relief of the Duero and Ebro basins confluence (North Iberia). *Journal of Maps*. 2021. Available online: https://doi.org/10.1080/17445647.2020.1869111 (accessed 02-09-2022).
10. IGME, 1994, Mapa geológico de España 1/50.000 Polientes, núm. 134 (18-8). Instituto Geológico y Minero de España (IGME). Madrid.
11. IGME 1997a, Hoja Geológica MAGNA50 núm. 133 (17-8). Prádanos de Ojeda. Instituto Tecnológico Geominero de España. Madrid.
12. IGME 1997b, Hoja Geológica MAGNA50 núm. 165 Herrera de Pisuerga. Instituto Geológico y Minero de España. Madrid.
13. IGME 1997c, Hoja Geológica MAGNA50 núm. 166 Villadiego. Instituto Geológico y Minero de España. Madrid.
14. IGME 1997d Hoja Geológica MAGNA50 núm. 167 Montorio. Instituto Geológico y Minero de España. Madrid.
15. DPB-IGME. Atlas del medio hídrico de la provincia de Burgos. Diputación Provincial de Burgos. 1998. Instituto Tecnológico Geominero de España. URL: https://aguas.igme.es/igme/publica/libro74/lib74.htm consultado 03-09-2022.
16. CHD. Propuesta de Plan Hidrológico 2022-2027. Confederación Hidrográfica del Ebro. 2021. Available online: https://www.chebro.es/web/guest/revision-plan-hidrologico-tercer-ciclo (accessed on 22-08-2022).
17. CHD Information System. Duero river basin web page. Available online: https://mirame.chduero.es (accessed on 29-09-2022).
18. De la Hera-Portillo, A.; Llorente-Isidro, M.; Moreno, L.; Sánchez, J.A.; Salman, K.; Corral, M.M.; Galindo, E.; López, J.; Ghanem, M.; Hind Mohammed, A.; Chulli, B.; Laftouhi, N.E.; Abdel-Gawad, F.Kh. Geoheritage and geoconservation in the Las Loras UNESCO Global Geopark. In: Pereira, P.; Monge-Ganuzas, M.; Bollati, I.M.; Rouget, I. (eds). 2022. *ProGEO SE Europe Regional Working Group. Virtual Conference on Geoconservation*. March 30-31, 2022. Abstracts Book Online. Pp: 14-16.
19. De la Hera-Portillo, A.; Llorente, M.; López-Gutiérrez, J.; et al. Hydrogeological Setting of Las Loras UNESCO Global Geopark (Palencia-Burgos, Spain): State of Knowledge and Needs for Water Resources Sustainability Research. In the book: *Eurokarst 2022, Málaga. Advances in the Hydrogeology of karst and Carbonate Reservoirs*. Springer Nature (in press).
20. Base de datos Puntos de Agua [Water Points database]. CN IGME. Base de Datos Puntos de Agua ©CN. Instituto Geológico y Minero de España (IGME). Available online: https://info.igme.es/BDAguas/ (accessed on 27-12-2021).
21. Servicio WMA GEODE. Mapa geológico Continuo de España a escala 1:50.000 © CN Instituto Geológico y Minero de España (IGME). Available online: https://info.igme.es/cartografiadigital/geologica/Geode.aspx (accessed 28-12-2021).
22. ADIF-AECOM. Estudio Informativo de la línea de alta velocidad Nogales de Pisuerga-Reinosa. *Geología y Geotecnia*. 2019. Anejo 05. 172 pp.
23. ADIF-AECOM. Estudio Informativo de la línea de alta velocidad Nogales de Pisuerga-Reinosa. Apéndice 12. *Estudio hidrogeológico*. 2019. 1287 pp.
24. Stiff, H.A. The interpretation of chemical water analysis by means of patterns. *Journal of Petroleum Technology*, 1951, v. 3. no. 10, section 1: p15,16 and section 2: p3.
25. Moreno and De la Losa. Interpretación de análisis químicos de aguas subterráneas mediante la hoja INAQUAS. 2016. Luis Moreno Merino, Almudena de la Losa Román, Amalia Romero Prados, Sergio Carro Martín. Available online: https://www.igme.es/Publicaciones/Consulta/Libro/36830 (accessed on 11-03-2022).
26. National Geographic Institute (IGN). Available online: https://www.ign.es/web/ign/portal (accessed on 17-09-2021).
27. Arc GIS Pro 2.6.2. Copyright © 2020 Esri Inc. All Rights Reserved.

28. IGME & ENRESA. Neotectonic Map of Spain, scale 1:1.000.000, and Memory of the Neotectonic and Seismotectonic Map of Spain, scale 1:1.000.000. 1998. Vol.1.
29. Base de Datos de Fallas Activas del Cuaternario v4. 2012. IGME. Available online: https://info.igme.es/qafi/ (accessed 15-08-2021).
30. IGME-IRMCDACM. Atlas de estructuras del subsuelo susceptibles de almacenamiento geológico de CO_2 en España. 2014. Suárez Díaz, I., ed.; Arenillas González, A. et al., (Authors). Madrid. Instituto Geológico y Minero de España; Instituto para la Reestructuración de la Minería del Carbón y Desarrollo Alternativo de las Comarcas Mineras.
