Geoscience communication tools in geoconservation: geological storytelling of Spanish geoparks

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Geoscience communication tools in geoconservation:

geological storytelling of the Spanish geoparks

Abstract

UNESCO Global Geoparks are designated areas with significant geological heritage on a global scale. They are managed using a holistic approach that promotes sustainable development, with a focus on geotourism, geoconservation, and education. Effective communication is essential in geopark management as it raises awareness of their importance, promotes sustainable use and engages with local communities. This dissertation proposes a Geological Evolution Framework for Spanish UNESCO Global Geoparks to contribute to a geological communication strategy for these regions and their geological heritage. The objective is to enhance appreciation for these areas by conveying their geological history.

The methodology used a systematic approach to break down Spain's complex geological history. This involved identifying significant geological events or periods and selecting representative geoparks, geological sites, and features. The narrative aimed to cover the entire geochronological scale and national geological units. A framework in the form of a diagram and a concise chronological narrative was developed, outlining the essential elements that the geological evolution should encompass in terms of its structure and content. The framework comprises of 19 key episodes, spanning from the Neoproterozoic to the Quaternary, each with a thematic focus that showcases the geodiversity of the country's significant geological events and sites.

The study proposes guidelines for the methodology and products to disseminate the geological history of geoparks. These guidelines aim to foster popular geoscience and educational initiatives globally, beyond Spain's borders. This proposal marks the initial step towards a unified effort for organized consultation and reference. It is expected that this framework can be adapted for similar strategies to promote and share the geological evolution of any country through the geological heritage present in its geoparks.

Ferramentas de comunicação em geociências para a geoconservação: narrativa geológica dos geoparques espanhóis

Resumo

Os Geoparques Mundiais da UNESCO são áreas designadas com um significativo património geológico a nível global. São geridos com uma abordagem holística que promove o desenvolvimento sustentável, com um enfoque no geoturismo, geoconservação e educação. A comunicação eficaz é essencial na gestão dos Geoparques, uma vez que sensibiliza para a sua importância, promove a utilização sustentável e envolve as comunidades locais. Esta dissertação propõe um Quadro de Evolução Geológica para os Geoparques Mundiais da UNESCO em Espanha, a fim de contribuir para uma estratégia de comunicação geológica para estas regiões e o seu património geológico. O objetivo é aumentar o apreço por estas áreas através da transmissão da sua história geológica.

A metodologia utilizou uma abordagem sistemática para desagregar a complexa história geológica de Espanha. Isso envolveu a identificação de eventos ou períodos geológicos significativos e a seleção de Geoparques representativos, locais geológicos e características. A narrativa teve como objetivo abranger toda a escala geocronológica e as unidades geológicas nacionais. Foi desenvolvido um quadro sob a forma de um diagrama e de uma narrativa cronológica concisa, delineando os elementos essenciais que a evolução geológica deve abranger em termos da sua estrutura e conteúdo. O quadro é composto por 19 episódios-chave, que vão desde o Neoproterozóico até ao Quaternário, cada um com um enfoque temático que destaca a geodiversidade dos eventos e locais geológicos significativos do país.

O estudo propõe diretrizes para a metodologia e produtos de disseminação da história geológica dos Geoparques. Estas diretrizes têm como objetivo promover as geociências populares e iniciativas educacionais a nível global, para além das fronteiras de Espanha. Esta proposta marca o primeiro passo para um esforço unificado de consulta e referência organizada. Espera-se que este quadro possa ser adaptado para estratégias semelhantes com vista a promover e partilhar a evolução geológica de qualquer país através do património geológico presente nos seus Geoparques.

Herramientas de comunicación de las geociencias en Geoconservación: relato geológico de los geoparques españoles

Resumen

Los Geoparques Mundiales de la UNESCO son áreas designadas con un significativo patrimonio geológico de relevancia global. Se gestionan mediante un enfoque holístico que promueve el desarrollo sostenible, con un énfasis en el geoturismo, la geoconservación y la educación. La comunicación efectiva es esencial en la gestión de los geoparques, ya que crea conciencia sobre su importancia, fomenta el uso sostenible e involucra a las comunidades locales. Esta disertación propone un Marco de Evolución Geológica para los Geoparques Mundiales de la UNESCO en España con el fin de contribuir a una estrategia de comunicación geológica para estas regiones y su patrimonio geológico. El objetivo es aumentar la apreciación de estas áreas transmitiendo su historia geológica.

La metodología utilizó un enfoque sistemático para desglosar la compleja historia geológica de España. Esto implicó la identificación de eventos o períodos geológicos significativos y la selección de geoparques representativos, sitios geológicos y características. El relato tiene como objetivo abarcar toda la escala geocronológica y las unidades geológicas nacionales. Se desarrolló un marco en forma de diagrama y una narrativa cronológica concisa, que detalla los elementos esenciales que la evolución geológica debe abarcar en términos de su estructura y contenido. El marco consta de 19 episodios clave, que van desde el Neoproterozoico hasta el Cuaternario, cada uno con un enfoque temático que destaca la geodiversidad de los eventos y sitios geológicos significativos del país.

El estudio propone pautas para la metodología y productos de difusión de la historia geológica de los geoparques. Estas pautas tienen como objetivo fomentar la popularización de las geociencias e iniciativas educativas a nivel global, más allá de las fronteras de España. Esta propuesta marca el primer paso hacia un esfuerzo unificado de consulta y referencia organizada. Se espera que este marco pueda adaptarse a estrategias similares para promover y divulgar la evolución geológica de cualquier país a través del patrimonio geológico presente en sus geoparques.

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1. Presentation

“UNESCO Global Geoparks are single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education and sustainable development”, as defined by UNESCO (2022), they work every day to contribute the Agenda for the Sustainable Development Goals (SDG, 2023) in a sustainable way from the educational field (Henriques et al. 2012; Rosado-González et al. 2020; Silva 2021). These areas are authentic sustainable territories that progressively increase their international relevance every year. The primary objective of UNESCO Global Geoparks is local sustainable development based on tourism, geoconservation, and education as key strategies. Regarding education, they play a significant role in promoting geosciences for sustainability through actively educating their local communities and their visitors of all ages. Thus, they are potential outdoor classrooms and incubators for sustainable development, sustainable lifestyles, appreciation of cultural diversity, and the promotion of respect for the environment and the integrity of the landscape[1].

The global recognition of these territories has been remarkable in countries like Spain, where it comprises 16 geoparks in 2023. The success of these designations in the country comes from an extensive geological heritage that has been extensively catalogued and studied for over 50 years due to its high geodiversity (Carcavilla et al. 2009). The Spanish Geological Survey, along with the autonomous communities, has created a national geosite inventory called IELIG (Spanish Geological Interest Sites Inventory). Moreover, Spain has participated in the Global Geosites Project (UNESCO-IUGS) during the first decade of the 21st century (García-Cortés et al. 2000; García-Cortés 2008). These geosites came from defined ‘geological frameworks’ that holds global significance and the understanding of the classification of these geological frameworks was highly beneficial in determining their suitability for UNESCO Global Geoparks (UGGp) designation, and nowadays these geological frameworks are well represented in the geoparks (Orús and Urquí, 2020).

This strong representativeness within all the geoparks suggests the need and an opportunity to communicate this geology to the population with common approaches in the network. This opportunity could be achieved through the Spanish Geoparks Forum.

The central motivation of this work is to contribute to this national communication strategy. Specifically, the geological heritage within geoparks is expected to tell certain episodes of the Earth’s formation, thus this work delineates a custom method to study the geological evolution of these territories followed by a model development of this geological evolution for communication. Moreover, it further explores potential outcomes and communication products that could be developed based on this study. It is expected that this approach delineates a baseline to be developed by the network, as one of

[1] https://en.unesco.org/global-geoparks/focus

many products they provide for the general public, and could demonstrate the first steps of explicitly communicating a nationwide geological evolution represented by its geoparks.

1.1. Objectives

Given the Spanish national context regarding the broad geoheritage and amount of geoparks, this work aims to contribute with a practical tool for effectively communicating the geological evolution of Spain, represented by its UNESCO Global Geoparks. Specifically, it seeks to analyse the geological evolution and geoheritage of each geopark and the role they play in the national context, to develop a general storytelling.

1.2. Methodology

This research was conducted in several steps, which included a literature review, fieldwork, analysis of the information, and the development of a final model with some guidelines and product proposals. The multi-step methodology is detailed as follows (Figure 1):

I. **Literature review** of the geological setting of Spain and its representation within Spanish geoparks, followed by developing a summary of the geological evolution of each geopark.

II. **Identification** of the main geological events, features, and sites within geoparks regarding the geological evolution, followed by an analysis of what to convey from this identification.

III. **Analysis** of communication strategies in geoparks, focused on geoscience storytelling and fieldwork observations in five geoparks to investigate the tools used to convey the local geological evolution.

IV. **Development** of a general geological evolution framework, supported by the previous steps and collaboration with experts during fieldwork.

V. **Development** of practical guidelines and product proposals to explain the utility of this study.

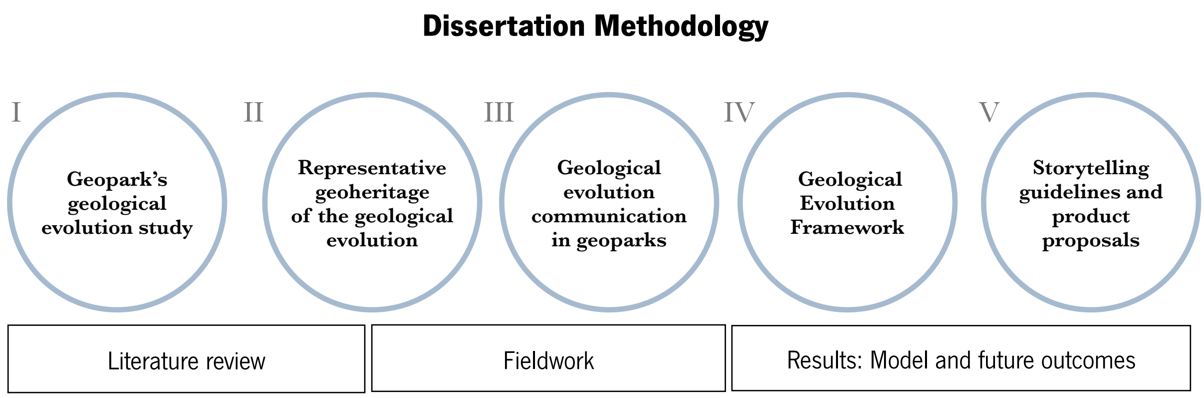

Figure 1: Dissertation Methodology. Multistep workflow of five stages to cover the objectives of this work

2. Earth science communication and storytelling in geoconservation

UNESCO Global Geoparks (UGGps) has become one of the most important territories for teaching geosciences and natural environment awareness in a sustainable development framework. Geotourism and geosciences as the main engine for territorial development has successfully created an outdoor classroom where people can learn about our planet in a scientific, cultural, and social manner. It is important to highlight the promotional activities of this type of programs to allow UGGps to achieve the relevance in education and communication that they deserve in today's society. Even though the topic of education and communication is well known in geoparks, we find only a few publications compared to other topics regarding geoparks (Martínez-Martin, 2023). They are a very interesting opportunity to educate about the environment, heritage protection, geosciences, climate change, disaster risk reduction, and resilience, among others, for which they deserve attention from international institutions, centres, and organizations to carry out future didactic actions aimed at creating an adapted, accessible, and a sustainable future for all of us. (Martínez-Martin, 2023). It is important to promote the activities, plans, and educational schemes in which UGGps work, and even make use of communication sciences to give them visibility within the scientific community to emphasize their importance as powerful educational territories for Earth Sciences and environmental protection teaching (Crisp et al., 2021).

The presence of a well-thought-out plan and objectives related to geoscience communication (i.e., dissemination and interpretation) is mandatory in all management plans and conservation strategies in protected areas and it has also proven beneficial for a solid outreach strategy in geoparks. Even efficient and well-planned communication of the values of certain territories can become a fundamental tool for securing funding, especially for privately owned and managed areas. As stated in Carcavilla et al. (2007), dissemination and interpretation are valuable tools in natural space management. It has been observed how dissemination and interpretation can help redirect behaviours that are not entirely positive in these areas. However, dissemination as a management system can go beyond rules and regulations. For instance, education and telling geological stories regarding geoheritage is one of the basic actions in the educative strategy in North American National Parks[2].

This dissemination as a management system offers various benefits (Page, 1992; Morales Miranda, 1998). Firstly, it enhances the visitor's experience by enabling them to understand the environment they are visiting and raising awareness about the fragility and conservation needs of the place. It also provides learning opportunities and meets visitors' demand for knowledge, increasing

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https://www.nps.gov/subjects/rockformations/what-we-do.htm satisfaction and clarity about what to do. Additionally, it promotes efficient use of space and contributes by reducing non-compliance with regulations by promoting responsible behaviour and decreasing vandalism, thereby saving maintenance costs and avoiding constant reminders about the rules. Finally, geological dissemination contributes to the promotion of sustainable tourism in the area and its surroundings, as well as to the positive image of the institution responsible for its management.

It is worth mentioning that dissemination can have impacts on visitation and the frequentation of certain places, as it often leads to the concentration of visitors in specific areas, eventually resulting in overcrowding. However, this can be controlled to some extent through infrastructure development or carrying capacity studies (Santos & Brilha, 2023) among other measures (Carcavilla et al., 2007).

The growing brand of UGGp is improving in terms of effective communication and it has become indispensable for territories, serving as both a dissemination strategy and a means of establishing a strong position in various development spheres. Regardless of the context, the ability to communicate a territory's resources, unique characteristics, and strategic initiatives is a vital competitive advantage that must not be overlooked (e.g. Patrocínio et al., 2018). Geoparks integrate the communication of scientific knowledge, heritage resources, tangible and intangible values, and the very essence of culture into their daily operations. It is an integral part of their mission and activities.

2.1. The role of storytelling in geoconservation

For those involved in geoconservation, communicating geosciences often entails sharing geological information with people who have little or no understanding of Earth sciences. However, new perspectives suggest that improving people's geological literacy is unlikely to be achieved simply by educating them with basic "geological data" (Rodrigues et al., 2023). As concluded by Migon and Pijet-Migon, 2017: "The deficit of in-depth interpretation at the properties may be addressed by developing complementary programmes to enhance on-site experience, based on storytelling rather than systematic but 'dry' explanation". Moreover, genuine and effective public engagement is more likely to emerge by conveying the "context" deeply rooted in our geological knowledge (Stewart & Nield, 2013).

As discussed by Stewart & Nield, 2013, by reframing these geological themes, concepts, and knowledge in terms of messages that present solid narratives, dramatic incidents, and human interest, we can foster a "geo-culture" (Stewart & Nield, 2013). Moreover, the role of this popular geological storytelling is not so much about providing specific information about Earth science issues, but rather about establishing the credibility of the "geoscience brand" in the public's mind (Stewart & Nield, 2013).

In this regard, geological history and narratives play an important role in conveying scientific information in geoscience. Overall, it is an essential component of geoscience communication, as it provides context and helps scientists explain complex scientific concepts to both the public and other scientists. This method can be used in different ways. For instance, most geoscience writing is about contextualising data and observations. This means first thinking about what you can observe, then thinking about the processes that led to your observations, and finally putting the observations in context to see the bigger picture, as observed in many in-situ initiatives regarding geoparks. Another example is about the historical geologists, who study the Earth's past to learn about the order in which events happened on Earth and how long it took for those events to happen. They use clues left on the Earth to learn about the past, such as fossils, rock formations, and other geological features. Thus, geoscience, like many other sciences, uses storytelling to communicate scientific facts. For example, the layers of rocks and fossils tell a story about their geological evolution in deep time, which enables geoscientists to communicate scientific facts by using a narrative approach (e.g. Wolniewicz, 2019).

The geological evolution can be complex, and it can be challenging to explain scientific concepts to both the public and other scientists. Thus, geoscientists must be aware of their audience when explaining geological content at appropriate levels of complexity. Students, for instance, can have difficulty learning about geological time and biological events. This can be due to the abstract nature of geological time and the difficulty in visualising the vast time scales involved (Johnson, 2014). Also, communicating contested geoscience to the public can be challenging because the general public may be unfamiliar with the geological realm. This can lead to misunderstandings and mistrust of scientific information (Stewart & Lewis, 2017). Considering these challenges, writing storytelling should be more about raising awareness and contextualising the geology in order to see the bigger picture.

2.2. Geological storytelling principles for this work

Developing geological storytelling involves creating foundational elements for a captivating narrative that highlights the unique geological features of geoparks. This helps increase geological literacy and encourage responsible behavior in these territories by emphasizing their intrinsic value. A key principle of this work is transforming complex geological information and concepts into an accessible storytelling timeline for the public. However, conveying abstract geological time scales and unfamiliar geoscience concepts to a broad audience poses challenges. The ultimate goal is to effectively promote Spanish geoparks as not only tourist destinations but also significant repositories of Earth's evolutionary history, highlighting their importance in understanding our past, inspiring communication efforts, and guiding visitors' appreciation of these geological areas.

3. Geological Setting of Spanish UNESCO Global Geoparks

3.1. General geological setting of Spain

Apart from the Canary Islands with their volcanic setting, Spanish geodiversity is linked to the complex and long history of the Iberian plate and its relations with the European and African plates (Vera, 2004). The geological record is continuous from about 600 Ma ago up to present, and there is a very high variety of rocks and fossils that have been affected mainly by the Variscan and Alpine orogenies (Gibbons and Moreno, 2002a). Spain can be divided into five main geological domains (Figure 2) (Vera, 2004).

Geological units and geoparks of Spain

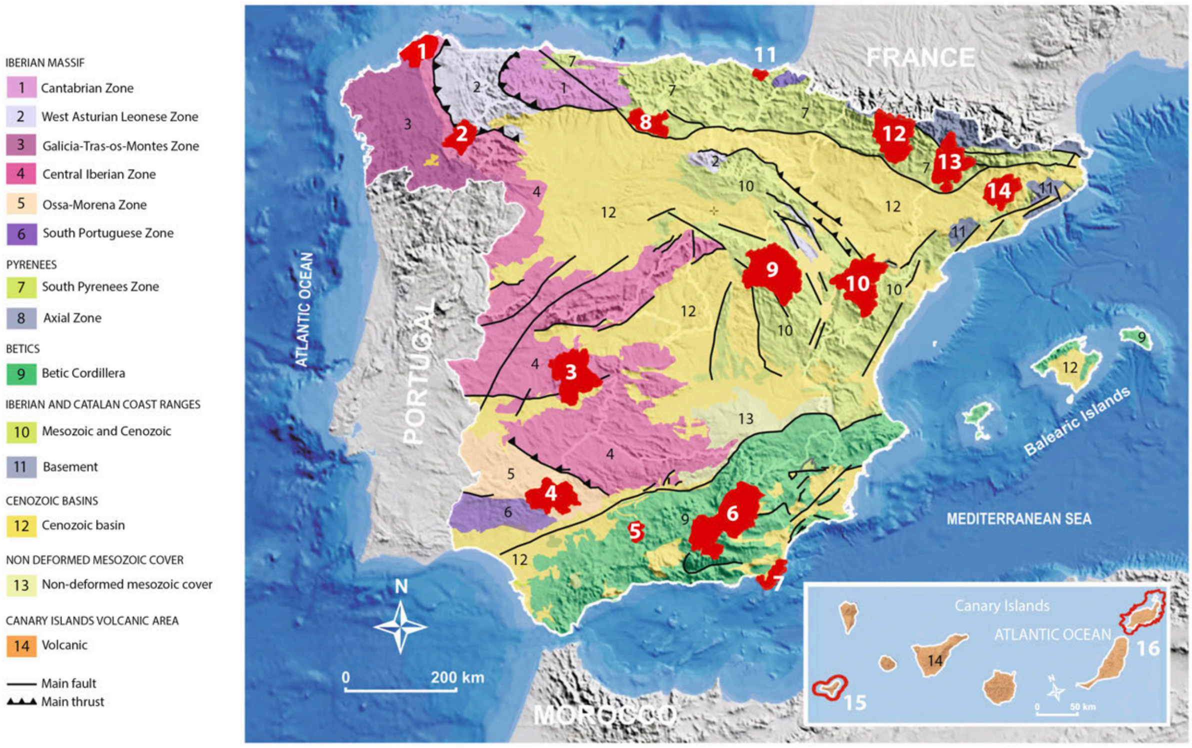

Figure 2: Main geological units of Spain. Outlined in red are the 16 Spanish UGGp. Background image:IGN. Data: Vera(2004). Geopark numbers: (1) Cabo Ortegal, (2) Courel Mountains, (3) Villuercas Ibores-Jara (4) Sierra Norte de Sevilla (5) Sierras Subbéticas, (6) Granada, (7) Cabo de Gata-Níjar, (8) Las Loras, (9) Molina Alto-Tajo, (10) Maestrazgo, (11) Basque Coast (12) Sobrarbe-Pyrenees, (13) Origens, (14) Central Catalonia, (15) El Hierro, (16) Lanzarote and Archipielago Islands. (Map modified from Orús and Urquí, 2020)

The Iberian or Hesperian Massif: The western sector of the Iberian Peninsula, from the Galicia/Tras-os-Montes region to Sierra Morena, is mainly composed of Palaeozoic and Precambrian Formations intruded by plutonic rocks and is known as the Iberian Massif (Gutiérrez et al., 2014). These formations exhibit igneous, sedimentary, and metamorphic rocks. This unit is subdivided into 6 zones according to different stratigraphic, structural, metamorphic and magmatism features (Lozte, 1945; Julivert et al 1972; Farias et al. 1987; Arenas et al., 1988): The Cantabrian Zone, The West Asturian Leonese Zone, Galicia-Tras-os-Montes Zone, Central Iberian Zone, Ossa-Morena Zone, and South Portuguese Zone. The Hesperian Massif is the remains of a large mountain chain formed during the Variscan Orogeny that occurred in the Upper Devonian and lower Carboniferous periods.

Pyrenees: The Alpine mountain belts, specifically the Pyrenean Mountain Range (Cantabrian Range and Pyrenees), were formed by the oblique convergence and collision of the Iberian and European plates from the Upper Cretaceous to the Miocene (Vera, 2004; Gutiérrez et al., 2014). Here, an Axial Zone is differentiated, located approximately on the axis of the chain and made up of rocks from the late Precambrian to the Carboniferous, intensively deformed and affected by metamorphism. The Axial Zone separates the North Pyrenean and South Pyrenean Zones, both predominantly formed by post-Variscan materials, although portions of the Variscan basement are incorporated in some thrust sheets. The North Pyrenean Zone, bounded to the north by the Aquitaine Basin, is mostly located in France, while the South Pyrenean Zone, on the Spanish side, extends to the Ebro Basin (Vera, 2004). The Vasco- Cantabrian Basin (Barnolas y Pujalte, 2004) domain, where Basque Coast UGGp and Las Loras UGGp are located, is an extensional basin formed during the Mesozoic, which was inverted during the formation of the Pyrenees in the Paleogene (Gómez et al., 2002). Between the Triassic and Lower Cretaceous periods, the extension of the basin was associated with the formation of the North Atlantic, particularly intense during the Aptian-Albian interval, with the rotation of Iberia during the formation of the Bay of Biscay (Montadert et al., 1979; Gómez et al., 2002). The onset of the Pyrenean orogeny caused the inversion of the Cretaceous basin, in a compressive regime, above the Keuper evaporitic level (Upper Triassic) (Gómez et al., 2002).

Betic Cordillera and Baleares: This unit is located in the south-eastern part of the Peninsula, and it is defined by a strong Neogene deformation, related to the collision of Alboran, Iberian and African plates (Gibbons and Moreno, 2002b; Vera, 2004). In the Betic Mountain Range, two major units of greater extent are distinguished, which during the Mesozoic and part of the Cenozoic corresponded to two different plates (or microplates). In the northern part of the Betic Mountain Range, and its extension in the Balearic Islands (except Menorca), the External Betic Zones are located, consisting of sedimentary rocks from the Triassic to the lower-middle Miocene. In the southern part, the

Internal Betic Zones recorded rocks from a fragment (Alboran Domain) of a plate (Mesomediterranean Plate) displaced westward from its original position until colliding with the paleo-South Iberian margin.

The Iberian and Catalan Coastal Ranges are two major partially eroded intraplate Alpine structures that constitute two tectonic units of similar age and style, collectively known as the Iberian Chain. This chain is a NW-SE trending intraplate Alpine mountain range extending from La Bureba in the Burgos region to the Mediterranean coast of Valencia. It is characterized by a series of NW-SE-aligned mountain formations that connect with the Catalanides in the eastern and southern extremities via El Maestrazgo. It encompasses a wide range of geological periods, from the scarce Precambrian and Palaeozoic deposits to the more prominent Mesozoic and Quaternary sediments. The most representative feature is the extensive Mesozoic cover, including Triassic, Jurassic, and Cretaceous formations, which unconformably overlie a pre-Permian basement. These materials predominantly consist of thick Mesozoic limestone formations. Additionally, the range contains detrital sediments from various Neogene basins. In localized areas, Palaeozoic basement materials are exposed in the cores of some anticlines, which have been uplifted during the Alpine folding. The Mesozoic record of the Iberian Chain is strongly influenced by extensional tectonics, characterized by two preferred orientations of normal faults (NW-SE and NE-SW). The stratigraphy of the range reflects a predominance of shallow-water and transitional environments over deep-water facies, with a notable contrast between the structural style of the basement and the Mesozoic cover.

Cenozoic Sedimentary Basins were formed due to the uplift of the alpine mountain ranges. The main rivers of the Iberian Peninsula flow through these basins, from which they derive their names. These basins are filled with Cenozoic sediments, primarily of detrital nature, derived from the erosion of alpine chains. They also contain chemically precipitated rocks such as limestone and evaporites, formed in lacustrine and saline environments like sabkhas. These basins belong to the Pliocene and Quaternary periods, where a significant system of fluvial terraces has developed within them. Alongside the formation of the alpine chains, some sedimentary basins were created with diverse origins. On one hand, they are associated with the formation of intraplate alpine reliefs, such as the Duero and Tagus basins. On the other hand, they are associated with the formation of mountain ranges on the margins of the Iberian Massif, like the Ebro and Guadalquivir basins.

The following are short descriptions of the sedimentary basins related to geoparks refereed in this study:

Ebro Basin: It borders the Pyrenees, the Iberian Range, and the Coastal-Catalan Range. It presents sequences of Paleogene marine sedimentation and continental Miocene deposits (alluvial, fluvial, and lacustrine environments with siliciclastic, carbonate, and evaporitic materials).

Duero Basin: It borders the Iberian Massif, the Iberian Range, the Cantabrian Mountains, and the Central System. The sediments have a continental nature.

Tagus Basin: It borders the Iberian Range, the Iberian Massif, and the Central System. The sediments are also continental.

Guadalquivir Basin: It borders the Betic Cordillera and the Iberian Massif. The sediments consist of marine clays and marls.

The Guadix-Baza Basin: It is an intra-mountain basin located at the contact between the External Zones (northern margin) and the Internal Zones (southern margin) of the Betic Cordillera. The basin is bordered to the north by the Sagra, Castril, and El Pozo (Cazorla) mountain ranges, to the west by the reliefs of the Eastern Mountains of Granada and Sierra Arana, and by the Sierra Nevada and Sierra de Baza massifs to the south. To the east, it is bordered by the Orce and María mountain ranges. These basins, surrounded by significant reliefs, form depressed areas and are also referred to as "hoya" (Hoya de Guadix and Hoya de Baza). This Guadix-Baza Basin was a marine sedimentary basin located in the central Betic Cordillera during part of the Late Miocene, specifically during the Tortonian stage (approximately between 10 and 7.6 Ma). A wide variety of deposits, both shallow and deep-water, accumulated in this basin.

3.2. Geoheritage and geoparks in Spain

In the geological context, Spain stands out for its rich and diverse heritage, ranging from emblematic geological landscapes to exceptional mineral deposits, revealing stratigraphic series, and complex tectonic structures. It also boasts a wide variety of fossil sites, including those that preserve the remains of human ancestors. The knowledge and management of this valuable geological heritage are crucial for its preservation. Through inventories conducted by the Geological and Mining Institute of Spain (IGME) and other entities, geological sites are identified, assessed, and proposed for management at the national, regional, provincial, and local levels. These efforts contribute to enriching and diversifying the natural heritage as new geological sites are discovered.

One of the initial projects about inventories is the Global Geosites project (UNESCO - IUCN, 1990) (Wimbledon et al., 2000) aiming to select events, areas and characteristics of fundamental global aspect to understand the geological history of the planet, to identify fundamental geological contexts to understand the evolution of the Earth. Each country had to identify its geological frameworks, and then compare with those selected in the neighbouring countries. IGME has established 21 geological frameworks of global relevance for this project (García- Cortés, 2008; García-Cortés et al., 2000; García-

Cortés, 2009; Carcavilla and Palacio, 2019). That project had the support of ProGEO, IUCN and UNESCO and was implemented in several European countries, but it did not manage to get the global acceptance that was initially expected.[3]

A new project inspired by the previous IUGS Global Geosites project was launched in 2021, the IGCP project 731. It is making a worldwide selection of geological heritage sites of international relevance where UGGp can also play an important role. Geological surveys, research institutions and geoparks from around the world cooperate and contribute towards this IUGS Geological Heritage Sites inventory. To this date (2023) the flysch of Zumaia (Gipuzkoa), the mercury mines of Almadén (Ciudad Real) and the volcanic relief of La Palma (Santa Cruz de Tenerife) are part of this inventory and there are more sites expected to come into this designation (Hilario et al., 2022).

The establishment of UGGp in Spain has been well developed during the past two decades, due their variety, wide geological representativeness and number of activities inside their territories. The country was one of the founding members of the European Geoparks Network (EGN) in 2000, along with France, Germany, and Greece (Carcavilla & García-Cortés, 2014). Today, Spain is the European country with the highest number of UNESCO Global Geoparks (16 in total). In 2011, the Spanish Geoparks Forum (FEG) was created, which, at that time, was composed of two representatives from each geopark, as well as a representative from the Spanish Commission for Cooperation with UNESCO and another from IGME (Carcavilla & García-Cortés, 2014). Nowadays, it includes the Spanish National Coordination Commission with UNESCO, various representatives of the Government of Spain-IGME, Environment and protected areas, tourism, culture, rural development-, representatives of the autonomous communities with geoparks, representatives of geoparks and other expert people. It is a chartered body of a consultative nature attached to the Ministry of Foreign Affairs through a working group within the framework of the Spanish National Commission for Cooperation with UNESCO, attached to the Spanish Agency for International Development Cooperation (Geoparques.es, accessed June 2023). This committee is looking for a formalisation as an Association (Asier Hilario 2023, personal communication).

There are many reasons to justify the successful development of geoparks in Spain (Orús and Urquí, 2020). Regarding geology, they represent the main geological units of the country and they include a high geodiversity, with many spectacular and accessible outcrops, allowing the characterisation of their geosites (Figure 2). Regarding the main geological units, The Iberian or Hesperian Massif is well represented by Cabo Ortegal UGGp (Galicia-Tras-os-Montes-Zone), Villuercas-

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https://www.unesco.org/en/iggp/igcp-projects/731

Ibores-Jara UGGp (Central Iberian Zone), Courel Mountains UGGp (Central Iberian Zone and West Asturian Leonese Zone) and Sierra Norte de Sevilla UGGp (Ossa-Morena and South Portuguese Zone). The Pyrenean unit, located in the Northeast, is well represented by Sobrarbe-Pyrenees and Origens UGGp, located in the core of the Range, and the Basque-Cantabrian Cordillera unit, where Basque Coast and Las Loras UGGp are located, representing the continuation of this chain to the NW (Barnolas and Pujalte 2004). The Betic Cordillera is represented by Sierras Subbeticas UGGp, specifically in the External Betic Zones. The Iberian Range is represented by Molina Alto-tajo and Maestrazgo UGGp. The Cenozoic Sedimentary Basins are represented by Catalunya Central UGGp (Ebro Basin), and Granada UGGp (Guadix-Bazar Basin), whereas the Volcanic Areas are represented in the peninsula by Cabo de Gata- Nijar UGGp while Lanzarote UGGp and El Hierro UGGp in the Canary Islands.

4. The geological evolution framework of the Spanish Geoparks

UNESCO Global Geoparks are well known for the sustainable use of geoheritage and thus the promotion and teaching of geological features of their territories. To contribute to this goal, this chapter intends to establish the baselines for the geological evolution that can be promoted in the Spanish network. The geological evolution of each UGGp is reviewed, from their outreach publications as well as scientific publications. Generally speaking, this procedure followed a comprehensive understanding of the geological evolution of each geopark and its representative geoheritage. These two stages were made using the current and accessible publications about the sixteen geoparks. Afterwards, in the final stage, a geological evolution framework diagram and descriptions were developed. This final framework was built from the first stages of the study and it was calibrated in a third stage of planned fieldwork, carried out in five selected geoparks (Catalunya Central, Origens, Sobrarbe-Pirineos, Costa Vasca, and Las Loras UNESCO Global Geoparks), also described in this chapter.

4.1. Geopark's geological evolution and its representative geological heritage

The geological evolution of each geopark can be transmitted in different ways inside the territories, for instance as an internal document, public outreach publications or simply by the in-situ interpretation or communicative projects carried out by the geopark staff. In this work, to structure and homogenise this relevant information, a literature review on the geological evolution of each geopark and fieldwork observations were carried out, laying the foundation for the further stages of the method.

After reviewing and understanding the geology of the geoparks, this section aims to provide an understanding of the representative elements that build up the geological evolution, but on a national scale context. This framework serves as a foundation for storytelling, offering a coherent and homogeneous body of knowledge that will facilitate the communication of a narrowed-down geological evolution of the whole country.

The method employed to study each geopark involved two stages (Table 1):

1. First, an understanding of the geological setting of the country and the role of each geopark within this context was carried out. Followed by a description of the geological evolution of each geopark, considering the geological units, events, evidence, and main characteristics. The aim was to identify the key geological episode(s) and the representation of each geopark in the context of the national geological evolution.
2. Secondly, a selection was made of key geoheritage that represents and contributes to the understanding of the national geological evolution. This identification process was based on

scientific and didactic criteria of the elements or sites and also benefited from collaboration during fieldwork.

Table 1: Stages I and II followed by the study of the geological evolution and representative geoheritage in each geopark.

I	The Geopark's Geological Evolution in the national context.	
↳	**National Geological Setting or General Geological Framework.**	
↳	**Geological Evolution description,** including:	
	Large scale Geological Units	Main events and processeses
	Main Geological Formations	Lithology and stratigraphical record
	Geological time-span of the area and it's global context	Paleontological Record
	Eras, Periods and Epochs	Paleo-geographical and Paleo-environmental interpretations

II	Representative elements regarding the national geological evolution
↳	**Identification of the geopark's main event (s)** in the national geological evolution.
↳	**Selected elements of geoheritage** Key sites from geoparks that represents the large scale geological events in the national geological evolution
↳	**Secondary elements of geoheritage** Secondary sites and features that contributes in the understanding of the geological evolution

In this section, the main elements of the geological evolution are divided into three terms: Event, Features and Sites. The term 'Event' is employed to refer to specific geological processes occurring within defined periods. 'Feature' is utilised to describe distinctive geological characteristics associated with a particular geological event, site, formation, object or process. Furthermore, 'Site' refers here to an officially designated geoheritage site, emphasising its relatively high scientific value, regardless of its broader recognition or classification (e.g., Global Geosite, LIG, etc.).

4.1.1.Central Catalonia UNESCO Global Geopark

The Central Catalonia UNESCO Global Geopark (since 2015) is located in Manresa, in the centre of Catalonia, includes 30 municipalities from the Bages county, 5 from de Moianès county at the east, and one municipality belonging to Baix Llobregat county bordering the south.[4]

[4] https://en.unesco.org/global-geoparks/central-catalonia

4.1.1.1.The geological evolution in the national geological context

Central Catalonia UGGp is located mainly within the geological unit of the Ebro Basin, except in some parts of the El Bruc and Collbató municipalities where it corresponds to the Catalan Coastal Range or Catalànids. These formations are mainly sedimentary and consist of detrital rocks (conglomerates, breccias, sandstones, and mudstones), carbonate rocks (limestones and dolomites), and evaporitic rocks (gypsum, salt, and sylvite). Metamorphic rocks (schists and shales) are found in the southernmost part of the geopark. (Oms et al., 2016)

Cambrian - Ordovician

During the Cambrian-Ordovician, a vast detrital marine platform extended across this area. In the Upper Carboniferous, the Hercynian orogeny deformed the shales, sandstones, and conglomerates. These reliefs underwent intense weathering to form a peneplain at the end of the Permian and possibly during the early Triassic. In the Lower Triassic, conglomerates, sandstones, and fluvial clays were deposited (Buntsandstein facies), which were later covered by sedimentation during a marine transgression, only interrupted by an intermediate episode of fluvial red sandstones, shales, and gypsum (lower, middle, and upper Muschelkalk facies). There is no record of the Jurassic or Cretaceous in this sector, it is until the Paleocene that a significant change occurs in the geological context.

Eocene

Around 41 Ma, the Ebro Basin began to form due to two simultaneous tectonic phenomena: the progression of the Pyrenean thrusts, which shifted the depositional center southward, and the formation of the Catalan Coastal Ranges, which created another depositional center south of the Ebro Basin. The Basin was an arm of the Atlantic Ocean that was filled mainly with marine sediments, affected by transgression and regression phases, it had similar depth across its entire extent. Towards its eastern end, it was bounded by reliefs associated with a northwest-southeast-oriented system of extensional faults. While the basin was active, it accumulated material from the surrounding reliefs, forming a wide variety of sedimentary environments during its evolution. Examples of this sedimentation are the coastal fans (delta fans) of Montserrat and Sant Llorenç del Munt.

Late Eocene to Miocene

Around 36 Ma ago, the Ebro Basin became endorheic and started to fill only with continental sediments, a condition that persisted until about 12 Ma ago. During the final stages of sedimentation, a limited connection with the Atlantic Ocean triggered the precipitation of salts, including potassium-magnesium salt and gypsum. Subsequently, due to continued structural evolution and the westward retreat of the Eocene sea, these restricted marine environments were later replaced by alluvial environments, essentially characterized by reddish materials.

Miocene

Approximately 20 Ma ago, while sedimentation continued in the western part of the Ebro Basin, a new Neogene extensional phase affected the Catalan Coastal Ranges. This extensional phase of the Alpine orogeny had begun incipiently at the end of the Oligocene. The Neogene extension created depressions or tectonic basins (Vallès-Penedès, Camp de Tarragona, Empordà, etc.) that were filled with marine and continental sediments.

Pliocene

Around 5.33 Ma ago, the Strait of Gibraltar opened, flooding the Mediterranean Sea along with some nearby basins. By the end of the Miocene, the Ebro Basin started to drain, transforming from an accumulation basin into an erosion zone. Sediments were transported by rivers to the Mediterranean Sea, while the northern slopes of the Pyrenees transported sediments to the Atlantic Ocean. This ongoing erosion process has shaped the current landscape in the region (Oms et al., 2019). For instance, approximately 5 to 2 Ma, erosion began to expose the conglomerate massifs in the south, such as Montserrat and Sant Llorenç del Munt. These erosional processes also initiated extensive karstification, both internally (caves, sinkholes, springs, etc.) and externally, resulting in the formation of canyons, rock needles, and other remarkable landforms in certain areas. The process of karstification can be observed in the Salitre Caves in Collbató, the Mura Caves, and other areas, including the steep limestone formations in Moià, where the complex of Toll Caves formed.

Pleistocene - Present

During the last 0.78 Ma, glacial-interglacial climate dynamics caused sea-level fluctuations, affecting the location of the coastline and sedimentation/incision relations in river valleys. During glacial intervals, sea levels dropped due to the storage of water in polar ice caps, while during interglacial maxima, sea levels rose due to the melting of polar ice caps. (Oms et al., 2016)

4.1.1.2.The representative geoheritage of the geological evolution

The area as a geopark stands out for its overall geological history rather than unique international geological sites (Ferran Climent, 2023, personal communication). This geological evolution developed in a relatively short time, leaving a well-preserved sediment sequence and high-quality sites related to the extinction of this sea and its replacement by river systems. As described above, the geological events are the result of a compressive and distensive phase, transitioning from marine to continental deposits through the extinction of the endorheic sea. This event is of international relevance and correlates with the Pyrenees area in terms of mountain uplift and the river incision that shapes valleys and landscapes. During this process, remarkable evaporitic deposits from the Catalan Potassic Basin are recorded.

According to the geopark inventory (Oms et al., 2019), most of the sites hold international significance, with educational and touristic potential. Regarding its geological evolution, the site 'Evaporite Deposits of the Catalan Potassic Basin' is key to understanding the sea extinction deposits. This basin in Catalonia is globally relevant and offers a unique glimpse into the basin's final stage as a marine environment. The evaporitic deposits found here, including salts and potash, provide insights into a time when this area was a saline lake cut off from the open sea. Additionally, the Ancient Deltas of Montserrat Mountain and Sant Llorenç del Munt are notable features and represent the ancient river delta systems and offer a geological window into past fluvial dynamics and sedimentary processes that have shaped this landscape.

Moreover, the rocks in the area have been extensively quarried and mined for various purposes. Sandstones have been used for construction, mudstones for brick production, limestones for lime production and as ornamental rock, and gypsum for furnace and mining products. Salt and sylvite have also been historically and currently exploited.

Among the various secondary values of the geopark, the Toll karst complex, Salitre caves, Quaternary fauna in caves, river terraces, and evidence of human presence since the Neolithic period can be considered to support the main message about the geological evolution of the area.

4.1.2.Origens UNESCO Global Geopark

Origens UNESCO Global Geopark (since 2018), with 2050 km2, is located on the Pyrenees, in the province of Lleida, Catalonia, and it includes 19 municipalities from the regions of Pallars Jussà, la Noguera, Pallars Sobirà, and l'Alt Urgell. These municipalities make up the Geopark Association, its management body.[5]

4.1.2.1.The geological evolution in the national geological context

The geopark area comprises the southern slope of the Central Pyrenees, which is the orogenic system that runs along the boundary between the Iberian and European plates and formed as these plates collided from Late Cretaceous to Miocene times (Roest and Srivastava, 1991; Rosenbaum et al., 2002). It is an asymmetric doubly vergent orogenic wedge that formed above the subduction of the

[5] https://en.unesco.org/global-geoparks/origens

Iberian lithospheric upper mantle and lower crust under the European Plate (Choukroune and ECORS Team, 1989; Muñoz, 1992; Pedreira et al., 2003; Campanyà et al., 2012; Chevrot et al., 2015).

Cambrian - Silurian

The geological events during the Paleozoic began with the thick layers of clay from the Rheic Ocean floor, from the Cambrian to Silurian periods. These layers have since transformed into slates. Some fossils, such as graptolites, are preserved within these rocks. These records are in the north of La Torra de Capdella area.

Devonian

During this time red and grey limestones from Devonian formations (Compte facies and Manyanet facies) were deposited as carbonate muds in the pelagic bottoms of the Rheic Ocean. In the area, there are records of ancient organisms such as conodonts, cuttlefishes, corals and others (Valenzuela-Ríos et al., 2017), these formations are located in the northern part of the geopark.

Carboniferous

The Carboniferous conglomerates and slates that outcrop inside the geopark record the beginning of the collision between the plates that formed Pangea and built the Hercynian chain. The volcanic deposits of the Erill Castell Formation consist of tuffs containing bombs up to one meter in size, covered by massive basaltic-andesite layers. A calmer period following this volcanic activity led to the accumulation of fluvial sediments during the Upper Pennsylvanian, which included coal deposits.

Permian

After this steady period, the red sandstones and clays of the Permian Peranera Formation contain the remains of the first tetrapods that colonized terrestrial environments on Earth.

Triassic

The Geopark exhibit an unconformity marking the onset of the Triassic period and the beginning of the Alpine geological cycle. During the Upper Triassic, Pangea break up began accompanied by the emission of basic volcanic rocks and multicoloured clays and evaporites, the Keuper facies. The records of the breakup can be found in the subvolcanic rocks of Gerri de la Sal and Senterada. This phase is followed by the Fourth Global Mass Extinction Event.

Jurassic

During this time, carbonate muds in the shallow water platforms of the Tethys Ocean were deposited in an extensional regime. It comprises a thick and complete series of limestones, dolomites and marls that spectacularly outcrop in the South Central Pyrenean Unit. The actual Pyrenean orogen resulted from the inversion of the rift system and related passive margin (northern Iberian Margin) that developed during the Late Jurassic-Early Cretaceous all along the northern Iberian plate connecting the Atlantic with the Alpine Tethys realms (Stampfli & Hochard, 2009; Tugend et al., 2014).

Cretaceous

The deposition of marine limestones during the Lower Cretaceous formed the Bóixols Thrust Sheet materials, with a thickness exceeding two kilometres and its onset in the early stages of the ocean rifting phase. Some deposits in the Montsec mountain range have preserved fossil remains from about 130 Ma that preserve their soft structures: insects, fish, amphibians, small reptiles, birds with feathers or the first flowering plants that appeared on the planet (Montsechia vidalii). Further south, the Montsec Thrust Sheet comprises over 1.5 kilometres of Upper Cretaceous marine limestones and records this ocean growth, including the most complete rudist record in the Pyrenees. This stage represents the passive margin phase in the ocean's evolution, reflecting the formation and subsequent activity of the Mid-Atlantic Ridge. The Upper Cretaceous limestones that constitute the Serres Marginals - Gavarnie Thrust Sheet, however, only offer a sparse, incomplete record of the late passive margin phase of the Atlantic Ocean's growth. The Late Cretaceous materials within the Central South Pyrenean Unit document the initial stages of collision between the European and Iberian plates.

This period has provided an excellent record both of coastal environments (accumulations of rudists at Collada de Basturs); transitional environments (site of marks of feeding rays at La Posa), and particularly more continental environments (Tremp basin, Riu Sallent valley at Coll de Nargó)

Cretaceous - Paleogene

Between the end of the Cretaceous and the beginning of the Paleogene, the landscape of the geopark evolved from a sea where limestone and marl were deposited to deltas and continental deposits. As mentioned, the Late Cretaceous to Palaeogene periods are recorded in the Tremp Formation, characterized by a thick accumulation of red clays, sandstones, and some lacustrine limestone beds. This formation encompasses the geological boundary between the late Cretaceous and early Palaeogene, known as the K-Pg boundary, synchronous with the Fifth Global Mass Extinction Event. The greatest paleontological records of dinosaurs come from these transitional sediments from the Upper Cretaceous.

The Iberian and European plates collided from Late Cretaceous to Miocene times forming The Pyrenees orogenic system that runs along the boundary between these plates (Roest and Srivastava, 1991; Rosenbaum et al., 2002). The aforementioned Pyrenean fold and thrust belts developed both thick- and thin-tectonic style southwards in this segment of the orogenic system, uplifting the materials mentioned above. The Alpine orogeny concluded after the closure of the Pyrenean arm of the Atlantic during the mid-Palaeogene and culminated in the formation of the Pyrenean Chain.

Eocene - Oligocene

The rise in sea level at the beginning of the Eocene led to the re-establishment of a sea in the Tremp and Àger basins that opened towards the west. This sea is currently represented by marls and calcareous rocks containing alveolinids. On top of these materials, river and delta systems developed, depositing gravels and conglomerates. Subsequently, during the most intense period of the Pyrenees uplift in the Eocene and Oligocene, the relief of the central Pyrenees was eroded, and large alluvial systems were established at the foot of the mountain range, giving rise to the conglomerates found today in the Collegats, Pessonada, Gurp, and Comiols mountain ranges.

Quaternary

Glaciers that formed in the north during the Quaternary period created glacial valleys, which are now recognisable by their U-shape. At the same time, intense river erosion allowed for the formation of extensive alluvial fans and the incision of river valleys, resulting in gorges such as Collegats or Mont-rebei and the karstic landscape. It is also worth noting that significant landslides have occurred, as can be seen in Puigcercós.

4.1.2.2.The representative geoheritage of the geological evolution

The Gerri de la Sal sections have one of the most important and diverse Lower Devonian conodont sequences (Valenzuela-Ríos et al., 2017). This makes the geopark an essential region for examining the evolutionary steps of numerous genera that played a significant role in establishing the first Lochkovian subdivision and subsequent high-resolution correlation. As a result, it is an essential area for improving our understanding of the geobiological history of Earth.

Moving forward to the Stephanian stage (Pennsylvanian Superior), the coal deposits exploited by the mines of Malpàs and its surroundings are included. These coal deposits are vital for the Xerallo cement factory's operations, producing concrete for the construction of hydroelectric dams in the surrounding area.

Moreover, the Upper Triassic evaporites are a significant feature, containing valuable salt deposits. These salt deposits are historically significant as they are the remains of natural salt evaporators in Gerri de la Sal, with a history dating back over 4,000 years.

The Lower Cretaceous is impressively represented by the outcrops of the Montsec range, notably the “La Pedrera de Meià” and “La Cabroa” quarries. These sites have been catalogued as Konservat-Lagerstätten and showcase exceptional preservation, providing valuable insights into the past.

Fossils from the last five million years of the Cretaceous period have been remarkably preserved. The Tremp Formation (Mey et al. 1968) contains a treasure trove of fossil plant remains, along with bones, tracks, and eggs from the final dinosaurs, as well as numerous fossils of crocodiles, turtles, amphibians, and fish. These findings vividly demonstrate the vitality of these Mesozoic groups just before the K-Pg boundary. It is important to note that this exceptional fossil record has only been discovered in select outcrops in the North American mid-west and the Tremp Formation of the southern Pyrenees.

Undoubtedly, one of the most significant geological events in the evolution of Spain is the formation of the Pyrenees, which has left its mark on this landscape, structures, and stratigraphy of the geopark. Four thrust sheets have shaped the terrain, leaving unconformable conglomerate sequences over Mesozoic materials visible throughout the area. Additionally, the geopark's landscape is shaped by geomorphological features resulting from fluvial erosion, including the stunning gorges of Collegats and Mont-Rebei, karst formations, and notable landslides. These natural formations stand as sites of immense educational and didactic value, offering a firsthand look into the recent geological evolution that has shaped the region.

Isona and Conca Dellà have various paleontological sites of interest, some of which can be visited through the Conca Dellà Museum. The museum displays the most relevant remains, and the Comiols viewpoint offers a magnificent panoramic view of the Pyrenees.

4.1.3. Basque Coast UNESCO Global Geopark

Basque Coast UNESCO Global Geopark (Since 2015), is covering only 90 km2. It is located on the Guipuzcoa coast, along the Cantabrian Sea. The geopark includes three municipalities (Mutriku, Deba, and Zumaia) and is characterized by cliffs that separate the Urola estuary and the bay of Ondarroa. It also extends slightly inland towards the Basque Mountains.[6]

4.1.3.1. The geological evolution in the national geological context

The Basque Coast UGGp area is located in the South Pyrenees Zone (Vera, 2004), specifically in the Basque–Cantabrian Basin domain (Barnolas & Pujalte, 2004), which is bounded by the Asturian Palaeozoic Massif to the west and the Basque Palaeozoic Massifs and the Pyrenees to the east. Its southern limits are the Basins of Douro and Ebro rivers, while to the north, it extends to the Bay of Biscay. The development of this basin is directly related to the processes that marked the evolution of the western part of the Pyrenean orogen. The geopark area is mainly made up of sedimentary rocks

[6] https://en.unesco.org/global-geoparks/basque-coast

dating from the upper Triassic Period (215Ma) to the Middle Eocene Epoch (45Ma) formed during the opening and closure of the basin.

Triassic

The Upper Triassic materials that correspond to the Keuper facies are characterized by clays and gypsums, along with associated subvolcanic rocks (located in Mutriku). These are the oldest rocks of the area formed in a dry and warm continental climate, favouring the creation of evaporites. Fractures formed due to the breakup of Pangea, allowing subvolcanic magmatic rocks to intrude.

Lower Cretaceous

The coastal area of the geopark was submerged under a tropical sea that separated the Iberian Peninsula from the European continent, connecting the ancient Thetys Ocean and the emerging North Atlantic. During the Lower Cretaceous, a prolonged phase of continental extension led to the opening of the Gulf of Bizkaia, creating an extensional setting in the basin and a seafloor composed of large uplifted blocks and sunken basins. In the sunken blocks the rocks known as 'black flysch' were deposited (Deba Formation, 106-100Ma), located in Deba and Mutriku. Large landslides, submarine canyons, and deltas can be distinguished, along with some volcanic activity. (Hilario et al., 2013)

Upper Cretaceous - Eocene

The instability of the gulf opening gradually subsided, resulting primarily in the deposition of calcareous remains, accompanied by the settling of fine turbidites from the shallower parts (Itziar Formation, 96-83My). Then the basin had already acquired a more classical morphology of platform, slope, and seafloor. The approach of Iberia to Europe began, and some significant tectonic movements led to the first continental reliefs in the eastern Pyrenees and generated quite a lot of instability in the Basque basin. As a result, a large amount of turbidites fell to the marly and calcareous bottom of the basin forming the sandy flysch of the Upper Cretaceous (Aginaga Formation, 83-68Ma). Subsequently, the limestone successions of the Maastrichtian and Paleocene (Zumaia, Aitzgorri, and Itzurun Formations, 68-56Ma) were deposited in the marine gulf that was already well-defined and it was a period of tectonic rest, in which primarily autochthonous sediments were deposited, resulting in very well-defined limestone-marly sequences. The Pyrenees went through their main collision stage, and the basin became unstable. The new Pyrenean reliefs located to the east were getting closer and bringing a large amount of sediment, filling the basin floor with extensive turbidites forming the sandy flysch of the Eocene (Jaizkibel Formation). In Jaizkibel, these turbidites can reach a thickness of up to 4 meters. During this event, the Alpine Orogeny, the Triassic rocks rose along active faults like the Berriatua fault and became part of higher Cretaceous rock layers (Hilario et al., 2013).

Eocene - Quaternary

Within the latest phases of the coast's development, the very active Quaternary geomorphological processes are developing an abrasion platform and intense karstic erosion at the interior of the area, showing more than 200 caves, pinnacle morphologies and poljes. (Hilario et al, 2013).

4.1.3.2.The representative geoheritage of the geological evolution

A 13-kilometer stretch of coastal outcrop unveils a remarkable 5,000-meter-thick flysch deposit, providing a comprehensive record of Earth's history spanning 60 million years. Numerous scholars have delved into the wealth of geological information contained within these layers. The main event and sites to consider in the geological evolution is the Cretaceous-Paleogene limit boundary, which marks the iridium evidence of an extinction event, dating back approximately 65.5Ma, notably linked to the demise of the dinosaurs and other organisms, such as foraminifera (Ward et al. 1986; Jehanno et al. 1987; Apellaniz et al. 1997; Rodríguez-Tovar et al. 2011). The K/Pg boundary is a highly geological attraction within the geopark, both nationally and internationally. It is a site located near Itzurun Beach and offers direct evidence of the extinction event. This feature distinguishes it from other geoparks in Spain in terms of the country's geological evolution (Asier Hilario, 2023, personal communication).