31. Pulgar, J.A.; Alonso, J.L.; Espina, R.G.; Marín, J.A. La deformación alpina en el basamento varisco de la Zona Cantábrica. 1999. *Trabajos de Geología*; **1999**. No 21. Pp: 283-294. Available online: http://dx.doi.org/10.17811/tdg.21.1999.283-295 (accessed on 23-03-2022).
32. Hernáiz, P.P. La falla e Ubierna (margen SO de la cuenca Cantábrica). The Ubierna falut (S.W. margin of the Cantabrian basin). 1994. *Geogaceta*, **1994**, *16*, 39-41.
33. Rubio, F.M.; Ayala, C.; García Senz, J.; Rey Moral, C.; García Lobón, J.L.; Ortiz, G.; de Dios, J.C. Caracterización mediante gravimetría de la estructura geológica de Hontomín (Burgos). 2014. In: *8ª Asamblea Hispano Portuguesa de Geodesia y Geofísica*. Évora. Available online: http://info.igme.es/SidPDF/166000/810/166810_0000001.pdf (accessed on 03-09-2022).
34. Rioseras, M.; Acha Alarcía, J.; Grupo Espeleológico Edelweiss. Cavidades de Orbaneja del Castillo I. El Conejal-Entrecaminos-Pico Resanquillo. Valle de Sedano. Burgos. 2016. Pp: 12-33. Available online: http://grupoedelweiss.com/pdf/Cubia20.Orbaneja_I.pdf (accessed 01-10-2022).
35. Edelweiss, G.E. El karst de Burgos. Grupo Espeleológico Edelweiss. Ruíz García, F.; Ortega Martínez, A.I.; Martín Merino, M.A. (Eds). www.grupoedelweiss.com(es). 2009. Boletín Nº 12, Septiembre. pp: 34-63.
36. Edelweiss. Cuevas de Orbaneja del Castillo. 2012. Available online: https://www.grupoedelweiss.com/web/index.php/principales-karst-mainmenu-49/rutas-espeleologicas/101-cuevas-de-orbaneja-del-castillo (accessed 29-09-2022).
37. Sanz Pérez, E.; Medina Ferrer, J. La morphologie karstique souterraine du Pozo Azul ("Puits Bleu") de Burgos (Espagne). 1986. *Karstologia* **1986**, nº 8 – 2ª semestre. Pp. 27-50.
38. Edelweiss public web page. Available online: https://www.grupoedelweiss.es/web/index.php/el-grupo-mainmenu-76 (accessed on 26-10-2022).
39. González Amuchástegui, M.J.; Serrano Cañadas, E. Acumulaciones tobáceas y evolución del paisaje: cronología y fases morfogenéticas en el Alto Ebro (Burgos). *Cuaternario y Geomorfología*. **2013**. Vol. *27*, No. 1-2. Pp. 9-32.
40. Serrano Cañadas, E.; González, M.J. Las Tobas y la Villa de Orbaneja del castillo. Un entendimiento obligado. Patrimonio geológico y geoparques, avances de un camino para todos / Miren Sorkunde Mendia Aranguren (ed. lit.), Asier Hilario Orús (ed. lit.), Manuel Monge Ganuzas (ed. lit.), Esperanza Fernández Martínez (ed. lit.), J. Vegas (ed. lit.), Ángel Belmonte (ed. lit.), 2015, pp. 197-202.
41. Iberpix. Instituto Geográfico Nacional. Available online: https://www.ign.es/iberpix2/visor (accessed 15-08-2021).
42. Piper A.M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. Eos, *Transactions American Geophysical Union*, 25(6), pp. 914-928.
43. Durov, S.A. (1948) Natural Waters and Graphic Representation of Their Composition. Doklady Akademii Nauk SSSR, 59, 87-90.
44. Chadha, D.K. (1999). A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. *Hydrogeology Journal* (1999) 7,pp. 431-439.
45. Cidad Pérez, J. Valle de Valdelucio (Apuntes Historia). 1986. Editorial Monte Carmelo. 228 pp. Available online: https://www.todostuslibros.com/libros/valle-de-valdelucio-apuntes-historia_978-84-7239-173-4 (accessed 21-09-2021).
46. De la Hera-Portillo. Informe sobre el posible hidrotermalismo asociado a la Falla de Ubierna [Report on the potential hydrotermalism associated to Ubierna Fault]. Argeol Association. Instituto Geológico y Minero de España-Consejo Superior de Investigaciones Científicas (IGME-CSIC) (in press), Madrid.
47. IGME-SIEMCALSA. Estudio y evaluación del potencial Hidromineral de Castilla y León. Ficha resumen explotaciones activas. Instituto Geológico y Minero de España, Sociedad de Investigación y Explotación Minera de Castilla y León, S.A. Paraje Nº 67 Valdelateja. 2008. Available online: https://www.igme.es/aguas_minerales/inventarios/castillayleon/PDFs/Fase%203/67.pdf (accessed 17-09-2021).