4.1.4.Las Loras UNESCO Global Geopark

Las Loras UNESCO Global Geopark (Since 2017) is located in the north of the Castilla and León Autonomous Community. The area is halfway between the Castilian Plateau and the Cantabrian Mountain Range. It covers 16 municipalities of the Burgos and Palencia regions. The area has an extremely low population.[7]

4.1.4.1.The geological evolution in the national geological context

The territory is located on the southern edge of the Cantabrian Range, southeast of the Asturian Paleozoic Massif, and in the southwestern portion of the Basque-Cantabrian Basin (Basconcillos Arce et al., 2005a; Salazar Celis, 2008).

Upper Triassic

The oldest rocks in the area are red clay with Keuper gypsum, overlaid by Lower Jurassic dolomites (Pujalte et al., 2004). They were formed in supratidal environments in arid coastlines-sabkhas, under arid climate conditions.

[7] https://en.unesco.org/global-geoparks/las-loras

Lower and Middle Jurassic

The sedimentary rocks within this interval were primarily limestone formations and originated from a marine carbonate platform (Andrés et al., 2016). The interval can be divided into two sections: the lower section consists of dense marl-limestones with few fossils, indicating a low-energy platform unaffected by currents or waves. The upper section comprises rhythmic limestones and contains abundant marine fossils, such as ammonites (Pujalte et al., 1988). These limestones were deposited in a high-energy environment during the Bajocian period, with significant sponge colonization. However, storm currents largely disturbed the organic remains.

Upper Jurassic to Lower Cretaceous

From the Callovian-Kimmeridgian, the Bay of Biscay opening phase started northwest of the Iberian Plate, from a triple junction with the Atlantic Ridge. Impacting progressively eastward (Kimmeric and Neo-kimmeric deformations and sedimentary cycles). These rocks provide insights into the development of marine lake systems on the continental shelf. The Aguilar Formation, near Aguilar de Campoo, has a considerable thickness of 500 meters, comprising marshy limestones, indicating the influence of both marine and alluvial systems at the margins (Robles, 2014). A series of inland lakes were developed in an offshore platform environment, leaving lacustrine carbonate sediments. Then, during the Valanginian to lower Aptian period, sedimentary rocks were deposited in environments resembling the Weald facies, including alluvial and marsh settings (Robles, 2014). Subsequently, In the lower Aptian, there were episodes of detrital deposition and marine incursions. These deposits primarily consist of continental materials (Sandstones and conglomerates), from alluvial and anastomosed fluvial systems, with intermittent occurrences of marshes and lakes (Vera, 2004).

Upper Cretaceous

During this interval, between the Cenomanian and the Campanian, carbonate sedimentation is established due to a marine transgression (Basconcillos Arce et al., 2005a). This sedimentary megacycle is related to the moments of maximum expansion of the marine environment of the Bay of Biscay. First, In the Cenomanian-Turonian, a regime of continental sedimentation in alternating fluvial and lacustrine environments it is established in the region. Recorded by arenaceous rocks. This Albian to Cenomanian period is characterized by detrital deposits of Utrillas facies. This unit was deposited contemporaneously with the widespread transgression from the upper Albian to the Turonian (Pujalte & Robles, 2008). It represents the accumulation of extensive coastal alluvial plains that gradually migrated inland into the Iberian Massif parallel to the aforementioned transgression. On top of the Cenomanian fluvial sediment, we found typical estuary deposits, with intertidal-subtidal characteristics, sometimes interspersed carbon levels. Overlying the Utrillas facies there are deposits from a shallow platform with carbonate bars, consisting of marls interbedded with limestones (Robles, 2014). A large number of fossils are found in the levels of the Cenomanian and Turonian, like Ostrea ouremensis, Exogyra flabellata, and Exogyra olisiponensis (Floquet & Lachkar, 1979). Abundant oyster shells, bivalves, gastropods, corals, ostracods, and algae are also present. There was a peak of marine influence throughout the area during the Santonian. From that moment, the sea gradually retreated, and the Upper Cretaceous bar complex was deposited in that period. This complex is more dolomitic than the lower layers and contains less fauna. The formation of these layers takes place on a rough average energy platform. The sequence ends with Maastrichtian red and green clay materials of similar affinity to the Garum facies. There is a certain resemblance to a fluvial-deltaic environment.

Paleogene - Neogene

Overlying the Upper Cretaceous materials are predominantly continental sedimentary rocks, including conglomerates, sandstones, and red clays, which represent a transitional fluvial cycle leading into the Cenozoic era (VV.AA., 2015). Following the deposition of these sequences, the Pyrenean compressive phase begins (Vera, 2004), and there are no significant records during the Paleogene and Neogene, but in the Villaescusa de Ecla Syncline, it has been established that a continental environment became established in the region during the early Paleogene, setting the general trend for the entire area until the Neogene.

From the Paleogene, the Cantabrian region is affected by the partial closure of the Bay of Biscay, resulting in an asymmetric behaviour of the margins. This leads to a compression regime that causes large-scale deformation. The most significant phases of this deformation likely occurred at the beginning of the Lower Miocene, resulting in converging folds and thrusts towards the south and southwest within the Mesozoic deposits.

Pleistocene - Quaternary

The formation of the present fluvial system commenced during the Pleistocene. Additionally, the incision of the large folds formed during the Alpine Orogeny took place, resulting in the formation of hanging folds in the relief. During the late Cenozoic, the characteristic forms of exokarst relief in the landscape also developed.

4.1.4.2.The representative geoheritage of the geological evolution

Overall, the key geological features recorded in the geopark area are the result of the opening and closure of the Bay of Biscay during the Lower Cretaceous, leaving a fairly complete record with marine fossil remains, rocks from lacustrine environments, and a remarkable vertebrate fauna. One notable feature is The Aguilar Formation, which contains significant fossils of macroflora that provide valuable information about the phytogeography and paleoclimate of southwestern Europe (Diéguez et al., 2009). Additionally, the discovery of ornithopod dinosaur remains in the Berriasian period supports the presence of Camptosaurus in the Lower Cretaceous European formations (Pereda Superbiola et al., 2006). These lacustrine carbonates likely represent one of the thickest accumulations of fossil lacustrine carbonate deposits worldwide.

Regarding the Cenozoic, the geopark is characterised by the Ubierna Fault and the development of the Folded Band that covers the area from this fault to the frontal thrust of the Cenozoic materials of the Duero basin, whose folds give name to the area, "Loras". The Loras are hanging synclines in a landscape undergoing compression with subsequent erosion by Quaternary fluvial incision (de la Hera-Portillo et al., 2023). The result is a hanging folded relief that gives a distinctive morphology to the landscape.

The vertebrate fauna, the large-scale folds and faults, the hanging synclines, and the relatively recent exokarst landforms are noteworthy in the local geological features to convey (José A. Sánchez, 2023, personal communication). From all of these features highlighted in the outreach publications (e.g. Basconcillos, 2018), the exposed Mesozoic sequences, shaped by river networks and deformation processes are remarkable, which in turn contributes to the didactic and scientific value. Thus, the hanging synclines and exposed Mesozoic sequences distinguish this geopark from others in Spain in terms of the large-scale geological evolution and can be seen in various viewpoint sites of the area (e.g Monte Bernorio, Las Tuerces, Mesa Peña, Peña Amaya, etc.).

4.1.5.Sobrarbe-Pirineos UNESCO Global Geopark

The Sobrarbe-Pirineos UNESCO Global Geopark (Since 2015) comprises the entire territory of the Sobrarbe region. It is located in the north of Spain, province of Huesca (Aragon). The territory of 2,202 km^2 is composed of 19 municipalities.[8]

4.1.5.1.The geological evolution in the national geological context

The geopark is located in The Southern Slope and Axial Zone of the mid-Pyrenees Mountain range. The Pyrenees exhibit an almost symmetrical structure in which the oldest rocks, mainly granites and Paleozoic metamorphic rocks, are strongly folded in the central zone of the mountain range. Over this Paleozoic basement, the entire Mesozoic and Cenozoic sedimentary cover is discordantly arranged.

The Mesozoic sedimentary rocks outcrop surrounding the axial zone and include a wide variety of lithologies, with marine-origin rocks and evaporites standing out due to their role as detachment

[8] https://en.unesco.org/global-geoparks/sobrarbe-pirineos

levels for many thrust faults. The Cenozoic sedimentary rocks are primarily of continental origin and correspond to the filling of foreland basins to the north and south, namely the Aquitaine Basin and the Ebro Basin, respectively, which occurred during the uplift of the mountain range. [9]

This Alpine chain formed as a fold and thrust belt during the Late Cretaceous to early Miocene at the collision front between the Iberian and the Eurasian plates as a result of roughly north–south crustal contraction. At the lithospheric scale, there are two main features (see Muñoz 1992; Teixell 1998), including (a) subducted Iberian lower crust beneath Eurasia, and (b) delaminated orogenic prism overlying the lower crust showing an asymmetric, fan-shaped body. Within the orogenic prism, south-divergent structures dominate in number and extension and form the south-Pyrenean zone. Bedrock in this zone includes: (i) a Hercynian basement with granitoids and low-grade metamorphic rocks, (ii) a Mesozoic pre-orogenic sedimentary succession up to late Santonian, (iii) a synorogenic assemblage of Upper Cretaceous to lower Miocene sedimentary rocks, and (iv) a post-tectonic sedimentary succession, which is developed mostly in the Ebro basin.

Palaeozoic

During much of the Paleozoic Era, the territory currently occupied by Sobrarbe was a seabed where silts, muds, clays, and sands accumulated. Currently, these sediments have transformed into slates, sandstones, limestones, and quartzites due to the Variscan and Alpine orogenies, which form the mountains and valleys of the northern region of the area. Numerous folds and faults provide evidence of these events, as well as the granites that formed during this period. The main geological units of the southern central Pyrenees are exposed in Sobrarbe. The Axial Zone extends through the high valleys of Ara, Bielsa, and Chistau, consisting of sedimentary, plutonic, and metamorphic rocks of varying degrees that span the entire Paleozoic era (Belmonte, 2018).

Mesozoic

There is limited documentation of the Jurassic Period, and the Lower Cretaceous is absent in Sobrarbe. However, during this time, the sea once again covered this region for most of the Mesozoic Era. As this marine basin expanded, significant amounts of limestone were formed, especially abundant in the Upper Cretaceous. Towards the end of the Cretaceous Period, the opening of the Atlantic Ocean caused the Iberian Plate to shift and close the connection between the Atlantic and the future Mediterranean. Within the South Pyrenean Zone, the northernmost part of the area forms a morphostructural barrier primarily composed of carbonate materials ranging in age from the Upper Cretaceous to the Eocene. These rocks represent formations from the Pyrenean trough and are part of the Monte Perdido thrust sheet within the larger Gavarnie thrust sheet in Sobrarbe (Belmonte, 2018).

[9] https://www.ign.es/web/resources/sismologia/tproximos/sismotectonica/pag_sismotectonicas/pirineos.html

To the east of the geopark, the large Cotiella mantle outcrops, constitute the northwestern termination of the Central South Pyrenean Unit (Martínez-Peña, 1991) and extend eastward into the Boixols mantle. On the other hand, Peña Montañesa and Sierra Ferrera are the continuation of the Montsec mantle (Seguret, 1972). These units are composed of Upper Cretaceous to Eocene limestones and overlap with successions of marine, transitional, and continental detrital materials that fill the Tremp-Graus Basin.

The Aínsa Basin, delimited by the north-south anticlines of Boltaña and Mediano, is an important geological structure in the central Pyrenees. This basin represents a complete succession of turbiditic materials in different facies, ranging from carbonate and siliciclastic platforms to the rocks of the Sobrarbe Delta and continental rocks from fluvial environments.

During the Santonian stage (Upper Cretaceous), the compressive phase of the sedimentary basin began, leading to the uplift of the Pyrenees. The primary phase of this deformation did not cease until the early Miocene.

Cenozoic

At the end of the Cretaceous and the beginning of the Paleogene, marine sedimentation of shallow waters predominated. Rocks rich in calcium carbonate related to biological activity typical of tropical seas are abundant. In Sobrarbe, these changes are represented in the fossils found in Paleocene marine-origin rocks. During the Eocene and Oligocene, the most intense phases of the Pyrenees uplift occurred, simultaneously with sedimentation, mainly of detrital nature, filling the Aínsa-Jaca basin. This basin developed over the Cotiella thrust, and most of the sediments it received came from the east and southeast until the Pyrenean relief rose sufficiently to supply new sediments from the north and south. As the sea receded at the end of the Eocene, sedimentation was characterized by transitional environments (Sobrarbe Delta), eventually becoming continental.[10]

Oligocene - Miocene

Since the Oligocene, erosive processes have dominated this territory, leaving conglomerate deposits. By the end of the Miocene, the Ebro River made its way towards the Mediterranean Sea, intensifying the erosion process.

Quaternary

During the Quaternary the landscape has been shaped through morphogenetic processes, mainly glacial, periglacial, karst and rivers, all of them active in varying degrees. The glaciers of Monte Perdido, Marboré and Llardana are still active. Erosive and depositional morphologies of all phases from

[10] https://www.geoparquepirineos.com

the Pleistocene glaciers to the Little Ice Age are clearly visible in the area. Karst is especially abundant and the fluvio-karstic ravines are a characteristic feature of Sobrarbe. The Cinca and the Ara rivers have terraced deposit systems correlated with their ancient glacial moraines, providing interesting paleo-environmental information. Finally, slope processes such as landslides complete the wide range of morphologies and active processes.

4.1.5.2.The representative geoheritage of the geological evolution

The main geological event in Sobrarbe is the formation of the Pyrenees. This geological phenomenon encompasses the disappearance of the Paleogene to Neogene narrow sea, the collision of continents, and the subsequent emergence of the mountain chain, followed by erosion during the Ice Ages. The geopark contains rocks ranging from the Cambrian to the Quaternary, representing the main geological units of the Central Pyrenees. These rocks bear the imprints of two major orogenies, the Variscan and the Pyrenean. As secondary values, from the Quaternary Period, the landscape of the geopark has been shaped by various morphogenetic processes, including glacial, periglacial, karst, and river dynamics. Glaciers such as Monte Perdido, Marboré, and Llardana are still active, and the area displays distinct erosive and depositional features from the Pleistocene glaciers to the Little Ice Age. Karst formations are abundant, and the presence of fluvio-karstic ravines is a notable characteristic of Sobrarbe. Moreover, the Cinca and Ara rivers have terraced deposits that are linked to ancient glacial moraines, providing valuable insights into past environmental conditions. Additionally, slope processes such as landslides contribute to the diverse range of morphologies and active geological processes found within the geopark. These features and events are clearly explained in the interpretative centre of the geopark located in Castillo de Aínsa, in Aínsa.

Among these geological characteristics, it is worth noting on a national level the complex structures of folds and faults developed throughout the evolution of mountain uplift during the Alpine Orogeny. As a whole, the Pyrenees can be explained through this tectonic configuration in a generalized narrative at the national level, with the geopark serving as the main window for observing these processes. The Origins UGGp also contains clear and didactic evidence of the Alpine phase, and both areas should be complemented.

4.1.6. Courel Mountains UNESCO Global Geopark

Courel Mountains UNESCO Global Geopark (Since 2019) is located in the province of Lugo in Galicia and is made up of the municipalities of Folgoso do Courel, Quiroga and Ribas del Sil.[11]

[11] https://en.unesco.org/global-geoparks/courel-mountains

4.1.6.1.The geological evolution in the national geological context

The geopark is part of the Variscan domain (Matte 1991). The Variscan bedrock recorded the sediments and environments of extinct Palaeozoic seas, where life fully spread. The geology of the Courel Mountains spans three tectonic cycles (Cadomian-Avalonian, Variscan, and Alpine) from the Permian to the Pleistocene, although the most prominent bedrock features are Variscan (Martínez Catalán et al. 1992).

Neo-proterozoic - Permian

Evidence of the Rheic Ocean is depicted in the Courel Mountains from its origin as the back-arc basin of the Cadomian-Avalonian magmatic belt during the Neo-proterozoic - Cambrian (Nance et al. 2012; Fernández-Suárez et al. 2000) to its closure by the Variscan orogeny in the lower Carboniferous (Martínez Catalán et al. 2004). During that time, large tectonic stresses compressed and deformed the rocks and metallic ore deposits were also formed (Tornos et al. 1995). The Courel Mountains exhibit a rich variety of marine species records that lived from the Cambrian to the Devonian (trilobites, archaeocyaths, graptolites, cephalopods, brachiopods, conodonts, and crinoids).

Oligocene and Miocene

Later on, during the Alpine orogeny, the westernmost part of the Courel Mountains was uplifted and eroded during the Oligocene and Miocene (Martín-González and Heredia 2011; Martín-González et al. 2012). The current rivers were formed, quickly carving their courses, or embedding in the relief, resulting in the 150 km of ravines, gorges, and canyons.

Quaternary

Alluvial terraces and fans were developed from the erosion of the mountains, and karst caves were formed since at least the Chibanian (middle Pleistocene) (Railsback et al. 2011, 2017). The Last Glacial Cycle began about 115,000 years ago and ended about 13,000 years ago. During this period, the Serra do Courel was intermittently occupied by small mountain glaciers. The glaciers of Courel were ice streams up to 150 m thick that flowed under their own weight through the valleys. The Glacial and interglacial periods have influenced the Quaternary climate and landscape evolution, overprinting previous landforms (Pérez-Alberti and Cunha 2016; Oliva et al. 2019; Viana-Soto & Pérez-Alberti 2019). Moreover, there are waterfalls (fervenzas) more than 30m high, of which ten are over 20 m high, including the Fervenza de Rexíu and Pedreira. In the calcareous areas of the north, groundwater dissolved the rock, leaving over 7 km of known caves to date.

4.1.6.2.The representative geoheritage of the geological evolution

The geological evolution of this area is primarily reflected in the Iberian Massif rocks that record tectonic evidence, metamorphism, and ore mineralization during the Variscan Orogeny, followed by uplift and erosion due to the Alpine orogeny. The Cenozoic outcrops and relief record paleo-glacial and erosional events, leaving behind characteristic geomorphological features, such as valleys and karst caves. This area contains a variety of marine fossils dating back to the Cambrian period. These fossils include trilobites, graptolites, and cephalopods, as well as tropical reefs composed of sponges and corals. One significant rock formation in the geopark is the Armorican quartzite, notable for its high content of trilobite fossil tracks (cruziana). The relief of the Variscan Orogeny was eroded, but its structural evidence is well-represented in the Courel Mountains by a unique 50-km recumbent fold, the Courel Syncline, which in turn it's a key site to observe Variscan Orogeny structural evidence in a national scale (Martínez Catalán et al. 1992; Fernández et al. 2007). Among the caves, Sima Aradelas is notable, with a depth of 137m, making it the deepest in Galicia, along with Sima de Teixeira, with its 3 km length. As a result of collapse processes, a labyrinthine landscape was formed, consisting of narrow corridors, pinnacles, and loose blocks on which mosses grew, lending the area an interesting aspect. Evidence of the glacial period is represented in the U-shaped Valley of A Seara and the Lucenza meadow, the formation of which is related to the over-excavation work carried out by an ancient glacier.

4.1.7.Maestrazgo UNESCO Global Geopark

Maestrazgo UNESCO Global Geopark (Since 2015) is located in the province of Teruel (Aragon) and made up of 43 municipalities inside this province (Andorra-Sierra de Arcos, Bajo Aragón, Comarca Comunidad de Teruel, Cuencas Mineras, Gúdar-Javalambre and Maestrazgo.).

4.1.7.1.The geological evolution in the national geological context

The area is located at the Iberian Range geological unit (Vera., 2004), southwest to the Ebro depression. Most of the outcrops are Mesozoic, whereas the Cretaceous deposits cover most of the area (Liesa, 2000; Salas & Casas, 1993).

Triassic

The Upper Triassic deposits in the area are from the Muschelkalk facies (mainly limestone) and Keuper facies (clays, marls, and gypsum of reddish colours). At this time, this territory was covered by coastal lagoons with an arid climate that facilitated the evaporation of water and the precipitation and accumulation of saline and evaporitic deposits. These rocks are found in Ejulve, La Zoma, Miravete de la Sierra, and Aliaga.

Jurassic

During the Jurassic, tropical carbonate seas were established. The materials have a high representation in various places in the area, with a predominance of limestone and marls in outcrops with less prominent reliefs. Outcrops can be representative in the middle valley of the Guadalope River, although there are good outcrops in the T.T.M.M. of Bordón, Castellote, Molinos and Miravete de la Sierra. The record between the Jurassic and Cretaceous is characterised by sandstone clays and limestone, deposited in coastal environments with tidal zones and brackish lagoons, like the Villar del Arzobispo Formation, with a good presence of dinosaur bones and footprints (e.g., the dinosaur ichnite site of Miravete de la Sierra, Las Cerradicas, and Barranco Luca.) (Luque et al. 2008)

Cretaceous

The territory underwent repeated cycles of transgression and regression, developing a sedimentation basin. During the Barremian period, various fluvio-marine environments were established after the sea gradually withdrew from the end of the Jurassic. These conditions allowed the existence of dinosaurs, pterosaurs, crocodiles, sharks, mammals, etc. Some prominent paleontological sites are located in Vallipón (Castellote), Camino de la Algecira (Ladruñán, Castellote), and Miravete de la Sierra. (Gasca et al.2007)

At the beginning of the Aptian, there was a significant transgression. Most of the province was submerged under the waters of a warm, shallow sea where a variety of marine organisms successfully developed (stratotype of Villarroya de los Pinares Formation). Then the province was affected by a significant marine regression during the Albian, developing a significant continental fluvial environment. The records are in the lignite of the Escucha Formation, the sands of the Utrillas Formation (with characteristic reddish and yellowish tones), and the fossiliferous sites of El Barranquillo (Castellote). The Upper Cretaceous involves the return to a marine platform environment that will stabilize for several million years. At this time, the sedimentation of carbonate rocks occurs, such as those exposed in the stratotypes of Órganos de Montoro and Barranco de los Degollados. The end of the Mesozoic era in Maestrazgo is characterized by a progressive withdrawal of the sea line, leaving the territory emerged until the present. (Canérot et al., 1982; Salas et al., 2001)

Cenozoic

During the Cenozoic, the Alpine Orogeny took place and affected the previous rocks (ca. 55My ago), an event that caused the superimposed folding, inverse faulting, and uplift of the sedimented materials, structures visible for example in the Estrecho de Molinos. There is also evidence of a periglacial period (e.g., protalus rampart Muela Mujer, solifluction bench lobes of Cuarto Pelado). Finally, during the Quaternary, the relief is shaped and the river network is installed, and the sedimentation of poorly consolidated gravels and silts occurs at the bottom and margins of the watercourses. Calcareous tufas also developed (like Fonseca Bridge, Castellote), and karstic forms (e.g. El Llovedor). (Peña et al. 2000)

4.1.7.2.The representative geoheritage of the geological evolution

The main attributes regarding local geological evolution are the sites that show the evolution of the Mesozoic basin, whether stratotypes or representative outcrops, the large alpine structures, and the notable paleontological records (Fundación Conjunto Paleontológico de Teruel-Dinópolis, 2007). Among these, the Órganos de Montoro stands out, a large natural outcrop of Cretaceous limestones with landscape and educational value about stratigraphic processes, tectonics, and erosion. Also, the tectonic structures of Estrecho de Molinos, form vertical layers creating colourful ridges. The cluse and knee fold of Cantavieja, or the structural modelling of El Llovedor are other examples. Regarding stratigraphy, the stratotypes of the Barranco de los Degollados, Órganos de Montoro, and Villarroya de los Pinares Formations, defined within the region, could be highlighted. The most noteworthy, thus widely publicised topic, from the area, are the paleontological sites, such as Vallipón, Mirambel, El Barranquillo, Abenfigo, and Miravete de la Sierra. Regarding ancient periglacial-type climate, the protalus rampart of Muela Mujer, composed of singular accumulations of stones formed during a periglacial climate, and the lobes and solifluction benches of Cuarto Pelado are good representatives. Concerning relief modelling, the Hoz and Nacimiento del río Pitarque stand out, represented by a deep canyon result of fluvial erosion on calcareous materials, and the karstic spring of El Llovedor. Exceptionally, the Grutas de Cristal or Cuevas de las Graderas, show the development of crystalline deposits of calcite, the formation of eccentric stalactites, and the fossiliferous and archaeological content displayed in the Interpretation Center of Molinos.

The current territory has provided fossils that pioneered dinosaur research in Spain. The first Spanish dinosaur, Aragosaurus ischiaticus (published in 1987), five other new genera of dinosaurs and six species were described from fossils found at Geopark sites. This makes it one of the most relevant areas in Spain for dinosaur research and has given rise to numerous scientific publications on palaeontology and the stratigraphy of the area. It has also led to the construction of several facilities to promote education and geotourism, like the Dinópolis satellite centre, Dinópolis-Teruel headquarters (Alcalá, 2009), Aliaga Geological Park Visitor Center or the Cretaceous Park in Galve. (Alcalá & Royo-Torres, 2021).

4.1.8.Granada UNESCO Global Geopark

The Granada Geopark (since 2020), with 4722 km2 is located in the south-west of Spain, specifically in the north of the province of Granada, within the region of Andalusia, and it includes 47 villages.[12]

4.1.8.1.The geological evolution in the national geological context

The Granada UGGp lies within the central sector of the Betic Cordillera (SE of Spain); surrounded by some of the highest mountains on the Iberian peninsula, all of these mountains make up a depression (Guadix-Baza. Basin) that represents most of the territory of the geopark. The connection between these mountain ranges and the depression is via a gently sloping glacis with altitudes ranging between 1150 m at the edge of the depression and 900 m towards the interior, where the depression is still preserved (García Tortosa et al., 2007, 2011).

Triassic

Triassic rocks outcrops in the area, such as red clays and versicoloured gypsums, appear in the Castril River valley or the Fardes River valley. The volcanic rocks in the Alamedilla sector (pillow lavas) are a remnant and example of the fracturing of the Earth's crust that occurred from the end of the Triassic Pangea Break-up to the Cretaceous. The sediments of the External and Internal Zones of the Betic Cordillera were deposited on the shelves of the new continents and on the beds of the new oceans, during a long time that encompasses the Jurassic, Cretaceous and Paleocene, with continuous changes in the position of the continents and the size and depth of the oceans.

Miocene

During the Alpine orogeny initial stages, the Betic Cordillera still did not exist and most of its materials were still submerged. In this tectonic process, the materials that make up the Internal Zone were displaced hundreds of kilometres to the west, becoming part of the Betic Cordillera. In the movement, it pushed and deformed the materials of the External Betic Zone. This 10Ma event occurred during the Early and Middle Miocene. From then on, the new last processes to have affected the Betic Cordillera began, characterised by a continuous kinematic situation up to the present, in which Iberia (Eurasian Plate) and Africa started approaching, at a speed of some 5 mm/year (DeMets et al. 1994).

Approximately 8 Ma marked the onset of a distinct geological phase. During this period, the Betic Cordillera, located in the southeastern part of the Iberian Peninsula, had already undergone significant uplift and the formation of prominent landforms. Meanwhile, various Neogene Basins, such as the Guadix-Baza basin, had emerged. These basins were predominantly submerged under marine

[12] https://en.unesco.org/global-geoparks/granada

conditions during that era.

Therefore, the actual mountain ranges areas of the geopark would have been part of a set of intermountain marine basins that surrounded large islands. The interconnection of these basins between the Guadalquivir basin and the Guadix-Baza basin via the North Betic Straits would also have enabled the marine connection between the Atlantic and the Mediterranean. The marine materials of this stage can be found in numerous outcrops within the area, such as in the La Peza, Negratín, some valleys in the north, the south of Caniles and in the most eastern part of the territory.

Miocene - Pliocene

The penultimate stage started between the end of the Miocene and the beginning of the Pliocene. This was the individualisation and origin of the Guadix-Baza continental basin due to the disconnection of the territory from the Mediterranean and the Atlantic. This disconnection was due to regional tectonic uplifting of the Betic Cordillera, resulting in one of the greatest average altitudes in the entire Iberian Peninsula. Tortonian marine sediments are exhibited at an altitude above 1000 m near the area (Sanz de Galdeano & Alfaro, 2004). Although the entire region was uplifted, the differential movements due to tectonics and the large inherited topographical depressions, allowed the continuous accumulation of significant sequences of continental sediments. Moreover, the abrupt and widespread fall in the sea level, during the Messinian, was also influential in the marine disconnection. This process probably did not occur simultaneously all over the basin but in a relatively short period.

Pliocene

Once the endorheic continental basin was formed, during the Pliocene to Pleistocene, the Baza fault movements enabled the development of a large lake in the central-eastern half (García Tortosa et al., 2008-2011), generating important accumulations of carbonate and evaporitic sediments in this sector, while in the western half, mainly fluvial environments and detrital sedimentation were developed (Vera, 1970). The western fluvial systems drained towards the lake via the paleo Fardes River. The differences in the sedimentary environments of the western and eastern sectors were controlled mainly by this fault, which enabled the subsidence of the eastern area. There were also fluvial systems and sediments in the eastern sector, originated in the surrounding mountain ranges (Castril, Huéscar, Periate, Estancias, etc.). Small lacustrine systems were formed among the fluvial systems in the western part.

A significant glacis surface formed from the endorheic basin's edges and it extended towards the center (García Tortosa et al., 2007, 2008, 2011). This region remained active until the basin transitioned to an exorheic system, which occurred around 0.5 million years ago (Scott and Gibert, 2009; Garcia Tortosa et al., 2011). This transition marks the beginning of the final stage in the area's geological evolution. During approximately 4.5 million years, a diverse large mammalian fauna thrived and coexisted on the glacis surface, which resembled the African savannah we see today (Arribas & Palmqvist, 1998; Palmqvist & Arribas 2001). The glacis consists of a combination of materials from various ages, thus there is no consistent sedimentation level within the basin. Different areas of the basin exhibit these materials in the upper part of the endorheic stratigraphic sequence. Thus, the glacis surface represents the last remnants of the endorheic stage of the basin's development (Garcia Tortosa 2007, 2008, 2011).

Quaternary

The last stage began approximately 0.5 Ma (Middle Pleistocene), when a tributary of the Guadalquivir River captured the endorheic basin, giving it an outlet to the Atlantic and transforming it into the present exorheic basin. After this, this tributary would become the present Guadiana Menor, which along with the Fardes River drains most of the territory towards the Guadalquivir River (the municipal area of Huéneja, the southeastern area of the geopark, showing the sole evidence of recent and incipient capture towards the Mediterranean).

The geopark is situated in a depression with a high average altitude. It experiences a semi-arid climate, and the materials in its central part are easily eroded. As a result, the current river network has been deeply embedded, with valleys reaching depths of up to 200 meters. After the last event, erosion became the dominant force, leading to the dismantling of the glacis and the ongoing formation of badlands. This process also resulted in the creation of valleys and fluvial terraces that define the landscape. These fluvial terraces provide valuable insights into the later stages of the area's geological history, closely connected to human history.

4.1.8.2.The representative geoheritage of the geological evolution

Granada UGGp is endowed with exceptional geological significance. Regarding the geological events, the Guadix-Baza Basin was a marine sedimentary basin located in the central Betic Cordillera during part of the Late Miocene, specifically during the Tortonian stage (approximately between 10 and 7.6 million years ago). A wide variety of deposits, both shallow and deep-water, accumulated in this basin. Marine deposits can be found in various locations within the geopark, where natural erosion has exposed exceptional outcrops that provide insights into the characteristics of the ancient sea that once occupied the geopark territory.

From the Quaternary, the main relevance lies in the geological history of a river (western sector) and a lake (central-eastern sector). These water bodies have left stone evidence of old Quaternary ecosystems during their sedimentary stage. Furthermore, in the modern Quaternary’s fluvial erosion stage, the rivers have exposed sedimentary and older rocks. Sedimentary rocks emerging in current river valleys are around 5 million years old, showcasing river plains and lacustrine shores that were once inhabited by a spectacular array of large mammals. The geopark's valleys also reveal marine rocks from former deltas and reefs dating back 8 million years (when the Atlantic Ocean connected with the Mediterranean via the North Betic Straits), as well as marine rocks from the Palaeogene and abyssal marine deposits from the Cretaceous, along with shallow shelves from the Jurassic (originating from the Tethys Sea). These epochs highlight the extensive Mesozoic era during which tectonic plate rifting was occurring, evident in vast stretches of basaltic pillow lavas forming part of the Geopark's southwestern mountains. Throughout the surrounding mountains that constitute the intermountain depression intersected by the valleys, one can observe, touch, and study the range of previous rock arrays and their corresponding geological domains, making the valleys the focal point of the area.

Regarding features and specific sites, the arid climatic conditions prevalent in the region have led to the development of unique geological features, such as the scarce vegetation observed on the slopes of the Granada Valley. The presence of Badlands further enhances its geological value, providing insights into the Quaternary record of Europe. Notably, the Geopark houses an extensive collection of paleontological deposits of Continental European quaternary micro-vertebrates, making it a good repository of scientific knowledge. The discovery of significant large vertebrate deposits within Early Pleistocene sediments, numbering over 150 identified sites, underscores its unparalleled geological richness. The outcrops within the geopark include the Mesozoic stages, thereby enabling a glimpse into an extended geological evolution. Active faults in the Betic Range offer a platform to observe recent geological deformations, with the added intrigue of these faults having played a role in ancient earthquakes that gave rise to singular structures known as seismites during the Quaternary stage.

The sites with international value are the Badlands (Marchal, Fonelas, Dehesa de Guadix, Gorafe, Negratín), many Paleontological (e.g "Vertebrates deposits from the Spanish Pliocene and Pleistocene" Global Geosite), Petrological (Pillow Lavas of Almedilla), Tectonic (Baza fault), and other stratigraphical and sedimentological sites (e.g Seismites of Castillejar). The site "Discordancia angular de Gorafe" is a key site to understand the geological history from one viewpoint, while the viewpoints as "Marchal" or "Beas de Guadix" are good examples of observing the badlands.

4.1.9. Villuercas Ibores-Jara UNESCO Global Geopark

The Villuercas Ibores-Jara UNESCO Global Geopark (2,544. 4 km2) is located in the southeast of the province of Cáceres (in Extremadura, Spain). It comprises 19 municipalities and 26 villages. The main village is Guadalupe.[13]

4.1.9.1. The geological evolution in the national geological context

The Villuercas-Ibores-Jara UNESCO Global Geopark belongs to the Central Iberian Zone of the Iberian Massif. (Vera, 2004)

Neo-Proterozoic to Cambrian.

During the Cadomian orogeny (ca. 630–550 Ma), lithospheric convergence along western Gondwana resulted in the formation of an orogenic belt flanked by adjacent fore- and back-arc basins (Sánchez-García et al. 2019; Álvaro et al. 2019). In the back-arc basin a several kilometres thick succession of deep-water shale and sandstone deposits formed, which forms the basement of the territory of the area, including some of the oldest sedimentary rocks of the Iberian Peninsula. The progressive collision of the arc with the margin of Gondwana from 570–535 Ma led to the closure of the back-arc basin and the deposition of more shallow water sediment deposits, including late Ediacaran carbonates of the Ibor Group. The remaining Cadomian suture was reactivated during the Variscan (Hercynian) and Alpine orogenies. Uplift and erosion led to a significant gap in the preserved younger pre-Ordovician sedimentary record, which left a few remains from the Cambrian within the territory of the geopark. However, there are small exposures of Lower Cambrian rocks within the geopark (e.g., Jensen et al. 2019) and well-preserved material of Treptichnus pedum, a trace fossil with a first appearance in the Cambrian are known from areas immediately adjacent to the geopark (Jensen & Palacios 2016). (Cortijo et al. 2021).

Mesozoic and Cenozoic

The current landscape is the result of millions of years of erosion action on a large folding that occurred during the Hercynian orogenic movement, leaving behind a vast synclinorium. The synclinorium was eroded throughout the Mesozoic and Cenozoic eras and rejuvenated by fractures and uplift movements of large blocks during the Alpine orogeny, around 35 million years ago. The fractures (faults) can be observed in various mountain passes of the geopark, in the Sierra de la Breña, in Deleitosa, in the Riscos de la Trucha in the Guadarranque Valley, or near Castañar de Ibor, beneath the "Cancho de las Narices."

[13] https://en.unesco.org/global-geoparks/villuercas-ibores-jara

The current shaping of the river network acting upon this intensely folded and fractured territory has formed the landscape we observe, with its characteristic geomorphological feature known as the "Appalachian relief"

4.1.9.2.The representative geoheritage of the geological evolution

The Ediacaran-lower Cambrian time represents a unique period in geological history, marked by the presence of the early mineralised metazoan Cloudina and ichnofossils. The rocks of the geopark and surrounding areas are the only places in Europe where remains of Cloudina have been found, which along with Sinotubulites, Namacalathus and other skeletal fossils from the late Ediacarian, are the precursors of the widespread biomineralization that occurred in animals at the beginning of the Cambrian.

Within this timeframe, lower Paleozoic rocks emerge as reservoirs of exceptional ichnofossils such as Cruziana and Daedalus (Lower Ordovician in the Armorican Quartzite), and a variety of fossils including trilobites, brachiopods, and graptolites. These tangible traces of ancient life evidences significant episodes in evolutionary history, such as the Cambrian Radiation, the Ordovician Radiation, and the devastating Ordovician mass extinction event.

As remarkable geological features of the area, it becomes apparent that the landscape has been heavily influenced by structurally controlled features. These have been responsible for creating an intensely folded and fractured landscape. The subtle dips and depressions of the anticlines preserve some of the area's oldest rock formations - the Ediacaran greywackes, shale, and carbonates. Moreover, the folding and fracturing patterns observed within these geological structures are remnants of the intense tectonic activity that occurred during the Cadomian orogeny.

The geographical relief of the area offers a visual demonstration of the geological processes. This is reflected in the intensely folded and fractured landscape, which displays an inverted topography. At its highest elevations, one can observe narrow Variscan synclines, a residual of the Appalachian Relief, exhibiting lower Palaeozoic siliciclastic rocks. The highest point of the relief is marked by the Armorican Quartzite.

Traces of the Alpine orogeny, another significant tectonic event, can be identified in the central Villuercas horst, which is bordered by two grabens, filled with Neogene fluvial braided marginal sediments. In more recent geological times, the Pleistocene "Rañas" include broad, clast-supported fluvial sediments that sculpt a surprisingly flat, horizontal landscape. This noteworthy change in the landscape signals the transition from internal to external drainage of the main rivers.

Lastly, the area is home to a significant natural feature, a karstic cave that has been designated as a Natural Monument.

The geopark features geosites that primarily showcase the geomorphology and tectonic structures, while also boasting numerous paleontological outcrops.

Highlighted sites from this geological evolution can be “Cerro de La Mina”. Cloudina's site on the Ibor River, “Risco Carbonero” is a good point to understand its geological history and paleontological records, as well as the Appalachian relief modelling. The “Sinclinal de Guadarranque-Gualijilla” and “Sinclinal de Santa Lucía - Río Ruecas” are good representative structures of tectonic events, among others. There are several sites to observe the relief modelling, such as “el Risco Gordo”. The site “rañas de Cañamero” is remarkable regarding “rañas”.[14]

4.1.10.Molina Alto-Tajo UNESCO Global Geopark

The Molina Alto-Tajo UNESCO Global Geopark (Since 2015) is situated in the Castilian Branch of the Iberian Range, it covers 77 municipalities. The most important town is Molina de Aragón. Its 4,520 km2 makes it one of the largest in the European Geopark Network.[15]

4.1.10.1.The geological evolution in the national geological context

Molina and Alto Tajo Geopark is located in the Iberian Range and is mainly shaped by Mesozoic rocks, but there are also extensive outcrops of Paleozoic and Cenozoic. It features continuous sedimentary sequences through the past 400 million years, such as the stratigraphic series of the Upper Ordovician, Lower Silurian, Permo-Triassic and Lower Jurassic. In the lower Palaeozoic, an extensive phase of the crust generated a depressed area which was successively stretched filling with sediments. The oldest records from this regime date back to the Ordovician. (Goy et al. 2021).

Ordovician

The geological history of the region dates back to this period when massive marine platforms began to develop around Gondwana. During this initial stage, the area and the entire Iberian Peninsula were located very close to the South Pole, where significant glaciomarine sedimentation occurred, greatly enhanced by a strong glaciation at the end of the Ordovician period.

These periods in the area comprise seven formations. The Lower Ordovician is characterized by quartzites and slates, followed by the Armorican Quartzite Formation which features thick quartzite layers with interbedded sandstones and shales (Gutiérrez et al., 2008). The Middle Ordovician consists

[14] https://geoparquevilluercas.es

[15] https://en.unesco.org/global-geoparks/molina-alto-tajo

of slates and greywackes in the Villar del Saz Formation, followed by two quartzite members separated by slates in the San Marcos Formation. The Upper Ordovician includes massive dolomites in the Ojos Negros Formation and granulated detrital sediments and glaciomarine pebbles in the Orea Formation (Fortuin, 1984 in Gutiérrez et al., 2008). An erosive discontinuity marks the end of the Ordovician and is associated with an eustatic drop related to glaciations. The Los Puertos Formation, consisting of quartzites, overlies this discontinuity and marks the boundary between the Ordovician and Silurian.

Silurian

At the beginning of Silurian, Gondwana's continent began to drift towards the North. These conditions are evident by carbonated sedimentation in subtropical conditions since the lower Devonian. Slowly, Gondwana's continent collided with the macro-continent Laurasia, forming Pangea during the Carboniferous (Variscan orogeny). The Silurian series begins with black shales containing nodules in the Bádenas Formation, followed by intervals of sandstones and ferruginous quartzites. These black slates have a thickness of 5 to 25 meters of a very fossiliferous level (graptolites, abundant conodonts, brachiopods, nautiloids, and some possible bivalves (San José et al., 1992). The geological record for the Upper Silurian is incomplete due to another discontinuity caused by significant erosion of Devonian and Carboniferous rocks. (Vera, 2004).

During the Middle and Upper Palaeozoic a compressive phase took place and these sediments were folded, faulted and uplifted. Palaeozoic materials located below Mesozoic deposits show signs of folding, breakage and in some cases metamorphism, all as a result of the Variscan Orogeny.

Permian

During the Permian, the supercontinent Pangea migrated towards the North, leaving the actual Guadalajara province located in the equatorial line. The climate was even warmer and more arid than previous ages. This caused sedimentation in global regressions, ending with evaporitic deposits in many epicontinental areas. Permian rocks in the Molina-Alto Tajo area are relatively scarce, but they appear significantly in certain locations, such as the Sierra de Aragoncillo (VV.AA., 2012). The Permian stratigraphic succession starts with the Capas de la Ermita Formation (Autunien age), made up by three lithologic sub-units (volcanic rocks, then shales and sandstones with dolomites, and finally limestones and dolomites with layers of mudstones) (Sopeña y Sánchez- Moya, 2008), the volcanic sequence appears unconformably on top of the lower Palaeozoic slates and quartzites, which is characterised by well preserved silicified tree trunks, buried by the Permian volcanic rocks (Castro et al. 2008).

Triassic

During the late Permian and early Triassic began extensional movements that would result in the subsequent fragmentation of Pangea and the westward movement of the Tethys Sea. This rifting during the Mesozoic comprises several pulses of stretching and extension of the Iberian plate crust and subsequent thinning.

Broad valleys of NW-SE ancient faults were formed, with a major river system. The process of widespread rifting and subsidence favoured the accumulation of powerful series of alluvial conglomerates, reddish-colored sandstones and shales that constitute the thick sequences of Buntsandstein facies, composed by 5 units of the Guadalajara Group (Sánchez-Moya et al., 1989). During this period, the vertical drainage network evolution was largely controlled by regional tectonics and climate (continental and arid).

During the Middle Triassic the Tethys was moving wesward. In the sedimentary record can be recognized two separate transgressive episodes and one regressive. The first transgressive episode reached the eastern end of the province of Guadalajara. This first transgression can be recognized in some Triassic outcrops at the east Molina de Aragon, characterized by the presence of small levels of carbonates and evaporites above Buntsandstein red series.

The second transgression of the Tethys sea into the interior of the peninsula (Vera, 2004), which affected the entire province, is recognized by the carbonate rocks (limestones, dolomites and marls) . These materials, belonging to the Germanic Muschelkalk facies correspond to a shallow marine carbonate complex with supratidal and tidal flats, lagoon and inner shelf development.

A late Middle Triassic, Iberian Massif reliefs are softened following the continuous supply sediment into rivers draining into the Tethys. Also during this time began a further sea level decrease and it generated large evaporite deposits in an extensive coastal plain regressive state. These German Keuper facies, from a restricted marine depositional environment (lagoon with occasional fluvial inputs) is composed by shales with abundant gypsum and some interbedded dolomite. Within the study area, specifically around the town of Molina de Aragón, there are two sequences in vertical succession, consisting of a lower level of dark shales with interbedded sandstones and carbonates, and an upper one generated in an environment of sebkhas or marshes in wet weather, composed by red shale interbedded with anhydrite and carbonates.

Jurassic

During Early Jurassic, Guadalajara was located under latitude of about 35°N, with a slightly warmer and drier climate than today. The marine environments during the Jurassic in the province of

Guadalajara took place in a series of transgressive-regressive pulses . The Jurassic materials that outcrop in the region (Lias and Dogger) continuously overlie the Keuper facies and are represented by dolomites with few fossils (Goy et al., 1976). Consequently, the upper package is a succession of limestones and dolomites with intercalations of marls with a large amount of ammonites and brachiopods, which facilitates the precise establishment of the ages of the formations (Goy et al., 1976). Overall the units starts with Renales Group, composed by grey dolomites overlayed by breccias, usually covered. The limit between Triassic and Jurassic is usually to be found on the upper part if this unit. Upon these rocks there is a carbonate unit, composed of limestones. After this group, Ablanquejo Group can be found, composed by different units of ironed surfaces, grey marls and bioclastic limestones. Also, rhythmic pattern of marls and limestones can be distinguished in Turmiel Formation (Goy et al., 1999). The latter is followed by Chelva Group, with many units, mainly constituted by limestones and dolomites. Afterwards the last Group Tura comprise units with rhythmical alternation between limestones and marls and fossils. (Goy et al. 2021)

Cretaceous

During the Lower Cretaceous, the sea level continued to fluctuate. The area alternated between reef zones and deeper seabed or even shallow areas affected by tides (Carcavilla, 2011). In the middle of the Cretaceous, small tectonic movements caused the sea level to drop enough for the Alto Tajo region to emerge again. It became a fluvial area with the influence of the nearby sea. The water current transported and deposited a considerable amount of sands, which can now be observed in many outcrops of Alto Tajo, called the Utrillas facies (during Late Albian - Cenomanian). The climate at that time was subtropical, and the vegetation was abundant, especially along the riverbanks and in swampy areas. The intense humidity favored the transformation of feldspars present in the Utrillas sands, leading to the formation of kaolin deposits, which are now an important economic resource (Carcavilla, 2011). Around 85 Ma, there was a new marine transgression. In the middle of the Upper Cretaceous, the sea level rose even higher than before, covering a larger territory compared to the Jurassic. The climate remained warm, promoting the formation of limestone visible today in the parameras and the walls of the Tajo canyon. A period of relative calm followed, lasting approximately 30 million years, during which the Alto Tajo region became a calmed tropical marine environment again (Carcavilla, 2011). In the Upper Cretaceous, there are intercalations of sandstones, clays, and microconglomerates. Subsequently, limestone, marl, and calcarenite are found, and until the end of this geological period, carbonate rocks, dolomitic rocks with some sand input into limestones also occur (Vera, 2004).

Cenozoic

About 55 Ma, the effects of the Alpine orogeny and consequent syntectonic erosion began in the Alto Tajo region. Evidence of this deformation can be observed in locations like the Hundido de Armallones or near Cuevas Labradas. The materials assimilated compressive efforts produced during the orogeny generating faults and deformation of large magnitude, becoming the Zocalo Varisco or Hercynian of the Iberian Range. The vertical displacement of some of the fractures present in the materials of Palaeozoic allows them to come to surface in some parts of the region as Aragoncillo or Checa area.

The Mesozoic materials in the region are now covered by Neogene outcrops, which are limited in extension and arranged unconformably. Researchers, as Olmedo et al. (2008), have classified this geological area into four distinct units. The first unit, known as the Villalba de la Sierra Formation, exhibits a gradual boundary with the latest Cretaceous materials. It is composed of alternating layers of calcareous or clay material with sandy intercalations and casts. This unit can be found in the Cuenca's Range and the Altamira's Range regions. The subsequent unit, referred to as the pretectonic series (Unit T1), overlays the previous one and consists of strongly cemented conglomerates, sandstones, and clays, with marly sections at the top. Above this, the Syntectonic Series (Unit T2) appears unconformably, characterized by quartzitic or calcareous gravel or sandstones and red clays, transitioning to calcareous sandy limestone, limestone, and marl at the upper levels. Finally, the Post-tectonic Series (Unit T3) fills the Tajo Basin and small intramontane basins found in the region.

During the quaternary, rivers have been one of the most effective erosive agents, including the Tajo River. Evidence of this is the deep canyon that the river, living up to its name, has carved through the limestone and dolomites. Also of great importance are the ravines and gorges of the Hoz Seca, Cabrillas, Bullones, Gallo, Arandilla, and Salado rivers.

4.1.10.2.The representative geoheritage of the geological evolution

Regarding the main events, it is remarkable the Permian-Lower Triassic Buntsandstein (Barranco de la Hoz stratotype or Sierra de Candeleros, in Guadalajara province), identified previously as a Global Geosite. This series was formed by the accumulation of sand and gravel particles in the channels of ancient rivers. These sediments originated from the erosion of the old mountains formed during the Variscan orogeny. This process took place in the Lower Triassic and is exceptionally well represented in the stratigraphic series, where we find very well-preserved sedimentary structures. Due to the erosion of the Gallo River, it’s possible to study these large fluvial deposits.

In more detail, the basal units of the Buntsandstein correspond to conglomerates and sandstones, which are unconformably arranged over red clayey sands from the Permian. From oldest to most recent, and in the order of appearance on the route, we find the formation of the "Conglomerates of Hoz del Gallo," resulting from the cementation of rounded pebbles and gravels carried by a river with abundant channels, where the strong current transported and accumulated large amounts of sediment. Above the conglomerates, Rillo de Gallo sandstones are formed by the accumulation of smaller-sized sandy sediment. It wasn't a single distinct channel, but rather an extensive network of meandering channels that covered a vast plain.

Moreover, during the transition from the early Cretaceous to the late Cretaceous (Late Albian - Cenomanian), there is material of Utrillas facies, which represents the most important mining deposits in the region. These deposits are exploited through open-pit mining for minerals such as kaolin, quartz, and feldspathic sands (PORN PNAT, 1999).

Regarding relevant sites, the Lower Silurian formations are among the most significant, serving as a worldwide biostratigraphic reference. The Lower Triassic Series has been included in the Spanish list of the Global Geosites project. Additional Global Geosite, the Toarcian-Aalenian section in Fuentelsaz, which was the sole GSSP in Spain recognised by the IUGS holds considerable importance. Other sites to consider are the graptolites outcrop in Checa and the Dropstone and Lower Silurian section of Checa.

Regarding some features, the region's lithological diversity is notable, featuring extensive outcrops of shales, quartzites, sandstones, limestones, dolomites, sands, salt deposits, gypsum, and volcanic rocks (dacites). Notably, the presence of mineral-rich layers like Compostela red quartz (red-coloured ferruginous quartz) and aragonites adds to its distinctive character. These are named after the Comarca de Molina de Aragón, where the initial units were first described. Abundant fossil deposits, including one of the most significant graptolite deposits on the Peninsula, are found here, alongside other plentiful Mesozoic outcrops.

4.1.11.Cabo de Gata - Nijar UNESCO Global Geopark

The Cabo de Gata-Níjar UNESCO Global Geopark (Since 2015) is part of one of the most important protected areas in Andalusia. Within the territory, there are three municipalities and 27 settlements connected by the national road that runs through it.[16]

[16] https://www.juntadeandalucia.es/medioambiente/portal/landing-page/-/asset_publisher/4V1kD5gLiJkq/content/geoparque-cabo-de-gata-n-c3-adjar/20151?categoryVal=

4.1.11.1.The geological evolution in the national geological context

Cabo de Gata is part of the SE Neogenic Volcanic Province (PVNSE in Spanish) and the 'Neogene basins' unit in Andalucía region. (Fernández Soler, 1987; Costafreda 2008)

Miocene - Holocene

The geological evolution of the Cabo de Gata-Níjar Geopark can be divided into three main stages. The first stage, known as the initial extension, occurred around 22 to 11 Ma. During this period, the collision between the African and Eurasian plates led to crustal extension, causing the formation of a marine basin. The geopark's oldest rocks, such as the sedimentary rocks and early volcanic products, were formed during this stage. The second stage, which occurred around 11 to 8 Ma, marked the peak of the volcanic activity in the region, giving rise to the formation of many volcanic edifices, lava flows, and pyroclastic deposits. The volcanic activity was mainly effusive and explosive, characterized by the formation of stratovolcanoes, calderas, and maar-type structures. The third stage, which began around 8 Ma and continues to the present day, involves sporadic volcanic activity and the subsequent erosion of the volcanic structures. The ongoing erosion has shaped the landscape of the geopark, exposing the volcanic deposits and rocks that we see today.

4.1.11.2.The representative geoheritage of the geological evolution

The geodiversity of Cabo de Gata-Níjar UGGp is usually associated with the volcanic range of Cabo de Gata, the most complex and extensive volcanic deposit in the Iberian Peninsula of ca. 16 to 8 million years old. The volcanic complex is classified as intermediate type (andesites and dacites). In fact, the geopark represents the most extensive and complex calco-alcaline fossil volcanism in the Iberian Peninsula. The emerged part of the complex comprises only 5% of the total complex, the rest can be found below the Alboran Sea, following the Carboneras Fault. It is also worth mentioning the scattered Tortonian and Messinian reefs deposits with excellent examples of Tyrrhenian fossilized beaches, and the Quaternary alluvial and coastal plain with a Wetland of International Importance known as Las Salinas. (Villalobos, 2003)

The exceptional weathering conditions of the territory and the sub-desert dwarf vegetation allow the observatioin of the geological landscape: domes, lava flows, columnar jointing, alluvial fans, coastal cliffs, dykes and fossilized reefs constructions. Inside the UGGp, 39 geological sites of cultural, scientific and didactic interest have been identified, most of them also included in the Andalusian Inventory of Geological Sites.[17]

[17] information from: https://en.unesco.org/global-geoparks/cabo-de-gata-nijar

From this inventory (2011)[18], out of the mentioned sites, nearly half of them are volcanic in nature; however, they do not hold the highest scientific value within the region. For example, the site "El volcán de los Frailes" aptly showcases andesitic to basaltic rocks dating back to 8 Ma (Fernández, 1987)., while "El Cerro de Vela Blanca" features a volcanic dome from 12 Ma, and the volcanic dome at Punta Baja displays didactic volcanic columnar disjunctions. One high scientific site is "Coladas Submarinas al sureste de Vera".

Representing the Miocene-Pliocene marine carbonate sediments are sites like "Los sedimentos Marinos de Cañada Méndez.". Aside from volcanism, sites of high didactic, scientific, and touristic significance are associated with stratigraphic series such as Molino Río Aguas; the sub-deserts of Almería, many karsts and reef deposits.

4.1.12.Sierra Norte de Sevilla UNESCO Global Geopark

The Sierra Norte de Sevilla UNESCO Global Geopark (Since 2015) is located north of the Guadalquivir River in the province of Seville, Andalusia, Spain. It is one of the largest natural parks in Andalusia and includes, either totally or partially, ten municipalities. [19]

4.1.12.1.The geological evolution in the national geological context

The area is part of the Iberian Massif, a part of the Variscan (or Hercynian) orogenic belt. It is located in the Sierra Morena mountain range and encompasses mainly the distinctive geological zones of Ossa-Morena, part of the South-Portuguese Zone (in the western part) and the suture zone between these two. (Vera, 2004; Sierra, 2003).

Precambrian

The Precambrian rocks outcrop in the northeastern sector, in the Loma del Aire Units, and in the northwestern sector, in the core of the Olivenza-Monesterio Anticlinorium, to the west of the Embalse El Pintado. These rocks correspond to schists, gneisses, marbles, and abundant volcanic material (metavolcanites).

Cambrian

During the Early Cambrian, the region was a coastline whose shallow marine floors were very oxygenated and experienced the deposition of calcium algae mud and growth of archaeocyathid colonies over long periods of time. Together with stromatolites, they were responsible for the formation of reefs that originated the massive limestones of the Campoallá Layers, an excellent example of this

[18] Available in https://www.juntadeandalucia.es/

[19]https://en.unesco.org/global-geoparks/sierra-norte-de-sevilla

type of formation. Later on, the region became emerged for some time, developing paleokarsts under a tropical climate (e.g., Cerro del Hierro and other places in the area). Later, in a deeper marine platform, sediments mainly of clay and silt, with some contributions of sand, transported by marine currents, were deposited. This unit includes a fossil record of trilobites. Fossil trilobites are frequent in the slates of the Capas de Benalija, well represented in the area.

Ordovician

During this period the continental fragments split from Gondwana and continue their movement towards the northern hemisphere across the Panthalassa Ocean. Here, sedimentary layers with graptolites were deposited in a shallow marine basin and are represented by dark and greenish-gray slates and quartzites of the Valle Unit, located to the east of Embalse El Pintado, and in the Cerrón del Hornillo, south of Constantina.

Silurian

During this period, the sea level rose, leading to a marine transgression. Slates with graptolites and intercalated limestones outcrop in the syncline of the Valle Unit and the Cerrón del Hornillo.

Devonian

The Devonian was a period of significant tectonic activity and widespread expansion of life on land, with Laurasia (the merging of Euramerica and Siberia) and Gondwana coming closer together. Devonian materials are mostly found in the Southern Portuguese Zone, south of Almadén de la Plata, although there are also some Devonian outcrops in the Sinclinal del Valle, and in several places, limestone conglomerates assigned to this period are found, reflecting the tectonic activity of this time.

Carboniferous

In the region, by the end of the Carboniferous, the new Variscan mountain range had reached its maximum height, and erosive processes largely determined its current gentle relief. On the deformed Variscan basement, small intramontane continental basins would open, which were filled with fluvial and lacustrine sediments derived from the erosion of the surrounding reliefs until the end of the Permian and the beginning of the Triassic.

Permian

These sediments were accompanied by abundant volcanic deposits and contributions of organic matter, which later transformed into coal, as well as numerous remains of fossilized flora. These records are observable in the basins of El Viar, Alanís-San Nicolás del Puerto, and the surroundings of the El Retortillo Reservoir. The Permian sediments are located in the Alanís-San Nicolás del Puerto Basin and the Viar Basin. Both basins are filled with conglomerates, sandstones, and shales with minor intercalations of limestone and thin coal levels, in addition to volcanic rocks (basalts and pyroclastics). The sediments contain abundant fossilized flora. In the Viar basin, there once existed a large forested area with Araucaria trees, gigantic trees reaching over 30 meters in height, which were buried by a series of volcanic eruptions. The ash emitted by the volcanoes covered some of these trees, and over time, the wood silicified, giving rise to fossilized tree trunks.

Mesozoic

During the Mesozoic, the supercontinent Pangea fragmented, and the Alpine orogeny began, which in this region would cause the uplift of the Betic Mountains and the sedimentary filling of the Guadalquivir Basin. There are no sediments of this era in the geopark, because the region was emerged and subjected to erosion processes, and, therefore, without sedimentary records.

Cenozoic

During this Era, the Betic Mountain Ranges continued to rise, south of the emerged Variscan Massif, and the sedimentary basin of the Guadalquivir was filled with sediments derived from the erosion of the massif and the Betic Mountain Ranges. To the east of the Embalse el Huéznar, south of Constantina, a small extension of sedimentary rocks belonging to the Guadalquivir Basin units outcrops, attesting that its coastline reached this point, about 7 Ma. These rocks correspond to limestone levels, rich in fossil records, and white and yellow-toned clays. Marine fossils of bivalves, brachiopods, barnacles, gastropods, scaphopods, corals, and sea urchins are relatively common. Regarding the recent landforms and aside from recent karstic morphologies, Cerro del Hierro stands out and displays a tropical karst morphology. This process began during the Cambrian period after an initial uplift of the land.

4.1.12.2.The representative geoheritage of the geological evolution

The geological history of the Sierra Norte de Sevilla geopark unfolds through a series of events that have shaped its distinctive landscape. During the Paleozoic era, from the Cambrian to the Lower Carboniferous, this region was part of the ancient Gondwana continent, experiencing marine sedimentation in platforms and oceanic bottoms.

The geology of the geopark is characterized by the prevalence of sedimentary rocks, which extend widely throughout the region, with a greater abundance in the northern half. In contrast, igneous rocks are primarily concentrated in the southern half, while metamorphic rocks are distributed across various sectors, including the northeast, north, west, and south. These geological features are mainly centered on Precambrian and Paleozoic periods, with some Cenozoic deposits also present.

Paleozoic rocks hold great significance in the geopark (Consejería de Medio Ambiente y Ordenación del Territorio, (2017). The geological system of the Cambrian, in particular, is manifested through extensive outcrops in the northeastern half of the territory. Notable formations such as the Torreárboles Formation, Capas de Campoallá Formation, and Capas de Benalija Formation stand out for their extent and paleogeographic and geomorphological relevance.

Geological systems of the Ordovician, Silurian, and Devonian are primarily concentrated in the Sinclinal del Valle and Sinclinal del Cerrón del Hornillo. These deposits reveal a unique paleogeographic context within the Iberian Massif, with a prevalence of sediment and pelagic fauna reflecting marginal environments of the Gondwana continental shelf.

The rocks in the geopark exhibit significant deformations due to the Cadomian and Variscan orogenies, which left their mark on the region's geology.

The geopark also reveals its richness through fossils present in the rocks. Stromatolites, archaeocyaths, trilobites, graptolites, and ichnofossils are just a few of the species found. Among the notable sites for this work, the Visitors Center at Cortijo El Berrocal in Almadén de la Plata showcases a spectacular fossilized tree trunk discovered in 2005 (Wagner & Álvarez-Vázquez, 2010). Around 40 species of flora have been found, confirming an Upper Carboniferous (303 Ma) - Lower Permian (290 Ma) age for the sediments of the Viar Basin (Wagner & Álvarez-Vázquez, 2010). Nearly all plant remains were discovered in deposits from a wet environment, generally alluvial or lacustrine facies, with various contributions of volcanic origin, such as pyroclastic flow deposits and breccias, which favored the process of silicification. Furthermore, the "Traces of Jellyfish" ("huellas de medusas" in Spanish) site from the Lower Cambrian is a highly relevant record of soft-bodied animals in terrigenous sediments, characterized by a unique concentration of traces within a single outcrop, also highlighted site in the geopark inventory (Consejería de Sostenibilidad, Medio Ambiente y Economía Azul, 2017).

4.1.13.El Hierro UNESCO Global Geopark

The territory of the El Hierro UNESCO Global Geopark covers the whole of the Island of El Hierro (278 km2) and includes a marine area around the whole Island (about 312 km2), forming a total area of 595 km^2.[20]

4.1.13.1.The geological evolution in the national geological context

The Canary Islands originated more than 70 Ma ago from intraplate volcanism in the African Plate (Anguita & Hernán 2000). In general terms, the formation can be divided into two types of ideas:

[20] http://www.elhierrogeoparque.es/

thermal and tectonic (See Anguita & Hernán, 2000; Sandoval-Velasquez et al., 2021). The geological evolution can be summarised as follows (Ramos et al., 2023):

El Hierro island, with an age of about 1.56 Ma, corresponds to submarine construction, although the oldest subaerial rocks have been dated at 1.12 Ma (Gee et al., 2001). The formation of the island is considered to have occurred rapidly due to the intense processes that have taken place (Gómez Sáinz de Aja et al., 2010). One of the singularities of El Hierro is the clarity of massive lateral landslides and rift volcanism. These facts have resulted in a star-shaped island. The first volcanic landmark was the Tiñor volcano, which was active between 1.2 and 0.88 Ma ago (Guillou et al., 1996; Barrera Morate & García Moral, 2011). The rapidity of its formation produced instabilities in the platform that led to gravity sliding (Gómez Sáinz de Aja et al., 2010).

This was followed by a significant period of inactivity and then, between 0.54 and 0.17 Ma, a second stage of formation began in the Tiñor slide basin, corresponding to the eruptions of the El Golfo volcanic edifice. The materials ejected by this volcano completely buried the Tiñor landslide scar and a large part of the preceding volcanic edifice. At the end of this new stage, there were two volcanoes separated by an almost vertical landslide scarp (Carracedo et al., 2001).

Subsequently, rift volcanism began, a stage characterized by several events. The emission centers are grouped in the main structural axes of the island, which are more concentrated in the center and south, and are more dispersed on the east and west flanks. Between 0.5 and 0.3 Ma was the El Julan gravity slip (Carracedo et al., 2001), of which there is no evidence on the surface, but there is evidence on the ocean floor. Between 0.54 and 0.17 Ma ago, a new lateral collapse took place to the northeast, at San Andrés (Day et al., 1997), which was not completed and ended up generating a system of step faults. Next, between 0.17 and 0.14 Ma was the Las Playas gravity slide (Gee et al., 2001), which has the smallest volume of all. The largest landslide occurred at El Golfo, which is also the best example of a large-scale collapse (Gee et al., 2001). After this mega-sliding, and also within the rift volcanism, there followed a stage of island formation characterized by recent volcanism that took place at various points in the El Golfo valley and filled in the escarpments of this valley. These episodes shaped the geography of the island as it is known today.

The last stage is limited to historical volcanism, represented by the eruption of the Tagoro volcano between 2011 and 2012. This is a submarine eruption that occurred SW of La Restinga and remained at just 88 m (Pérez-Torrado et al. 2012) from sea level. Therefore, volcanism on the island is still active. Both the ages of the different episodes of its formation, as well as the last volcanic landmark, suggest that the activity will continue in the future. (Ramos et al., 2023).

4.1.13.2.The representative geoheritage of the geological evolution

It emerged above the sea level about 1.2 Ma ago as the last volcanic island in the region. It has over 500 open craters and another 300 covered by more recent lava flows. The island's construction was rapid, leading to the creation of highly unstable reliefs over short periods, causing several giant landslides. Some of these landslides have morphological expressions in the form of arch-shaped megastructures. The most recent activity occurred on 10 October 2011, with an underwater eruption at a depth of 300 meters, approximately 1.5 kilometers off the southern coast.

Regarding its features and sites, El Hierro is the smallest and geologically the most recent island of the Canaries, and it registered the last submarine eruption in Spain during the years 2011 and 2012. It is an oceanic, subtropical and volcanic island. It comprises geodiverse volcanic morphologies (cinder cones, lava flows, lava deltas, lava tubes, hornitos, tumuli), erosion processes (landslides, ravines and cliffs) and sedimentary processes (beaches, dunes, alluvial and colluvial deposits) which have been geoconserved. More than 52% of its territory are natural protected areas by the Canary Law of Natural Spaces. El Faro-Orchilla geozone of the geopark is one of the best examples of recent monogenetic basaltic volcanism in the Canary Islands (Dóniz-Páez & Pérez-Chacón, 2023; Dóniz-Páez et al. 2019). The diversity of this geozone is associated with the presence of one of the best examples of recent monogenic, basaltic magmatic volcanism in the geopark, where different types of volcanic edifices can be identified (cinder cones, spatter cones, hornitos, etc.)

The geological history of the Island of El Hierro can be understood through the visit of about 61 geosites, which are representative of the growth and destruction of an oceanic Island in an intraplate environment. The geological heritage represented by these geosites has as foremost exponents those related to the formation of mega-landslides and the formation of extensive fields of pahoehoe lava-flows related to the historical or prehistoric fissure volcanism concerning the activity of its three rifts. (Ortega et al., 2023)

4.1.14.Cabo Ortegal UNESCO Global Geopark

The Cabo Ortegal UNESCO Global Geopark is part of the regions of Ferrol and Ortegal, in the north of the province of the Autonomous Community of Galicia. It has a total area of 799,72 km^2. It covers seven municipalities.[21]

[21] https://proxecto.xeoparquecaboortegal.gal/en/

4.1.14.1.The geological evolution in the national geological context

The area is located in the Galicia-Trás-os-Montes geological zone of the Iberian Massif unit. The zone is composed of allochthonous terrains that migrated from other areas and became attached to the rest of the massif after the breakup of Pangea. It consists of several complexes of rocks of great depth with a high degree of metamorphism, along with ophiolites. One of these allochthonous complexes is the Cabo Ortegal complex (Canosa F., 2015; Asociación para a Xestión do Xeoparque do Cabo Ortegal, 2021).[21]

Paleozoic

The area provides evidence of the Variscan Orogeny, which led to the formation of the supercontinent Pangea. The rocks found in this geopark emerged from the Earth's upper mantle at a depth of over 70 km due to the collision between two continents, Laurussia and Gondwana. The copper deposits in the geopark originated from thermal activity on the seabed, where fumaroles released gases and minerals at high temperatures, subsequently cooling upon contact with water. The predominant rocks in the area include peridotites, serpentinites (known as "toelo"), metavolcanics, and metasediments. Additionally, there are amphibolites, granulites, and gneisses, along with some of the best-exposed eclogite outcrops.

Cenozoic

Among the more recent records, there are caves, active faults dating back 20 Ma, and beaches with non-volcanic black sands (e.g., Teixidelo) and others with a reddish hue due to their abundance of garnet particles.

4.1.14.2.The representative geoheritage of the geological evolution

As mentioned above, the different geological formations present in the Cabo Ortegal UGGp are part of one of the most complete allochthonous terrains of the Variscan Orogeny in Europe. The relevance of this area is due to the presence of rocks from the mantle.[22]

There are several remarkable sites, with international and national value, high scientific and didactic potential (Canosa F., 2015; Asociación para a Xestión do Xeoparque do Cabo Ortegal, 2021), from which we highlight here the largest continuous eclogite outcrop known to date, Punta dos Aguillóns, including also an exceptional panoramic view, and Miradouro da Miranda, Outcrop of eclogites with impressive views over the Ortigueira estuary. From the landscape, the site Cantís de Vixía

[22] As mentioned in the official dossier 2021 of the geopark (https://proxecto.xeoparquecaboortegal.gal), from Girardeau et al., 1989; Marcos et al., 2002; Martínez Catalán et al., 2002; Martínez Catalán et al., 2007; Arenas et al., 2009; Díez Fernández et al., 2011; Arenas et al., 2014; Arenas and Sánchez Martínez, 2015; Arenas et al., 2016a; Henry et al., 2017.

Herbeira is an extensive set of tectonic cliffs, in some cases with slopes of more than 600 metres, considered the highest in continental Europe developed on mantle rocks. Regarding erosional processes, Macizo dos Penidos is a remarkable site with differential-erosion eclogite outcrops that has created a structural synform. Important granulite massifs, where 5 facies have been identified according to their chemical and mineralogical composition are also important. The Miradoiro da Fontá is a recumbent fold of Ouzal massif and developed into granulites and ultramafic rocks. Moreover, an almost complete and well-preserved ophiolitic sequence with pillow-lavas, mafic dykes, gabbros and serpentinites can be found in the site Praia da Concha. Praia de San Antón is also an Ophiolite sequence (mélange with serpentinites and marbles), overlapping between allochthonous units (metabasites) and autochthonous units (metapelites).

In a national level, the site Praia do Picón is an exceptional case of dropstone in black slates, alveolar weathering (haloclasty). Macizo de Herbeira site, comprises a wide variety of mantle rocks, both peridotites and pyroxenites and presence of chrome-platinum mineralizations. There is a locality type of 2 mineral species, morenosite and zaratite, supergene alteration of nickel sulphides in the site Val e litoral de Teixidelo wich is a glacial valley. Costa do Bico site is an exceptional occurrence of Mohorovičić discontinuity, between granulites and peridotites (Crust-Mantle). We can find Volcanogenic Massive Sulphide mineralisation (VMS) in connection with black-smokers in different Mines. Acidic and intermediate submarine volcanism of Ordovician age, with good examples of ignimbrites, cinerites and pyroclasts are also remarkable. Regarding tectonic features, a brittle-ductile fault zone in relation to late-Variscan or Alpine structures is present in the area.

Secondary values can be related to good outcrops of mylonitic zones associated with thrusts within the ophiolitic units, significant copper sulphate speleothems over 3 metres high, granitic landscape with the presence of boulders, tafoni, etc; presence of non-volcanic black sand beaches or those consisting solely of garnet (e.g in site Praia de Fornos.) and a variety of coastal shapes, lagoons, marine arches, tombolos, cuspate forelands, estuaries.

4.1.15. Sierras Subbéticas UNESCO Global Geopark

The territory of the geopark and the Subbéticas Mountains is located in the Betic Mountain Range, in the southern part of the province of Cordoba, in the heart of Andalusia. They were declared a Natural Park in 1988, mainly due to their geological features. It comprises 8 municipalities.[23]

[23] https://www.juntadeandalucia.es/medioambiente/portal/landing-page-índice/-/asset_publisher/zX2ouZa4r1Rf/content/sierras-subb-c3-a9ticas-geopark/20151?categoryVal=

4.1.15.1. The geological evolution in the national geological context

The area of the natural park and geopark is located in Betic Mountain Range unit (Vera, 2004), specifically in the lower-Guadalquivir lands of the External Zones domain. Its geological units are mainly composed of sedimentary rocks from the Jurassic and Cretaceous periods, although there are also smaller outcrops of Triassic and Cenozoic materials (Molina et al., 1999).

Triassic

During this period, an extensive coastal plain developed to the south of the Sierra Morena that was periodically flooded by the sea resulting in deposits of limestone, sand and lutite. These are interspersed with evaporate deposits of gypsum and halite and form the oldest sediments of the area.

During the Upper Triassic, a significant transgression occurred, submerging a considerable portion of this Andalusian area. This led to the formation of layers of marine limestone containing a substantial number of fossilized shells such as bivalves, gastropods, and brachiopods. Following this period, during a subsequent regression, the coastal plain emerged, gradually burying the existing vegetation (e.g., Neocalamites), which is evident in specific layers of compacted silt that preserve frequent examples of plants like horsetails. The rock evidence is easily recognizable, displaying a range of colors and featuring intercalations of gypsum and salt, as seen in locations such as Rute, Carcabuey, and Envinas Reales. The warm, shallow Tethys Sea, continuously subsiding and at times compartmentalised, facilitated water evaporation and the deposition of significant volumes of evaporite rocks like gypsum and salt on its bed. Furthermore, the separation of continents caused substantial fractures in the Earth's crust, leading to the outpouring of volcanic rocks from underwater magma. Within the sediments of the Subbetic region, magma settled into cracks or between strata near the surface, giving rise to subvolcanic rocks of a dark green-gray hue. These rocks are well observable today along the course of the Salado River as it passes through the Cubé region. (Serna & Moreno-Arroyo. 2020).

Jurassic

At the beginning of the Jurassic period, there was a general collapse of the plain and it was once again flooded by the Tethys Sea, the sedimentation came from carbonate shallow marine environments, leaving the actual limestone outcrops. The Gavilán Formation represents these environments, with ‘Lithiotis’, crinoids, brachiopods, echinoderms, ammonites and gastropods records. During the mid Lower Jurassic the two major domains of the ancient southern Iberian platform can be differentiated, the External Zones of the Betic Cordillera: the Prebetic and the Subbetic. Magma reached the surface during this period, and pillow lavas are formed coming into contact with seawater, as seen in the village of Venta Valero, in Almedinilla. (Serna & Moreno-Arroyo. 2020).

Following the breakup of the Southern Iberian platform at the end of the Early Jurassic (180 Ma), the primary domains of the Betic Cordillera can now be distinguished. There is a transition from fairly uniform sedimentation across the entire platform to significantly heterogeneous sedimentation. In the Prebetic Domain, terrigenous sediments originate from the continent; in the Subbetic Domain, clayey sediments mixed with carbonates (marls and marly limestones) are present. On top of these, calcareous sediments develop within the marine environment itself, eventually giving rise to limestones and dolomites. As the platform subsides, the sea deepens, facilitating the influx of ammonites and belemnites, which are documented in the marls of the Zegrí Formation. Foraminifera are also recorded in this context.

During the Middle Jurassic, the seafloors sink and tilt, as evidenced in the Sierra de Cabra. These coastal proximal seafloors record the presence of oolites, visible in Arroyo de Jarcas within the Camarena Formation. Small colonies of corals, sea lilies, brachiopods, and numerous calcareous algae balls established themselves on these sandy areas. Oolitic limestone is a distinctive and abundant feature in the Sierra de Cabra. Towards the end of this period, significant sea lily meadows return, and reddish sediments are deposited on paleokarst surfaces, overlying the aforementioned sands. In deeper environments, red limestones containing ammonites or flint were formed. The profound fractures in the crust facilitated the ascent of silica-rich magma, leading to the appearance of radiolarians and subsequently flint nodules (e.g., Veleta Formation).

During the Late Jurassic, a relative sea level change led to the platform's seafloor being at greater depths and the coastline receding, resulting in a stratigraphic discontinuity of approximately 5 million years. During these sedimentation periods, nodular limestones or 'Ammonitico Rosso' facies formed during Upper Jurassic to Lower Cretaceous, characterized by red and orange colors and abundant ammonites. Thalassinoides are also registered in the area. The stratification is observable in Cañada de Hornillo. In deeper marine environments, significant sediment volumes accumulated in comparison to the nodular limestones.

The boundary between the end of the Jurassic period and the beginning of the Cretaceous is especially well represented, such as in the Puerto Escaño series, located very close to Carcabuey.

Cretaceous

The plain began to fracture, leading to the formation of horsts and grabens. All the exposed carbonate rocks, marls, and marly limestone we see today are outcomes of these tectonic processes.

This new subsidence deepened the Subbetic Sea. Abundant clay from the continent reached this sea, mixing with the carbonated mud from the ocean. The irregularities present on the seafloor began to fill and level out. Furthermore, due to Milankovitch cycles, rhythmites of marly limestone and marls were formed, resulting in the Carretero Formation.

Around 125 Ma, during a period of higher sea levels, a renewed activation of fractures caused a portion of the Subbetic seafloor to reemerge amidst the southern Iberian platform like a distant island, leading to sedimentation hiatuses.

Around the middle of the Cretaceous, approximately 95 Ma, a high activity at oceanic ridges, an increase in sedimentation from continents, and perhaps the absence of ice at the poles contributed to a rise in sea levels, placing the sea nearly 200 meters above the current sea level. The Capas Rojas Formation in Priego, characterized by rosy marls with foraminifera, provides evidence of a fresh surge in oxygen levels in the waters. Around 93 Ma, this enrichment diminished once again.

Cenozoic

During the Alpine Orogeny, a collision between the African and European tectonic plates took place, leading to the uplifting of the Betic Cordillera alongside the Thetys seabed sediments. Abundant bivalves, calcareous algae, corals, bryozoans, foraminifera, and other organisms are preserved within the sands, calcarenites, and marls.

Throughout this collision, the entirety of the limestone rocks slid over a layer of Triassic clays that acted as a detachment zone. The limestones underwent compression, resulting in folds and thrust faults. New reliefs began to take shape and emerge in the sea, to the south of Sierra Morena. Gradually, the connection between the Atlantic and the Mediterranean narrowed until it closed completely around 5.6 Ma. The Mediterranean became entirely isolated, dried up, and its level dropped by around 1500 meters compared to the Atlantic.

Around 5 Ma, the entire region experienced its greatest uplift, leading to the definitive emergence of the land. Approximately 600,000 years later, the connection between the two bodies of water was reestablished through the opening of the Strait of Gibraltar.

Quaternary

The aforementioned carbonate rocks have undergone extensive karstification, giving rise to a intricate landscape dominated by features like poljes, karrens, dolines, canyons, caves, and springs. Within this emerging Subbetic region, various deposits formed through the action of rivers, streams, and sediment accumulation on mountain slopes, accompanied by the precipitation of continental limestones. This process led to the development of sinkholes, dolines, limestone pavements, caves, and more. Notable examples include Polje de la Nava de Cabra, Los Hoyones, Los Lanchares, and Cueva de los Murciélagos (Zuheros), along with the travertine platform in Priego de Córdoba. Moreover, Subbetic caves like Sima Abraham and Sima del Ángel house fossil evidence from the Pleistocene era, showcasing diverse species such as lynx, goat, deer, bear, horse, hyena, rhinoceros, aurochs, bison, wild boar, and elephant. These caves also contain a wealth of human remains and Neolithic tools. Additionally, the Triassic salt is dissolved by groundwater, giving rise to the Salado River of Priego de Córdoba and other saline streams in the region.

4.1.15.2.The representative geoheritage of the geological evolution

The 'Ammonitico Rosso' is one of the most studied as well as most unusual facies developed in the Tethys Ocean, mainly during the Jurassic. This calcareous to marly-calcareous facies was typical on high seabed seawards from the main platforms and emerged lands, sites where fine sediments accumulated discontinuously, while invertebrate animals tunnelled the sea bottom during pauses in deposition. The reddish facies occurs widely in the geopark, where four Jurassic–Lower Cretaceous sections have been included in the List of Geological Sites of International Importance (Geosite), as the most representative sites for Ammonitico Rosso facies in Spain (Serna-Barquero et al, 2021).

4.1.16.Lanzarote and Chinijo Islands UNESCO Global Geopark

Located at the Northeast of the Canary Islands, this geopark is separated by a strip of sea about 100 km from the Northwest edge of the African continent. It includes the whole island of Lanzarote, the islets La Graciosa, Montaña Clara, Roque del Este, Roque del Oeste y Alegranza, known as "Chinijo Island", as well as the abrasion platform around these islands.[24]

4.1.16.1.The geological evolution in the national geological context

From the Volcanic Area of the Canary Islands unit (Vera, 2004), the island of Lanzarote, known as the Island of the Volcanoes, has a morphology, with a large central oval and two appendices (north and south), which are called Famara and los Ajaches, respectively. The average height is modest in comparison with the other islands of the Canary Archipelago, with the maximum elevation being reached at Peñas de Chache, at 670 meters. (Mateo et al. 2019)

Cenozoic

The geological evolution of Lanzarote and Chinijo Archipelago is a relative recent one dating back to the Oligocene epoch. The islands were built almost entirely of basaltic materials during three volcanic construction stages: one submarine and two subaerial. The basement was constructed during

[24] https://geoparquelanzarote.org/en/

the Oligocene epoch and is made of submarine volcanic materials, plutonic rocks and sediment. During the Mio-Pliocene and the Pleistocene-Holocene there were two stages of subaerial volcanic activity separated by an eruptive hiatus of at least 2.5 Ma when the ancient Mio-Pliocene volcanic structures were continuously eroded to model their original morphologies, giving place to different sedimentary deposits, with an important presence of aeolian sands throughout the islands and beaches in the coastal areas. In more recent times, two historical eruptions have occurred in Lanzarote Island, in 1730–36 and in 1824, indeed causing a great impact on the landscape and life of the inhabitants something that remains until now (Mateo et al. 2019).

4.1.16.2.The representative geoheritage of the geological evolution

Lanzarote stands as one of the oldest islands in the Canary Archipelago and has witnessed a significant history of volcanic activity. The eruption known as Timanfaya holds a prominent place in the geopark, internationally acclaimed for its geological importance. This extended eruption occurred between 1730 and 1736, leading to substantial alterations in the island's landscape and the lives of its inhabitants. It has become a symbol of human adaptation. The emergence of volcanic materials dates back around 15 Ma. Notably, the release of abundant basaltic materials shaped the distinct volcanic formations in the southern and northern regions of the island, namely the Ajaches and Famara. Approximately 2 Ma, extensive lava fields formed, overlaying some of the earlier deposits (Mateo et al. 2019)

What sets this geopark apart within Spain, particularly in terms of volcanic regions, are the historical eruptions. The 1730-1736 event standing out due to its prolonged duration and extensive coverage. The most recent eruption on the island occurred in 1824, resulting in the formation of three new cones—Tao, Nuevo del Fuego, and Tinguatón—which emitted relatively smaller amounts of materials, noteworthy on a local scale. When considering the islets of the Chinijo Archipelago, their formation is attributed to hydromagmatic eruptions that occurred around 2.5 to 2 Ma. Beyond the volcanic terrain, the geopark provides insights into sand dynamics, coastal and underwater formations, and evidence of climatic shifts spanning millions of years.

The geopark encompasses a total of 82 designated geosites that represent the geological history and geodiversity of this area. These sites are crucial for understanding the evolution of this Atlantic volcanic island. Noteworthy among these sites are the Calderas Quemadas and Mar de Lavas de Timanfaya in Lanzarote, which hold significant importance in Spain's geological evolution (Galindo et al., 2019).

4.2. Communication strategy insights of five geoparks

In order to consider a national strategy or tool for communicating the geological heritage within the geoparks, it is important to align the contents and methods to what their own management bodies have already worked on in their territories, as well as collaborative networking.

To reach this goal and calibrate the proposal of this work, this section briefly discusses the communication strategy insights of five different geoparks that were visited during a fieldwork: Catalonia Central, Origens, Sobrarbe Pyrenees, Basque Coast, and Las Loras UGGp (Figure 3). The selection of these five geoparks was made based on a planned one-and-a-half-month route through the Pyrenees and the acceptance of scientific coordinators to collaborate in this work (see ANNEX 2). The author had also visited the Courel Mountains UNESCO Global Geopark.

The main tasks during the fieldwork were (Table 2):

- Visiting sites or geo-routes and carrying out surveys to the management team or scientific coordinator. These were used to understand the geological evolution that had occurred over time in each geopark area and the understanding of key sites about this geological evolution.
- Observe and note down good practices of how geoparks were communicating their stories and complex geological information in an easy-to-understand manner. This gave insights about some engaging communication methods that were working well conveying the geological evolution.
- Aligned with the previous one, the final task was about collaboration. This was made defining the key geological features of each geopark that should be communicated to the wider public. This collaboration made sure the most interesting and important features of each geopark were highlighted nationwide.

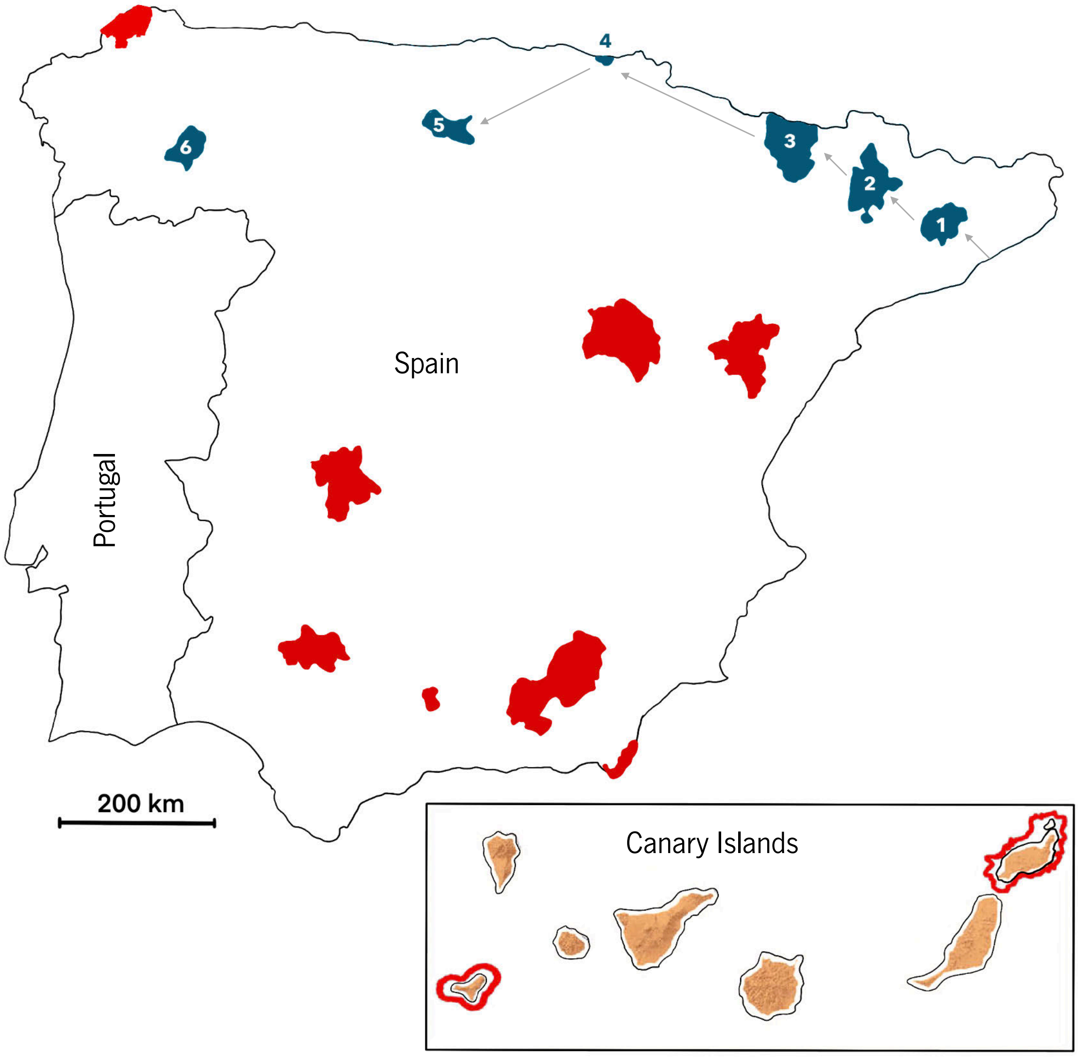

Figure 3: Fieldwork route through the UNESCO Global Geoparks carried out during this work (in blue); (1)Catalonia Central UGGp (2)Origens UGGp (3) Sobrarbe-Pyrenees UGGp (4) Costa Vasca UGGp (5) Las Loras UGGp. Courel Mountains UGGp was also visted in a previous ocasion, not from this fieldwork (6).

Table 2 : Stage III, Communication strategy from the UGGps, the 3 steps followed in the data collection and collaboration.

III	UNESCO Global Geoparks communication strategy
↳	**Communication strategy regarding the geological evolution** Understanding of the management strategy regarding communication
↳	**Good practices from the geoparks** Consultation and observation of the didactic tools used within the territories to communicate the geological evolution
↳	**Collaboration with the management body** Decision making regarding the contents to incorporate in the general storytelling

Figure 4: Montserrat Mountains. Observed interpretative contents during the fieldwork. Catalonia Central Geopark publications promoted and distributed within the geopark. On the left the brochure explicitly including the geological history. (Photographies: Kevin Quinzacara)

The main observations and insights are described and summarised in Table 3:

Table 3: Fieldwork summary, including the data collection and observations of the geoparks

Item/UGGp	Catalonia Central	Origens	Sobrarbe	Basque Coast	Las Loras
Communication of the geological evolution					
Main message in the communication strategy	As a unique history about the endorheic sea extinction during the Paleogene	Highlighting the last dinosaur of Europe and the pyrenees structure evolution.	The tectonic geological features, Glaciers and Karsts.	As a continuous history about the flysch sequence. considering the main limit boundaries.	The relief modelling evolution and paleoenvironments during the mesozoic.
Main features highlighted	Montserrat Site and Salt mountain Cardona.	Paleontological museums and the Pyrenees evolution in outreach materials.	Geological episodes in their geo-routes.	The complete cretaceous sequence between Zumaia and Deba.	Las Loras hanging synclines, Oil reservoirs (museum) and karst systems.
Good practices					
Interpretation and education	Holistic approach on each site, regarding interpretative panels	Intervention on each interpretation center. Educational Toolkit. Use of technology (e.g VR) .	Educational well planned contents in Castillo de Aínsa interpretation center.	The complete flysch sequence storytelling is well outreached by tourist operators, using visual support.	Participative interpretation center using clear science illustrations about paleonvironments.
Management regarding communication	Visibilization of the geological evolution in touristic materials and website	Different comercial branding	The geological history was subdivided into Episodes, still used today in the Geo-Routes	Adaptation to the audience	Regular use of a "field book"as an educative tool. innovative interpretation center.
Suggestion for the national storytelling					
Feature, event and site to convey nationwide	"History about the endorheic sea extinction"	"The last dinosaurs of Europe"	"The evolution of the Pyrenees"	"The K/Pg limit, evidence of the dinosaurs extinction."	"Las Loras hangling synclines, the mesozoic paleoenvironments and the exokarst"
Secondary elements to convey nationwide	Salt deposits, Cardona.	The pyrenees evolution.	Glaciers and karsts.	GSSPs and limit boundaries.	Karst formations and the Oil reservoirs.

4.2.1.Catalonia Central UNESCO Global Geopark

In Catalonia Central geopark, the communication strategy regarding the geological evolution is focused as an unified storytelling about the endorheic sea extinction during the Paleogene. Noteworthy is their practice of adopting a commercial branding approach, with colours, imagery and slogans specifically aligned with the geological history.

The geopark good practices stand out of including a geological history text in their website and touristic brochures, meanwhile a further communication strategy will incorporate the whole storytelling concepts into the future interpretation project, such as panels, new satellite center and new materials

(Ferran Climent, 2023; personal communication). In this regard, Catalonia Central is known for its Montserrat Site and Salt Mountain in Cardona, and these two sites will aim to spread the knowledge about the landscape evolution. This will be conveyed through visual resources, on-site panels, and tourist brochures that briefly recount the geological history, always intertwined with other cultural and natural aspects.

Regarding the communicative content of Catalonia Central UGGp, the most notable aspect for the national narrative is the evolution of the Ebro basin and the erosive processes of the landscape (Figure 5). The collaboration made about the nationwide geological storytelling was regarding the global context and values to convey about the endorheic sea extinction, included in the summary and emphasized in the geological story of the previous chapter.

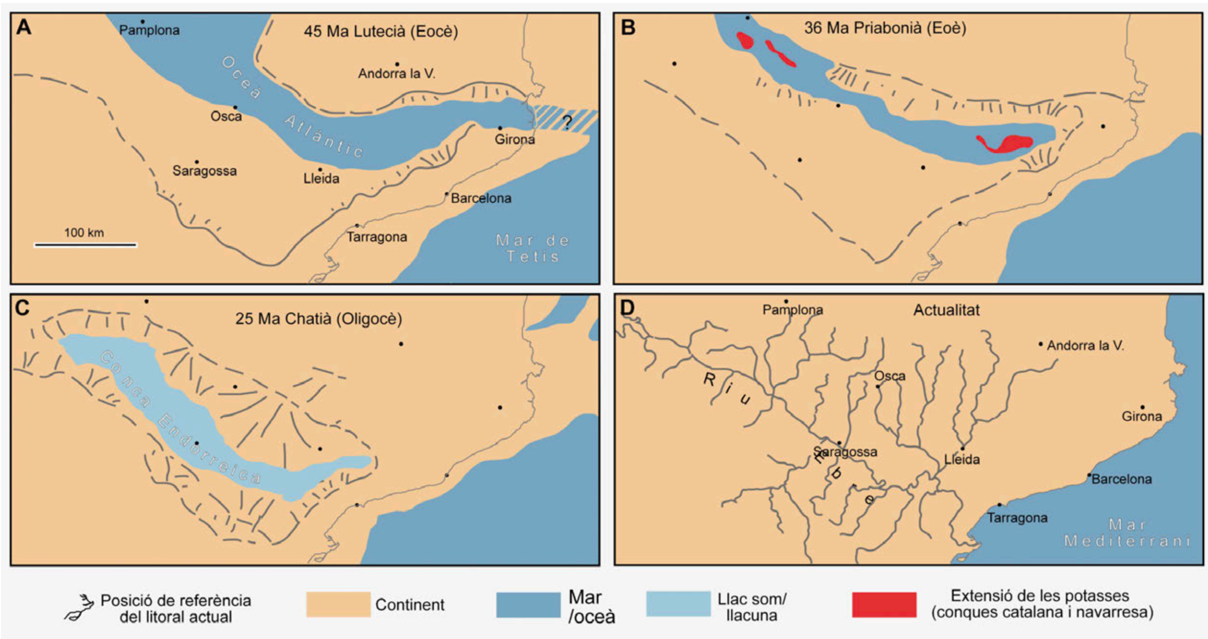

Figure 5: Palaeogeographical evolution of the eastern part of the Ebro Basin during the Palaeogen (A, B and C), compared to the present time (D), carried out from different sources. Author: Oriol Oms, a: Olmos, O., López-Blanco, M., Vilaplana, M.(2016).

4.2.2.Origens UNESCO Global Geopark

The geopark ensures the dissemination of its geological history by maintaining constant dialogue between managers, scientists and the scientific coordinator. In an exceptional move among geoparks in Spain, the geopark implemented a name change as part of a strategic commercial approach and to strengthen the geological storytelling. This approach aimed to effectively communicate the geopark's values and unify the territory. The rebranding effort involved adopting the concept of "Origens" (Origins in Catalan), emphasizing the geological origins and historical roots of the region. This commercial strategy follows the principles of place branding, seeking to promote the geopark's unique heritage assets by aligning the interpretation narrative with local tourism promotion efforts. By showcasing the extensive geological evolution and geodiversity within the territory, the geopark aims to engage and attract tourists. The new brand not only tries to highlight the geological aspects but also conveys a sense of authenticity with the territory due to its stakeholders and associates. Furthermore, the paleontological richness of the territory is prominently highlighted through the leitmotif of "The last dinosaurs in Europe." This thematic approach serves as a key strategy in promoting the most important episode of the geological storytelling and exceptional paleontological heritage. The efforts of the network "Dinosaurs of the Pyrenees" play a crucial role in the conservation, research, and innovation related to this heritage. By emphasizing the presence of the last dinosaurs in Europe, the promotion of the territory's unique and significant heritage is effectively carried out. This communication strategy is a key tool to engine the rural area towards identity and participation, even though the strict geological events and features (e.g Tremp formation and the Pyrenees evolution) are under risk to be diluted under the commercial strategy “Origens”.

The good practices regarding communication emphasizes a variety of methods and materials, including the use of technology such as VR, geotouristic operators, and an educational toolkit. Museums and geologically-adjusted panels at the centers are also common practice. The central features outreached are following the work done by the paleontological museums alongside the Pyrenees evolution history. The efforts try to focus on the Tremp Formation and secondary on the Pyrenees evolution, even though all the contents are constantly suggesting a complete geological history though deep time (Figure 6). Moreover, the geopark disseminates its geological history by creating educational resources to support the official education program in collaboration with the Pyrenees Territorial Support Center. One notable resource is the educational toolkit that has been utilised in different educational institutions, encouraging the audiovisual creation of the geological evolution of the Pyrenees, focused on the geomorphological features, geological risks and the local dinosaurs (Figure 6). Regarding good practices in tourism, the geopark promotes its geological history through a partnership with a geotourism company (‘Eureka SGN’, since 2011). They achieve this by offering georoutes within the geopark and specialized routes, providing information and engaging visitors. Visual resources, such as illustrations, sections, and explanations, are utilised to educate and captivate visitors about the geological evolution, while simultaneously raising awareness about its fragility (Jordi Panisello 2023, personal communication).

In Origens UGGp the main features and events decided to convey are the same as the one they have been developing during the project: the last dinosaurs of Europe and the Pyrenees formation witnessed in the four thrust sheet structures and sequences, even thought this second event is more restricted to Sobrarbe-Pirineos geopark.

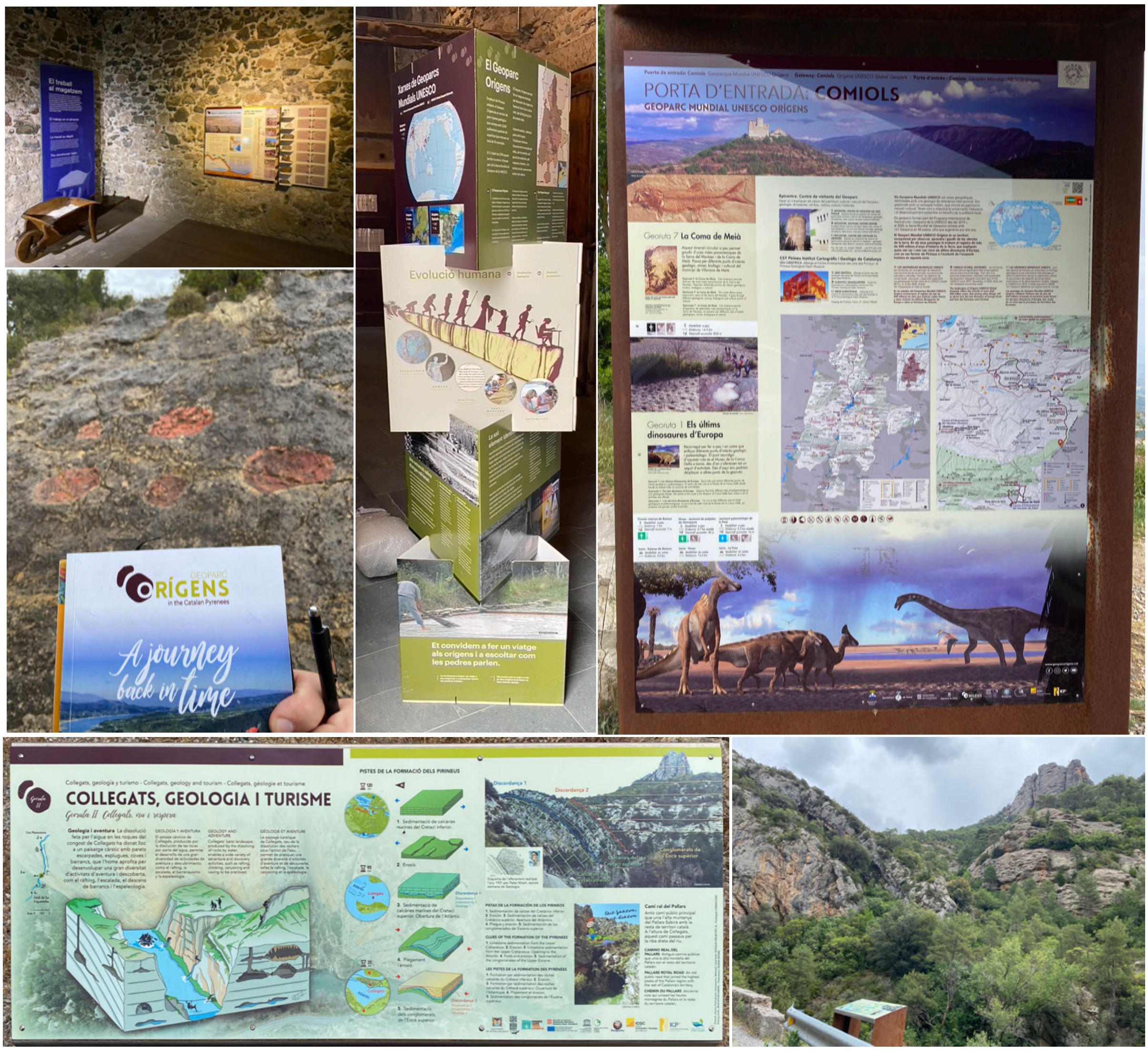

Figure 6: Origens UGGp interpretation strategy insights: The geologically-adjusted panels at the centers (e.g Gerri de la sal), The commercial branding inspired by a geosite (Dinosaur footprints in Orcau), the contents of the geological routes panels (e.g Comiols).

4.2.3. Sobrarbe-Pirineos UNESCO Global Geopark

The Sobrarbe-Pirineos Unesco Global Geopark communicates its geological history through the Castillo de Aínsa Center, focusing on the Pyrenees' tectonic evolution and glaciers (Figure 7). The didactic potential and the tourism perspective provided by the interpretive center are noteworthy, even though it has limited space. Regarding the informative tools, the educational intent of the center about the geological evolution, the Alpine Orogeny and Glacier is commendable for this endeavor.

A good practice carried out by the geopark is the geological history division into different episodes and geological routes, which are still utilized today. These publications are available on the website and for the use of visitors focused through pathways, in which each one delivers an introduction about episodes of the geological history of the territory.

Figure 7: Sobrarbe-Pirineos UGGp. Current contents exhibited in Castillo de Aínsa interpretation center. Notice the geological explanations of the Pyrenees evolution and the new paleontological evidences.

In Sobrarbe, the primary feature to be conveyed nationwide is "The evolution of the Pyrenees," with secondary focus on the glaciers and karsts.

4.2.4. Basque Coast UNESCO Global Geopark

The Basque Coast UGGp takes a unique approach, offering the complete flysch sequence as a 'continuous geological book', catered to different audience levels of understanding. This approach and the storytelling about the remarkable continuous layers is the strongest message by the tour operators, also visited in this work (Figure 8). Regarding the way they communicate the main values of geological history, it is to highlight the work done regarding the levels of audience to which the geopark tries to transmit, in that way the geological information is adapted according to the needs of the visitor (geologists, tourists, students, etc). The collaboration in Basque Coast, with the scientific coordinator concluded that the K/Pg limit, iridium evidence of the dinosaur extinction, is the main feature of the geopark selected to communicate within the Spanish geological storytelling. Secondary features might include the GSSPs, limit boundaries, paleontological record, and caves.

Figure 8: Algorri site and its panels in Basque Coast UGGp. The K/Pg limit evidence of the dinosaurs extinction.

4.2.5.Las Loras UNESCO Global Geopark

In Las Loras UGGp they spotlights the geomorphological evolution of the hanging synclines and the paleoenvironments during the Mesozoic in the new interpretative center of Villadiego. In the Petroleum Museum the geological history is communicated. They also employ an outreach "field book" tool for education, which aims to be an interactive tool, as well as the geopark's guidebook as the main source of information for visitors who want to get deeper into the natural values and features of the area. It is worth noting here that the project considered the scientific illustration as a powerful tool to reconstruct the geological evolution of the area (Figure 9). This can be easily seen in the interpretation center and the didactic outreach field book. Las Loras UGGp also followed an approach to give a special identity to the geopark regarding the main geomorphological feature of the area (Las Loras), visible in its commercial branding. The primary feature decided with the scientific coordinator to be communicated is the relief of "Las Loras" and the Mesozoic paleoenvironments. Secondary points of interest include karst formations and the oil reservoirs.

Figure 9: Las Loras UGGp. On top an image of the Villadiego interpretation center showing the big-size paleonvironments illustrations used to explain the geological evolution of the area and the tools used to explain the hanging synclines. On the right the Petroleum museum exhibiting the geological history of Las Loras. In the bottom right the Aguilar de Campo Formation outcrops. On the left and bottom left side the Hanging synclines in the landscape and the exokarsts systems. (Photographies: Kevin Quinzacara)

4.3. The Geological Evolution Framework of the Spanish geoparks

The dissemination of the geological evolution is done in different ways within each geopark, for example by episodes (e.g Sobrarbe-Pirineos or Molina Alto-Tajo UGGps), themes, or by different periods of the geological timescale.

4.3.1. Elements of the geological evolution

For a practical and neutral method to present the information, the unified Spanish geological evolution represented by all the geoparks is presented here following the geochronological timescale and it is subdivided in episodes. These episodes include the 16 geoparks with the main geological events and their representative geoheritage. These selected contents aim to be representative of all geological periods in order to follow a chronological storytelling.

Table 4: Stage IV: Elements of the geological evolution framework. The 3 steps followed to select the contents or elements of the geological evolution framework.

IV	Geological Framework elements
↳	**Episodes and its geoparks** The main geological episodes that encapsulate key events of the national geological evolution.
↳	**Selected geoheritage of each geopark** Geoheritage sites and its scientific and didactic values
↳	**Secondary features of each geopark** Complementary geological information to understand the main episodes.

Moreover, to enhance the effectiveness and clarity of the geological evolution framework as a communication tool, each event and site is presented within a thematic area. These thematic areas or scientific interest (e.g Pulido et al, 2013) are usually used as a practical tool to group the local geodiversity or to effectively present the geological information in the communication strategy in geoparks and their inventories (e.g Hilario et al, 2013).

While studying the communication materials in previous stages, 15 main thematic areas or interest were identified from the Spanish geoparks publications related to their inventories and outreach. These themes are currently used by the geoparks in their communication materials (e.g inventories, dossiers, promotional materials, etc).

From these thematic areas or scientific interests, nine of them represent the geological evolution framework in this work and the rest of them could be used as well in the outreach products if more information is included from the geoparks (see discussion).

Table 5: Thematics selected to present the geological events, features and sites of the geological evolution framework. In grey colour the nine thematic areas used in this work.

Pa	Paleontological	Re	Resources	Me	Methamorphic	Gr	Geological Risks
St	Stratigraphic	En	Environmental	Gl	Glacial	Se	Sedimentary
Ge	Geomorphological	Ed	Edaphological	Vo	Volcanic	Pe	Petrological
Te	Tectonic - Structural	Hy	Hydrogeological	Ka	Karst		

After building the body of knowledge for each geopark from this study and fieldwork, the following table summarises the main representative geological events nationwide, their general features, and some representative sites and values. The sites and brief descriptions of the values are taken from the application dossiers from each geopark, their inventories or scientific publications, considering that they have national or global relevance.

Table 6 : Geological evolution framework: Representative elements from the geoparks. Summary of the main geological features, sites and events of each geopark. Selected from the study of the geological evolution of all of them.

UGGp	Geological events	Features	Representative Site(s)	Geological values
El Hierro	Recent monogenetic basaltic volcanism in the Canary Islands	Various volcanic edifices can be identified and with varied shapes.	El Faro-Orchilla geozone	High geodiversity representativeness and accesible. (Dóniz-Páez et al. 2019).
Granada	Endorheic Guadix-Baza basin development and its drainage.	Glacis, Badlands and large mammals records.	Badlands viewpoints: e.g Marchal, Beas de Guadix. Paleontological Vertebrates deposits (Global Geosite)	International paleontological and geomorphological sites.
Lanzarote and Chinijo Islands	15 Million years of volcanic basaltic an hydromagmatic eruptions.	Basaltic volcanic materials, underwater and coastal formations.	Calderas Quemadas and Mar de Lavas de Timanfaya	International significant last eruptions.
Cabo de Gata-Nijar	Intermediate Volcanic eruptions during the Betic Cordillera uplift (16 to 8 Ma)	Neogene fossil Volcanic complex. Marine reposit remains.	Dome at Punta Baja, Volcán de los Frailes. Coladas Submarinas al sureste de Vera.	Most extensive and complex calco-alcaline fossil volcanism of Iberia
Catalonia Central	Endorheic sea extinction and evaporites precipitation in El Ebro Basin.	Ancient delta systems and evaporite deposits	Montserrat and Cardona Mountains.	Unique evidence of a Basin's final stage as a marine environment.
Sobrarbe- Pyrenees	South-Pyrenean Mountain Chain basin formation during the Alpine Orogeny and Quaternary glaciation	Pyrenees structures, sedimentary sequences and active glaciers	Alpine range structure and Monte Perdido, Marboré and Llardana glaciers	Clear evidences of the Pyrenean chain formation

UGGp	Geological events	Features	Representative Site(s)	Geological values
Origens	The dinosaurs in the Upper Cretaceous and the Alpine Orogeny effects.	Fossil plant remains, bones, tracks, and eggs (The Tremp Formation). And clear four thrust sheets of the pyrenean chain.	Isona i Conca Dellà fossil records (Conca Dellà museum). And Comiols viewpoint (Pyrenees structures observation). Collegats unconformities.	Unique evidence from the final dinosaurs of Europe and ECORS section though the Pyrenees.
Basque Coast	The Fifth Global Extinction.	K-Pg Boundary in a continuous K-Pg marine sequences.	K-Pg Boundary in the cove of Algorri, near Itzurun beach.	International significance of key geological boundaries and global extinction evidence
Sierras Subbéticas	The Subbeticas System formation and its marine deposits development.	Jurassic to Lower Cretaceous 'Ammonitico Rosso' facies	Four sections included in the Global Geosites	One of the most studied as well as most unusual facies developed in the Tethys Ocean (Serna-Barquero et al, 2021).
Las Loras	Alpine Orogeny Folding and Fractures and the relief modelling	Hanging synclines in the landscape and lacustrine environments	Ubierna Fault, Folded bands, Hanging Syclines (e.g Monte Bernorio, Las Tuerces, Mesa Peña, Peña Amaya, etc.)	Didactic value of the relief modelling of the folded Mesozoic sequences.
Maestrazgo	Existence of dinosaurs, pterosaurs, crocodiles, sharks, mammals, etc, during de Upper Jurassic - Cretaceous.	Particular abundance of fosils from Tithonian to Barremian, spanning a number of geological formations	Vallipón (Castellote), Camino de la Algecira (Ladruñán, Castellote), and Miravete de la Sierra. Órganos de Montoro	The most relevant areas in Spain for dinosaur research (Alcalá and Royo-Torres, 2021)
Molina Alto Tajo	Germanic facies: accumulation of sand and gravel particles in the channels of ancient rivers	Bundanstein series.	Barranco de la Hoz stratotype or Sierra de Candeleros, in Guadalajara province	Exceptionally well represented in the stratigraphic series with very well-preserved sedimentary structures
Sierra Norte de Sevilla	Burried wet-environment forest by volcanic eruptions during the Permian.	Carboniferous to Permian silicified tree trunk (Araucaria) and flora.	Viar Basin, Alanís-San Nicolás del Puerto. (Can be seen at Visitors Center at Cortijo El Berrocal in Almadén de la Plata)	Upper Carboniferous to Lower Permian age confirmation due the flora species.
Courel Mountains	Variscan Orogeny tectonic effects.	50-km recumbent fold.	The Courel Syncline	Observation of the Variscan Orogeny structural evidence in a national scale
Cabo Ortegal	Emerged rocks due to the collision between Laurussia and Gondwana.	Peridotites, serpentinites, metavolcanics, and metasediments. Additionally, there are amphibolites, granulites,and exceptional eclogite outcrops.	Largest continuous eclogite outcrop known to date, Punta dos Aguillóns. Praia da Concha ophiolitic sequences.	The most complete allochthonous terrains of the Variscan Orogeny in Europe
Villuercas Ibores Jara	Ediacaran fauna and the 'Apalachian Relief'	Exceptional ichnofossils such as Cruziana and Daedalus. Cloudinia fossil records	"Cerro de La Mina". Cloudina's site on the Ibor River, "Risco Carbonero" viewpoint, among others.	Tangible traces of ancient life evidences (Precambrian).

4.3.2. The geological evolution framework

After selecting the events and the elements that constitutes the framework of the general geological evolution, a written geological evolution is summarised by the identified geological episodes. The following description includes the general geological setting of each geopark, the selected geopark(s) that represents that episode, the geological events and their evidences, the representative geological sites and their scientific value. Paleo-geographical and paleo-environmental interpretations are also included to contextualise the information. Moreover, this geological evolution description is not exhaustive and it might filter or narrow down geological information. The framework acts as a guiding principle and organisational structure for presenting the geological information in a cohesive and chronological manner. It also acts as a guiding structure for the future communication product proposals. Detailed descriptions and bibliography is included in the previous stages of this work. The geological evolution framework is described and organised chronologically as follows (Figure 10):

4.3.2.1.The oldest rocks and the origins of life (Precambrian-Silurian)

The western sector of the Iberian Peninsula, from the Galicia-Tras-os-Montes region to Sierra Morena, is mainly composed of Palaeozoic and Precambrian Formations intruded by plutonic rocks and is known as the Iberian or Hesperian Massif. Here we find the representative geoparks of the oldest rocks and ancient life evidences.

At the end of the Precambrian, in the Ediacarian, the entire continental crust formed a gigantic continent called Rodinia, surrounded by the Panthalassa, a single marine body of water, and during this period single-celled organisms appear, the first living beings on Earth. After Rodinia, the lands that emerged during the Ediacaran were centred on a single continent called Pannotia, around the southern hemisphere. The appearance of the first living animals with hard parts played an important role in their diversification. Villuercas Ibores-Jara is the only UGGp with Cloudina, a millimetric tubular fossil from this Ediacaran to Cambrian transition. The remarkable sites are "Cerro de La Mina", Cloudina's site on the Ibor River, "Risco Carbonero" viewpoint, among others.

The Cambrian begins with the so-called Cambrian Explosion, an increasingly warmer climate which favoured a rapid diversification of complex multicellular organisms. At the same time, the continent Pannotia starts the fragmentation into Gondwana, Laurentian, Siberia and Baltic continents. The Sierra Norte de Sevilla UGGp area was once a coastal zone with oxygen-rich marine environments and Calcium algae mud and archaeocyathid colonies were formed, creating reefs and massive limestone layers. Emerging from the sea, paleokarsts were also developed under a tropical climate.

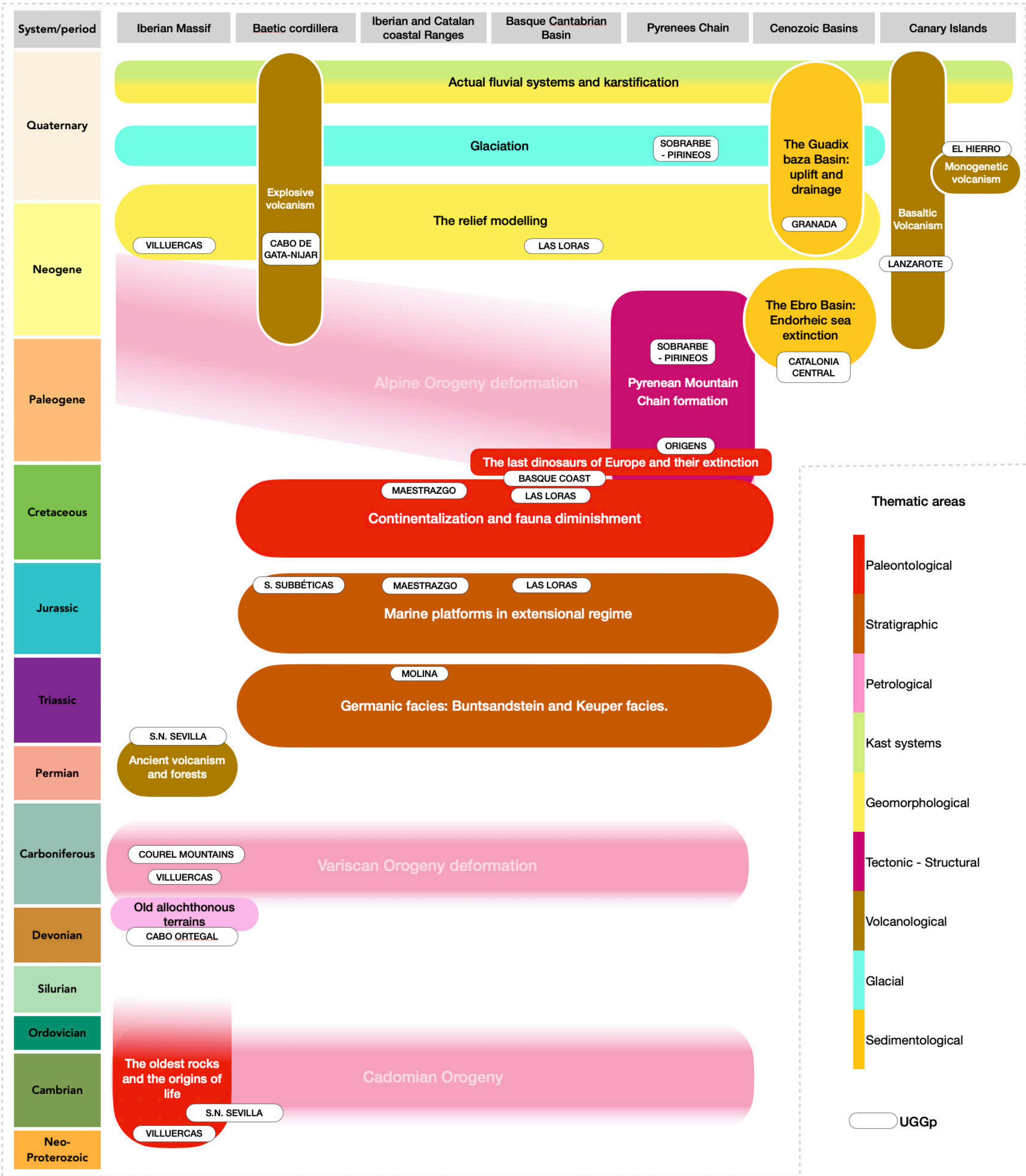

Figure 10: The final diagram presenting the Geological Evolution Framework, with the selected episodes and geoparks in a geochronological time scale. Also the main Thematic Areas are shown, which indicate the main interest(s) of the episodes. On the top of the diagram the column organises the episodes according to the main geological units of Spain, described in the text. The Cadomian, Variscan and Alpine Orogeny are shown in the background with less opacity, but they belong to the Thematic Area ' Tectonic-Structual'.

Sediment was accumulated in the deeper marine areas, and nowadays the Capas de Benalija slates hold fossilized trilobites in this geopark.

During the Ordovician, massive marine platforms began to develop around Gondwana. During this initial stage, the entire Iberian Peninsula was located very close to the South Pole, where significant glaciomarine sedimentation occurred, greatly enhanced by a strong glaciation at the end of the

Ordovician period. The tangible traces of this ancient life marks clear episodes in the evolutionary evolution, such as the Ordovician Radiation. Some of these evidences can be found in the Armorican Quartzite unit which features thick quartzite layers with interbedded sandstones and shales, where Villuercas UGGp is the best representative, followed by Molina Alto-Tajo UGGp. During this time, sedimentary layers with graptolites were deposited in a shallow marine basin, which is represented by dark and greenish grey slates and quartzites of the Valle Unit in Sierra Norte de Sevilla UGGp and they are also present in Origens UGGp rocks, outcropping in the axial zone of the Pyrenees. In a different geological context, acidic and intermediate submarine volcanism of Ordovician age were forming during this time, remarkable recorded in Cabo Ortegal UGGp area, with good examples of ignimbrites, cinerites and pyroclasts.

At the beginning of the Silurian period, Gondwana's continent began to drift towards the North and carbonated sedimentation occurred in subtropical conditions. In Molina Alto-Tajo UGGp, the Lower Silurian formations in this geopark are among the most significant, serving as a worldwide biostratigraphic reference. The sites to consider are the Graptolites outcrop in Checa and the Dropstone and Lower Silurian section of Checa. In Sierra Norte de Sevilla UGGp there are more Silurian evidences, such as slates with graptolites and intercalated limestones outcrop in the syncline of the Valle Unit and the Cerrón del Hornillo. These outcrops are evidence of a marine transgression in this area.

During the Devonian period, significant tectonic activity occurred alongside a widespread expansion of life on land. During this time, Laurasia, which resulted from the merging of Euramerica and Siberia, drew closer to Gondwana. In Sierra Norte de Sevilla UGGp region, these materials are primarily concentrated in the Southern Portuguese Zone, located to the south of Almadén de la Plata. Notably, also limestone conglomerates attributed to the Devonian period can be found here, reflecting the tectonic movements of that era. In the Origens UGGp region, red and grey limestones from Devonian formations are exposed. These limestones, referred to as Compte facies and Manyanet facies, were deposited as carbonate muds on the pelagic seabed of the Rheic Ocean. Moreover, fossils of ancient organisms such as conodonts, cuttlefish, and corals have been discovered in these formations. Finally, the Lochkovian conodont sequence found in the Gerri de la Sal sections, represents the Lower Devonian and stands out as one of the most abundant and significant globally.

4.3.2.2.The Cadomian Orogeny (Cambrian - Silurian)

During the Cadomian Orogeny, lithospheric convergence along western Gondwana resulted in the formation of an orogenic belt flanked by adjacent fore- and back- arc basins. There are few outcrops of this period in Villuercas Ibores-Jara and Sierra Norte de Sevilla UGGps and the rocks are intensely metamorphized. The uplift and erosion during the next geological periods led to a significant gap in the preserved younger sedimentary record, which left a few remains from the Cambrian within the geoparks territories. In the aforementioned back-arc basin, a thick succession of deep-water shale and sandstone deposits were formed, which now constitutes the basement of Villuercas Ibores - Jara UGGp. Here, the subtle dips and depressions of the anticlines preserve the oldest rock formations of the Iberian Peninsula - the Ediacaran greywackes, shale, and carbonates. Moreover, the folding and fracturing patterns observed are remnants of the intense tectonic activity that occurred during this orogeny. Progressive collision of the arc with the margin of Gondwana, from 570 to 535 Ma, led to closure of the back-arc basin and deposition of more shallow water sediments deposits, including late Ediacaran carbonates of the Ibor Group, from Villuercas Ibores Jara UGGp.

Evidence in the south, in Sierra Norte de Sevilla UGGp, the Precambrian rocks have no fossil records, but there are schists, gneisses, marbles, and abundant volcanic material that outcrop in the north-eastern sector of the area, in the Loma del Aire Units, and in the north-western sector, in the core of the Olivenza-Monesterio Anticlinorium, to the west of the Embalse El Pintado.

4.3.2.3.Old allochthonous terrains (Devonian to Carboniferous)

The Hesperian Massif was a mountain range formed during the Variscan Orogeny (Upper Devonian and lower Carboniferous). Slowly, Gondwana's continent collided with the macro-continent Laurasia, forming Pangea.

During the Devonian to lower Carbonifeours, subducted fragments of continental and oceanic lithosphere were subsequently obducted and imbricated during the collision between Laurasia and Gondwana, approximately 350 Ma ago. This remarkable event is registered in the northwestern part of the Iberian Peninsula, in Cabo Ortegal UGGp with the most complete allochthonous terrains of the Variscan Orogeny in Europe. Here, we find the largest continuous eclogite outcrop known to date, Punta dos Aguillóns, including an exceptional panoramic view, and Miradouro da Miranda, an outcrop of eclogites with impressive views over the Ortigueira estuary. From the landscape, the site Cantís de Vixía Herbeira is an extensive set of tectonic cliffs, in some cases with slopes of more than 600 metres, considered the highest in continental Europe developed on mantle rocks.

4.3.2.4.The Variscan orogeny (Devonian to Carboniferous)

Moving to the Pyrenees, Sobrarbe Pyrenees UGGp and Origens UGGp territories includes part of the Variscan basement in the Axial Zone of the pyrenees, although portions of the Variscan basement are incorporated in some thrust sheets. The Carboniferous conglomerates and slates that outcrop inside Origens UGGp record the beginning of the collision between the plates and the volcanic deposits of the

Erill Castell Formation (tuffs containing bombs, covered by massive basaltic-andesite layers) are key evidence of this period. A calmer period following this volcanic activity led to the accumulation of fluvial sediments during the Upper Carboniferous, which include coal deposits.

By the end of the Carboniferous, the Variscan mountain range had reached its maximum height. Nowadays, its structural evidence is well-represented in the basement of some geopark areas. Remarkably, the Courel Mountains UGGp exhibit an unique 50-km recumbent fold, the Courel Syncline, which in turn it's a key site to observe the structural evidence in a national scale. We can also observe narrow eroded Variscan synclines in Villuercas Ibores Jara UGGp, exhibiting Lower Palaeozoic siliciclastic rocks from the Armorican Quartzite.

4.3.2.5.Ancient volcanism and forests (Permian - Triassic)

During this time the supercontinent Pangea migrated towards the North, leaving the area located in the equatorial line. The climate was even warmer and more arid than previous ages. This caused sedimentation in global regressions, ending with evaporitic deposits in many epicontinental areas.

From the upper Carboniferous to lower Permian the Viar Basin was formed, where there once existed a large forested area with Araucaria trees, gigantic trees reaching over 30 meters in height, which were buried by a series of volcanic eruptions. This event can be seen in Sierra Norte de Sevilla UGGp, where a spectacular fossilized tree trunk and around 40 species of flora have been found. Nearly all plant remains were discovered in deposits from a wet environment, generally alluvial or lacustrine facies, with various contributions of volcanic origin, such as pyroclastic flow deposits and breccias, which favored the process of silicification. Moreover, a few outcrops in Molina-Alto Tajo UGGp units are also characterised by well-preserved silicified tree trunks, buried by the Permian volcanic rocks.

Synchronous to this volcanic activity, on the aforementioned Variscan basement, small intramountain continental basins would open, which were filled with fluvial and lacustrine sediments derived from the erosion of the surrounding reliefs until the end of the Permian and the beginning of the Triassic.

4.3.2.6.Germanic facies: Bundanstein and Keuper facies (Triassic)

Extensional movements of Pangea fragmentation and the westward movement of the Tethys Sea begun during this time. This rifting during Mesozoic comprises several pulses of stretching and extension of the Iberian plate crust and subsequent thinning.

From the erosion of the old mountains formed during the Variscan orogeny, sedimentary sequences were formed in the Lower Triassic by the accumulation of sand and gravel particles in the channels of ancient rivers.

This process is exceptionally well represented in the stratigraphic series with well-preserved sedimentary structures. Representative records can be found in the remarkable Permian to Lower Triassic Buntsandstein series in Molina Alto-Tajo UGGp, located in Barranco de la Hoz stratotype or Sierra de Candeleros, in Guadalajara province.

During the Middle Triassic the Tethys kept moving westward and during the late Middle Triassic, Iberian Massif reliefs are softened following the continuous supply sediment into rivers draining into the Tethys. Later on, during the Upper Triassic, the Pangea break up rifting phase is evidenced in the Pyrenees outcroping materials by the emission of basic volcanic rocks and multicolored clays and evaporites of the Keuper facies.

These rocks of the Keuper facies were uplifted and exposed due the following tectonic events and they can be found in all the geoparks with sedimentary Mesozoic sequences. For instance:

- In Origens UGGp we find these subvolcanic rocks in Gerri de la Sal and Senterada outcrops. Moreover, during this arid climate, evaporitic deposits were formed and nowadays they have historical significance, as they are the remains of natural salt evaporators in Gerri de la Sal.
- The oldest rocks in Las Loras UGGp are red clay with Keuper gypsum. They are predominantly shaly-clay materials with gypsum levels and they were formed in supratidal environments in arid coastlines- sabkhas, under arid climate conditions. This Keuper evaporite outcrops along the path of Ubierna Fault .
- In Maestrazgo UGGp rocks belonging to the Muschelkalk facies (mainly limestone) and Keuper facies (clays, marls, and gypsum of reddish colors) were formed by coastal lagoons with an arid climate that facilitated the evaporation of water and the precipitation and accumulation of saline and evaporitic deposits. These rocks are in Ejulve, La Zoma, Miravete de la Sierra, and Aliaga.
- In Granada UGGp red clays and versicoloured gypsums from this event occur in the Castril River valley or the Fardes River valley. Moreover, the pillow lavas in the Alamedilla sector are a remnant and example of the fracturing of the Earth's crust during this time.

4.3.2.7.Marine platforms in extensional regime (Jurassic)

During the Early Jurassic, Iberia occupied a latitude of approximately 35°N and experienced a warmer and drier climate compared to the present day. During this period of extensional regime, tropical carbonate seas were established. The marine environments of the Jurassic era were characterized by a series of transgressive-regressive pulses, as exemplified in the geoparks of the Iberian Range. Within the Maestrazgo UGGp area, limestone and marls predominate in the outcrops, with less pronounced relief features.

In the southern Iberian Platform, In the actual Betic Cordillera, a marine plain initially subsided, enabling the Tethys Sea to inundate the area that presently constitutes the Sierras Subbéticas UGGp. This resulted in shallow marine carbonate sedimentation and the formation of limestone outcrops. The Gavilán Formation preserves this environment, housing a diverse range of marine organisms. In this area, as the platform underwent fragmentation, the Betic Cordillera divided into two primary domains: the Prebetic and Subbetic. Terrigenous sediments were sourced from the continent in the Prebetic Domain, while the Subbetic Domain saw the deposition of a combination of clayey sediments and carbonates. Subsidence led to the deepening of the sea, facilitating the flourishing of ammonites and belemnites, which were documented in the marls of the Zegrí Formation. Subsequently, during the Middle Jurassic, oolites and coral colonies emerged on sinking and tilting seafloors. However, the Late Jurassic brought about sea level changes, resulting in stratigraphic discontinuities and the notable formation of the 'Ammonitico Rosso' facies. These facies are distinguished by their red and orange nodular limestones containing an abundance of ammonites from that period, serving as the primary feature of the geopark. This transitional boundary is well-preserved in the Puerto Escaño series near Carcabuey.

In the Pyrenean Range, throughout the Jurassic Period, carbonate muds were deposited on the shallow water platforms of the Tethys Ocean. These platforms developed along the northern Iberian Plate within an extensional rifting regime, connecting the Atlantic with the Alpine Tethys realms. Here, a thick series of limestones, dolomites, and marls record these events and are impressively exposed in the South Central Pyrenean Unit.

During this extensional regime, the rocks found in Las Loras UGGp were formed from the development of marine lake systems on a continental shelf. For instance, materials from the Aguilar Formation, spanning the Upper Jurassic to the Lower Cretaceous boundary, reflect the influence of both marine and alluvial systems at the margins. The Aguilar Formation contains significant fossil records of macroflora, providing valuable insights into the phytogeography and paleoclimate of southwestern Europe. Inland lakes formed in an offshore platform environment, leaving behind lacustrine carbonate sediments.

4.3.2.8. Continentalization and fauna diminishment (Cretaceous)

The present-day Pyrenean mountains emerged as a result of the inversion of the jurassic rift system and the related passive northern Iberian margin. The Cretaceous Period was a time of significant geological change in the Iberian Peninsula. The opening of the Bay of Biscay and the Alpine orogeny had a major impact on the landscape and ecosystems of the region. The Bay of Biscay began to open, causing the Iberian Peninsula to rotate counterclockwise and the Pyrenees mountains to form.

The transitional period between the Jurassic and Cretaceous featured sandstone, clays, and limestone deposits, located now in Maestrazgo UGGp, representing coastal environments with tidal zones and brackish lagoons. Notably, the Villar del Arzobispo Formation within this context boasts a substantial presence of dinosaur bones and footprints. This territory underwent repeated cycles of transgression and regression during all these events, developing a sedimentation basin. During this time, various fluvio-marine environments were established after the sea gradually withdrew since the end of the Jurassic. These conditions allowed the existence of dinosaurs, pterosaurs, crocodiles, sharks, mammals, etc. Some prominent paleontological sites of Maestrazgo UGGp are located in Vallipón (Castellote), Camino de la Algecira (Ladruñán, Castellote), and Miravete de la Sierra. All these paleontological evidences are well disseminated in the museums of this geopark.

In the Pyrenees area, the Lower Cretaceous marine limestones onset the early stages of the ocean rifting phase. This stage is impressively represented in Origens UGGp by the outcrops of the Montsec range, notably the “La Pedrera de Meià” and “La Cabroa” quarries, catalogued as Konservat-Lagerstätten are showcasing exceptional preservation and providing valuable insights into this past. This actual Montsec Thrust Sheet comprises marine limestones, and records the ocean growth, including also the most complete rudist record in the Pyrenees. These materials represent the passive margin phase in the ocean's evolution, reflecting the activity of the Mid-Atlantic Ridge.

The opening of the Gulf of Bizkaia started in the Upper Jurassic, from a triple junction at the Atlantic Ridge. This opening was creating an extensional setting in the basin and a seafloor composed of large uplifted blocks and sunken basins in the north. The coastal area of Basque Coast was submerged under a tropical sea that separated the Iberian Peninsula from the European continent. From this moment onwards, these materials were deposited and now it outcrops in this coast as a n outstanding continuous stratigraphic sequence from this time until the Paleogene.

In Las Loras UGGp area, Lower Cretaceous sedimentary rocks were deposited in environments resembling the Weald facies, including alluvial and marsh settings. The Cretaceous rocks sequences are the most prominent outcropping in this territory.

In the Sierras Subbéticas UGGp area, the aforementioned plain began to fracture, forming horsts and grabens. The exposed carbonate rocks, marls, and marly limestone we see today are the result of these tectonic processes. This new subsidence deepened the Subbetic Sea, which was filled with abundant clay from the continent and carbonated mud from the ocean. The irregularities on the seafloor began to fill and level out. Furthermore, Milankovitch cycles caused the formation of rhythmites of marly limestone and marls, resulting in the Carretero Formation.

Afterwards, is worth mentioning the Upper Cretaceous in Maestrazgo UGGp, that also records marine platform environments that will stabilize for several million years. At this time, the sedimentation of carbonate rocks occurs, such as those exposed in the stratotypes of Órganos de Montoro and Barranco de los Degollados.

The end of these environments is characterized by a progressive withdrawal of the sea line due the continental collision, and the territories started emerging.

4.3.2.9.The last dinosaurs of europe and their extinction (Upper Cretaceous)

Continental fossils from the last five million years of the Cretaceous period have been remarkably preserved in the The Tremp Formation in Origens UGGp. It contains a treasure trove of fossil plant remains, along with bones, tracks, and eggs from the final dinosaurs, as well as numerous fossils of crocodiles, turtles, amphibians, and fish. These findings vividly demonstrate the vitality of these Mesozoic groups just before the Cretaceous - Paleogene boundary. Some of the sites to observe these evidences are in 'Isona i Conca Dellà fossil records' (exhibited in Conca Dellà museum).

In contrast, the evidence of the fifth extinction event linked to the demise of the dinosaurs it is located in the K/Pg limit boundary layers, in between the well-known continuous layers in Basque Coast UGGp. The K-Pg Boundary site is located in the cove of Algorri, near Itzurun beach.

4.3.2.10.The Pyrenean Mountain Chain formation (Cretaceous - Miocene)

The Pyrenees recorded the collision and closure to the Mid-Atlantic Ridge, and the basin became unstable. During the initial Alpine Orogeny, there were some significant tectonic movements that led to the first continental reliefs in the eastern Pyrenees. These new eastern reliefs were getting closer and bringing a large amount of sediment, filling the basin floor with extensive turbidites. This collision and the filling of turbidites is also well recorded in the marly and calcareous bottom filling of the basin in the Basque Coast UGGp.

The collision took place from late Cretaceous to Miocene and the fold and thrust belts developed both thick- and thin-tectonic style southwards in this segment of the orogenic system, uplifting the materials. The Alpine chain formed as a result of roughly north–south crustal contraction.

At lithospheric scale, there are two main features including a subducted Iberian lower crust beneath Eurasia, and a delaminated orogenic prism overlying the lower crust showing an asymmetric, fan - shaped body. Within the orogenic prism, south-vergent structures dominate in number and extension, and form the south-Pyrenean zone. Bedrock in this zone includes a Hercynian basement with granitoids and low-grade metamorphic rocks, a Mesozoic pre-orogenic sedimentary succession, a synorogenic assemblage of Upper Cretaceous to lower Miocene sedimentary rocks, and a post-tectonic sedimentary succession, which is developed mostly in the Ebro basin. The Pyrenean Chain formation concluded after with the closure of the Pyrenean arm of the Atlantic during the mid-Palaeogene.

As these new Pyrenean reliefs located to the east were getting closer and bringing a large amount of sediment, the basin floor was covered by extensive turbidites forming the sandy flysch of the Eocene that we see today in Basque Coast UGGp. During this compression, the Triassic rocks rose along active faults like the Berriatua fault and became part of higher Cretaceous rock layers in this geopark.

4.3.2.11.The Alpine orogeny deformation (Cretaceous - Miocene)

The 12 hanging synclines we see today in Las Loras UGGp were formed 65 million years ago by this compression with subsequent erosion by Quaternary fluvial incision. The result is a hanging folded relief that gives the distinctive morphology.

In the Maestrazgo UGGp the Alpine orogeny affected all rocks older than 55Ma, an event that caused the superimposed folding, inverse faulting, and uplift of the sedimented materials, tectonic structures visible for example at Estrecho de Molinos.

The vast synclinorium in Villuercas Ibores-Jara UGGp was eroded throughout the Mesozoic and Cenozoic and rejuvenated by fractures and uplift movements of large blocks during the Alpine orogeny, around 35 million years ago for this part of Iberia. The faults can be observed in various mountains of the geopark, in the Sierra de la Breña, in Deleitosa, in the Riscos de la Trucha in the Guadarranque Valley, or near Castañar de Ibor, beneath the "Cancho de las Narices."

4.3.2.12.The Ebro Basin: endorheic sea extinction (Oligocene - Miocene)

Due to the progression of the Pyrenean thrust and the formation of the Catalan Coastal Ranges, the Ebro Basin began to form around mid-Eocene (41 million years ago). This basin was an arm of the Atlantic Ocean that filled mainly with marine sediments, affected by transgression and regression phases and it had similar depth across its entire extent. While the basin was active, it accumulated material from the surrounding reliefs, forming a wide variety of sedimentary environments. Examples of this sedimentation are the coastal fans (delta fan) of Montserrat and Sant Llorenç del Munt in Catalonia

Central UGGp. These formations represent this ancient river delta systems and offer a geological window into past fluvial dynamics and sedimentary processes that have shaped this landscape.

In the Pyrenees area, the sea level rise at the beginning of the Eocene led to the re-establishment of a sea in the Tremp and Àger basins that opened towards the west. On top of these materials, river and delta systems developed, depositing gravels and conglomerates. During this time marine sedimentation of carbonate shallow and tropical waters predominated in Sobrarbe as well. Subsequently, during the most intense period of the Pyrenees uplift, the relief of the central Pyrenees was eroded during Eocene and Oligocene, and large alluvial systems were established at the foot of the mountain range, giving rise to the conglomerates found today in the Collegats, Pessonada, Gurp, and Comiols mountain ranges in Origens UGGp area. Simultaneously with this sedimentation, Aínsa-Jaca basin in Sobrarbe - Pyrenees UGGp was being filled with detrital sediments. The Aínsa-Jaca basin developed over the Cotiella thrust, and most of the sediments it received came from the east and southeast until the Pyrenean relief rose sufficiently to supply new sediments from the north and south. As the sea receded at the end of the Eocene, sedimentation was characterized by transitional environments (Sobrarbe Delta), eventually becoming continental.

At the end of the Eocene until the mid-Miocene (around 36-12Ma), the Ebro Basin became endorheic and started to fill only with continental sediments. During the final stages of sedimentation, a limited connection with the Atlantic Ocean triggered the precipitation of salts, including potassium-magnesium salt and gypsum. During this process, remarkable evaporitic deposits from the Catalan Potassic Basin are recorded. Subsequently, due to continued structural evolution and the westward retreat of the Eocene sea, these restricted marine environments were later replaced by alluvial environments, essentially characterized by reddish materials.

While sedimentation continued in the western part of the Ebro Basin (20 Ma ago), a new late Paleogene to Neogene extensional phase was affecting the Catalan Coastal Ranges. The Neogene extension created depressions or tectonic basins such as Vallès-Penedès, Camp de Tarragona or Empordà, w hich were filled with marine and continental sediments.

4.3.2.13.Basaltic volcanism in Lanzarote (Oligocene - present)

While El Ebro basin was becoming endorheic, the islands of Lanzarote and Chinijo Archipelago were forming. The islands were built almost entirely of basaltic materials during three volcanic stages: one submarine and two subaerial. The basement was constructed during the Oligocene and is made of submarine volcanic materials, plutonic rocks and sediment. Since the Miocene there were two stages of subaerial volcanic activity separated by an eruptive hiatus of at least 2.5 Ma when the ancient Mio-

Pliocene volcanic structures were continuously eroded to model their original morphologies, giving place to different sedimentary deposits, with an important presence of aeolian sands throughout the islands and beaches in the coastal areas. In more recent times, two historical eruptions have occurred in Lanzarote Island, in 1730–36 and in 1824, causing a great impact on the landscape and on the life of inhabitants. The most recent eruption on the island occurred in 1824, resulting in the formation of three new cones—Tao, Nuevo del Fuego, and Tinguatón—which emitted relatively smaller amounts of materials. Regarding the islets of the Chinijo Archipelago, their formation is attributed to hydromagmatic eruptions that occurred around 2.5 to 2 million years ago. Beyond the volcanic terrain, the geopark provides insights into sand dynamics, coastal and underwater formations, and evidence of climatic shifts spanning millions of years. Noteworthy sites are the Calderas Quemadas and Mar de Lavas de Timanfaya in Lanzarote.

4.3.2.14.Intermountain Guadix Baza Basin and its drainage (Miocene - Present)

The Betic Cordillera uplifting was late in relation with the Alpine orogeny deformation, and most of its materials were still submerged. During the tectonic process, the materials that make up the Internal Zone were displaced hundreds of kilometres to the west, becoming part of the Baetic Cordillera. In the movement, it pushed and deformed the materials of the External Baetic Zone. This 10 Ma event occurred during the Early and Middle Miocene. From then on, the new last processes to have affected the Betic Cordillera began, are characterised by a continuous kinematic situation up to the present, in which the Eurasian Plate and Africa started approaching rapidly. During the uplifting of the Betic Cordillera, there were moments when the sea extensively invaded depressed areas that are now emerged, such as the Guadalquivir Depression and other intramountain basins like Guadix - Baza, Tabernas, Sorbas, or Almería - Níjar.

Eight million years ago, the Betic Cordillera had already undergone significant uplift and the formation of prominent landforms. The basins were predominantly submerged under marine conditions, but the Neogene Guadix-Baza basin had emerged. Therefore, the actual mountain ranges areas of the Granada UGGp would have been part of a set of intermountain marine basins surrounded by large islands. The interconnection between the Guadalquivir basin and the Guadix-Baza basin via the North Betic Straits would also have enabled the marine connection between the Atlantic and the Mediterranean. The marine materials of this stage can be found in numerous outcrops within the area, such as in the La Peza, Negratín, some valleys in the north, the south of Caniles and in the most eastern part of the territory.

After this, the Betic Mountain Ranges continued to rise. A new stage in this range started between the end of the Miocene and the beginning of the Pliocene. During this collision and uplifting, the Sierras Subbéticas alongside the Thetys seabed sediments were also uplifted; The limestones with marine organisms underwent compression, resulting in folds and thrust faults. New reliefs began to take shape and emerge in the sea, to the south of Sierra Morena.

Gradually, the connection between the Atlantic and the Mediterranean narrowed until it closed completely around 5.6 million years ago. The Mediterranean became entirely isolated, dried up, and its level dropped by around 1500 meters compared to the Atlantic. This disconnection due to regional tectonic uplifting resulted in one of the greatest average altitudes in the entire Iberian Peninsula. Tortonian marine sediments are exhibited from at an altitude above 1000 m near the area and continental sediments are also exhibited in Cerro Molicias.

Around 5 million years ago, the entire region of Sierras Subbéticas experienced its greatest uplift and definitive emergence of the land. Approximately 600,000 years later, the connection between the two bodies of water was reestablished through the opening of the Strait of Gibraltar.

Once the endorheic Guadix-Baza continental basin was formed, during the Pliocene to Pleistocene, the Baza fault movements enabled the development of a large lake in the central-eastern half, generating important accumulations of carbonate and evaporitic sediments in this sector, while in the western half, mainly fluvial environments and detrital sedimentation were developed. Important glacis surface formed from the endorheic basin's edges and it extended towards the center.

During approximately 4.5 million years, a diverse large mammalian fauna thrived and coexisted on this glacis surface. The glacis consists of a combination of materials from various ages, thus there is no consistent sedimentation level within the basin. Different areas of the basin exhibit these materials in the upper part of the endorheic stratigraphic sequence. This region remained active until the basin transitioned to an exorheic system. Thus, the glacis surface represents the last remnants of the endorheic stage of the basin's development.

The transition to an exorheic system began approximately 0.5 Ma (Middle Pleistocene), when a tributary of the Guadalquivir River captured the endorheic basin, giving it an outlet to the Atlantic. After this, this tributary would become the present Guadiana Menor, which along with the Fardes River drains most of the territory towards the Guadalquivir River. After the last event, erosion became the dominant force, leading to the dismantling of the glacis and the ongoing formation of badlands. This process also resulted in the creation of valleys and fluvial terraces that define the landscape. Notably, the geopark has impressive badlands in almost a quarter of the area (e.g Badlands of Castilléjar and Galera), and it houses an extensive collection of paleontological deposits and Quaternary vertebrates. Active faults in the Betic Range offer a platform to observe recent geological deformations, having played a role in ancient earthquakes evidenced in the seismites.

4.3.2.15.Explosive volcanism in Cabo de Gata (Miocene - present)

During the Miocene epoch, volcanic rocks began to form in Cabo de Gata UGGp area. The geological history of the geopark can be divided into three main stages. The first stage occurred between 22 to 11 million years ago, during which the collision of African and Eurasian plates resulted in crustal extension, forming a marine basin. The second stage spanned from 11 to 8 million years ago and marked the peak of volcanic activity. During this period, many volcanic edifices, lava flows, and pyroclastic deposits were formed. The volcanic activity was mainly of effusive and explosive nature, leading to the formation of stratovolcanoes, calderas and maar-type structures. The third stage that started around 8 million years ago and continues to the present day involves sporadic volcanic activity and the subsequent erosion of volcanic structures. The ongoing erosion has shaped the landscape of the geopark, exposing the volcanic deposits and rocks.

4.3.2.16.The relief modelling (Pliocene)

The Strait of Gibraltar opened around 5.33 Ma, flooding the Mediterranean Sea along with some nearby basins. By the end of the Miocene, the Ebro Basin started to drain, transforming from an accumulation basin into an erosion zone to the Mediterranean Sea, while the northern slopes of the Pyrenees transported sediments to the Atlantic Ocean. This ongoing erosion process has shaped the current landscape in El Ebro basin. The abrupt and widespread fall in the sea level, during the Messinian, was also influential in the marine disconnection of Guadix-Baza basin. This process probably did not occur simultaneously all over the basin, but in a relatively short period.

This erosion began to expose the conglomerate massifs in the south, such as Montserrat and Sant Llorenç del Munt. These erosional processes also initiated extensive karstification in the entire peninsula, both internally and externally, resulting in the formation of canyons, rock needles, and other remarkable landforms in certain areas. Since the Oligocene, erosive processes have dominated in the Pyrenean Chain, leaving conglomerate deposits.

While these Cenozoic basins were being developed, the current shaping of the river network acting upon the intensely folded and fractured territory of Villuercas has formed the landscape we observe, with its characteristic geomorphology known as the "Appalachian relief". At its highest elevations, one can observe narrow Variscan synclines, a residual of the Appalachian Relief, exhibiting Lower Palaeozoic siliciclastic rocks. The highest point of the relief is marked by the Armorican Quartzite.

Moreover, traces of the Alpine Orogeny, can be identified in the central Villuercas horst, which is bordered by two grabens, filled with Neogene fluvial braided marginal sediments. In more recent geological times, the Pleistocene "Rañas" include broad, clast-supported fluvial sediments that sculpt a surprisingly flat, horizontal landscape. This noteworthy change in the landscape signals the transition from internal to external drainage of the main rivers as well.

4.3.2.17. Monogenetic volcanism in El Hierro island (Pleistocene)

El Hierro UGGp volcano emerged above the sea level about 1.2 Ma as the last volcanic island in the region. It has over 500 open craters and another 300 covered by more recent lava flows. The island's construction was rapid, leading to the creation of highly unstable reliefs over short periods, causing several giant landslides. Some of these landslides have morphological expressions in the form of arch-shaped megastructures. The most recent activity occurred on 10 October 2011, with an underwater eruption at a depth of 300 meters, approximately 1.5 kilometers off the southern coast.

4.3.2.18. Glaciations (Pleistocene)

Since the Pleistocene, glacial-interglacial climate dynamics caused sea-level fluctuations, affecting the location of the coastline and sedimentation/incision relations in river valleys. The Last Glacial Cycle began about 115,000 years ago and ended about 13,000 years ago. During this period, the valleys in Iberia were intermittently occupied by small mountain glaciers. Remarkably, the glaciers of Monte Perdido, Marboré and Llardana are still active. Erosive and depositional morphologies of all phases from the Pleistocene glaciers to the Little Ice Age are clearly visible in this area. Additionally, there is also evidence of a periglacial period in Maestrazgo (e.g., protalus rampart Muela Mujer, solifluction bench lobes of Cuarto Pelado).

4.3.2.19. The actual fluvial system and karsts (Quaternary)

The actual relief is shaped in Iberia, the river network is installed, and the sedimentation of poorly consolidated gravels and silts occurs at the bottom and margins of the watercourses. Endokarsts and exokarsts are especially abundant in all geoparks, with high scientific and educational value. Finally, some recent processes complete the wide range of morphologies and active processes that can be observed, such as landslides, geological risks, environmental changes or soil development. The geomorphological features of Las Loras UGGp were eroded by the Quaternary fluvial incision. The result is a hanging folded relief that gives the distinctive morphology we see today.

5. Guidelines and future outcomes

UNESCO Global Geoparks represent the integration of geological, biological, and anthropogenic factors, as well as tangible and intangible values. This integration is essential for interpretation, communication, education, and enhancement practices that aim to strengthen the sense of place in local communities and guide these areas towards sustainable economic growth. This is one of the main reasons why geoscience communication is a key aspect that every geopark tries to develop.

Innovative tools are being developed to strengthen the potential of UGGs as repositories of the Earth's evolution and its geoheritage. For example, the use of technology (Hincapie, 2023), storytelling (Phillip, 2012), immersive tourism experiences, and interactive maps (e.g., Antoniou et al., 2023) etc. are becoming more engaging tools and channels than formal scientific communication for non-expert audiences (Green, 2006; Dahlstrom, 2014; Migon & Pijet-Mignon, 2017).

5.1. Guidelines to communicate the geological evolution

We propose an adaptable and practical method, a few principles and product proposals as part of the outcomes of this work, focused on the use of geological evolution framework to develop future initiatives regarding the promotion and dissemination of the Spanish geological evolution, represented by its geoparks, which are active territories that can develop common initiatives and products in this regard (Figure 11).

Guidelines to communicate the geological evolution of a country, from the UGGps.

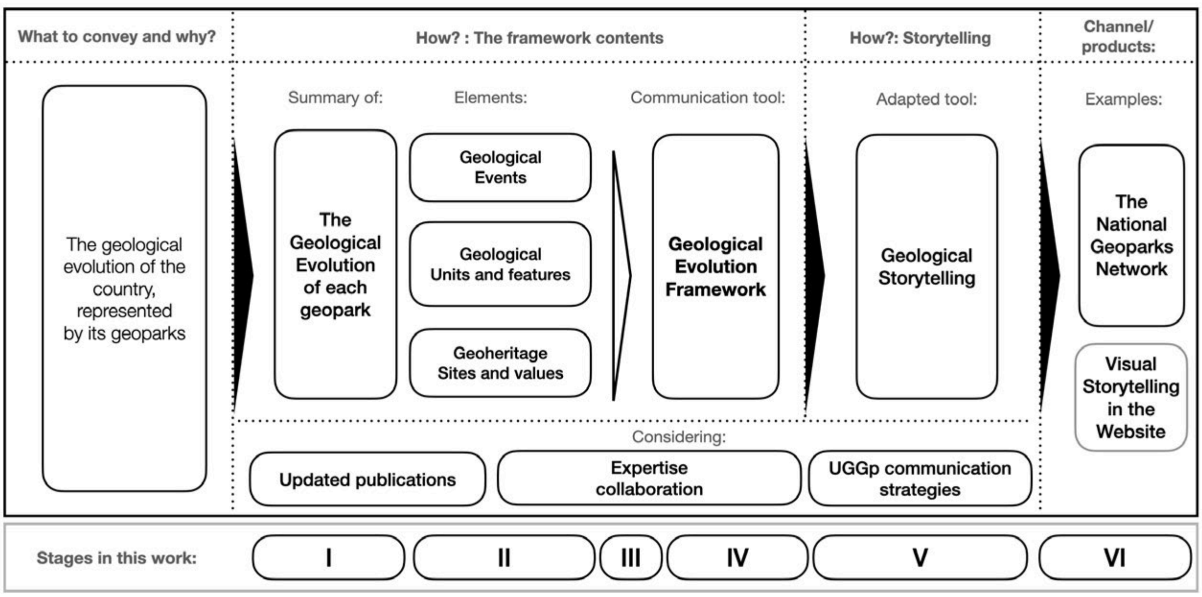

Figure 11: General guidelines to construct a geological evolution framework and storytelling of a country, represented by its UNESCO Global Geoparks. To be communicated by the national network of the country.

The stages followed are shown in Figure 11 and summarised in the Table 10 as a guideline.

Table 7: Summary of the guidelines. Method to construct and communicate the geological evolution of a country, represented by its UNESCO Global Geoparks.

I	**The Geopark's Geological Evolution in the national context.**
	National Geological Setting or General Geological Framework.
	Geological Evolution description
II	**Representative elements regarding the national geological evolution**
	Identification of the geopark's main event (s) in the national geological evolution.
	Selected elements of geoheritage
	Secondary elements of geoheritage
III	**UNESCO Global Geoparks communication strategy**
	Considerations regarding the communication of the geological evolution
	Good practices from the geoparks
	Collaboration with experts or management body
IV	**Geological Framework elements**
	Episodes and its geoparks
	Selected geoheritage of each geopark
	Secondary features of each geopark
V	**Adapted Storytelling**
	Narrowing down the message
	Defining the audience and contents
	Presentation, dissemination and channels
VI	**Products and channels**
	e.g. Illustrated geological storytelling in the website

5.1.1. What to convey and why?

First, in any initiative in this regard, there are key questions to consider when developing this model. The first one was “What to convey and why?”, which is relevant when sufficient geoparks in the country represent the main geological units and therefore an almost complete geological evolution can be disseminated (Figure 11).

5.1.2. How?: The framework contents

The second question is “How?”, and the main outcome from this were constricted to a method of 3 tasks (Figure 11):

1) First, each geopark have or should have an explicit and clear geological evolution communication strategy. Usually, they develop communication of the tangible geoheritage and geological sites within the territory, but when it comes to create an identity of the territory outside its borders it is important to compare and differentiate the identity of each geopark in the national network and what geoheritage they host nationwide regarding the geological evolution.

2) The geological and geoheritage elements should be clearly stated to be representative of the geological evolution nationwide. Even though many sites can be selected for this endeavour, we propose that national or globally relevant sites with high scientific and didactic values should be selected. This way the network can promote the geoparks not only as tourist destinations but also as repositories of interconnected relevant sites of the history of Earth.

3) Creation of an official general framework as a communication tool. The present work was developed by an updated bibliography review and fieldwork. Nevertheless, this task can be achieved by in the national network of the country, considering expertise collaboration. This stage can be aligned to the communication strategy efforts of each geopark or it can be developed only by considering the geology and geological heritage. After reviewing the publications of all the geoparks, some of them include different descriptions (e.g. global events, geological settings, rock formations, etc.). From this review, we identified the minimum contents that should be included to describe a useful general framework. These are summarised in the following table (Table 7):

Table 8: Items to consider for the description of the geological evolution framework.

Geological Evolution, contents:
General geological Setting of the geopark(s)
Main global and national geological events and what geopark(s) represent that event.
Geological evidences in the UNESCO Global Geoparks
Selected geoheritage and sites in UNESCO Global Geoparks with national and global significance
Relevance/values of the selected sites
Palaeogeographical/Palaeoenvironmental interpretations

5.1.3. How?: The Storytelling

As part of the "How?", the method, we propose here the creation of a storytelling using the framework, adapted for the respective audience and possibly aligned with the actual communication strategies of the network, their materials and the initiatives already developed.

Table 9: Stage V, Geological Storytelling guidelines to construct a written and/or visual storytelling based on the Geological Evolution Framework.

V	**Adapted Storytelling**			
	1) Narrowing down the Message			
	2) The target audience			
	3) Contents: Adapted Framework Episodes			
	Geoparks	Events	Features	Sites
	4) Presentation and visual support			
	Episodes	Timing	Thematic	Plots
	Visual Imagery, such as:			
	Storytelling Maps	Scientific Illustration (e.g dynamic processes):	Nature landscapes (e.g photographs, or illustration)	Geological elements (e.g photographs, or illustration)

Narrowing down the message

The steps to be followed for using and developing a product should primarily revolve around the central message. In this context, after a thorough review of the key events, values of the sites, and essential features to convey through the Spanish geoparks network, it is advisable to concentrate on communicate the most significant episodes in a easy-to-understand manner. Generally, these episodes should mirror a crucial geological aspect of the country. The episodes can be used as narrowed down topics to communicate the geological evolution of the country. Notably observed, geoparks like Origens, Costa Vasca, or Las Loras have undertaken exemplary work formulating a core message for the region to convey to partners, public authorities, and the community. By combining the efforts in storytelling, design, commercial branding, initiatives, education and materials these geoparks created an clear narrowed down identity around the geological features of the area that can easily be exported outside their borders. Similarly, it is intended that this episodes, sites and features could also be used as tools to exemplify the key moments of the evolution of Earth registered in Spain.

The target audience

Naturally, the contents and presentation of how this narrative will be conveyed vary depending on the specific audience. In this case, and part of the motivation of this work, it would be tailored to those who visit the national network's website and digital channels. To achieve this, it is proposed that the language and content should focus on presenting the episodes along with their respective names and associated themes, but probably with renamed titles of the episodes and sites. This approach will largely depend on whether the target audience is the tourism sector, educational institutions, enthusiasts, online audiences, or others. From the beginning of this work, it was suggested that those who could directly benefit from this approach include the tourism sector, educational initiatives, and enthusiasts interested in geology and nature, all of whom would access this information through the website or an outreach publication. This aligns with the efforts made by the network so far, such as the distribution of the freely available publications.

The contents

One way to use the geological evolution framework contents is through a short narrative, filtering out the most exciting and captivating aspects of the story to be conveyed to the audience. In this case, we propose the national network's website. As an example, the following table of contents is proposed to rename and narrow down the episodes (Table 9), as well as filtered sites that can be accessible and visually didactic for the webpage.

Table 10 : Narrowed down geological storytelling. Proposed storytelling elements to be promoted by the network of geoparks, adjusted for general public and website. Based on the Geological Evolution Framework. Visual support suggestions are included.

Episodes	**Features/Event**	**Geoparks**	**Sites examples.**	**Visual support.**
The origins of life	Ediacaran Fauna	Villuercas, Cabo Ortegal	"Cerro de La Mina". Cloudina's site on the Ibor River,	Fossil Reconstructions
Variscan orogeny	Alloctonous terrains and Structures	Courel Mountains, Cabo Ortegal	Punta dos Aguillóns. Courel Syncline	Dynamic tectonic processes
Germanic Facies and ancient volcanism	Bundanstein and Keuper Facies.	S.N de Sevilla, Molina Alto Tajo.	Barranco de la Hoz stratotype	Sedimentation and stratigraphic sequences in arid climates
Marine platforms in extensional regime	Ammonites, marine-lacustrine sequences. Fossil records	Sierras Subbéticas, Las Loras, Maestrazgo.Basque Coast	Ammonitico Rosso Global Geosite	Marine paleonevironments and its fauna
Continantalization and its fauna	Lacustrine and marine sequences	Maestrazgo, Basque Coast, Las Loras	Órganos de Montoro, Miravete de la Sierra.	Cretaceous dinosaurs and the shallow marine paleoenvironments
The last dinosaurs of Europe and their extinction	Tremp Formation and the K-Pg Limit.	Origens, Basque Coast	Isona i Conca Dellà fossil records. K-Pg Boundary in the cove of Algorri	Cretaceous paleoenvironments and the Fifth extinction imagery
The Pyrenean Mountains formation and deformation	Geological Structures of the pyrenees and westward deformation.	Sobrarbe-Pirineos	Comiols Viewpoint and Sobrarbe Valleys	Geological cross section of the pyrenees
The relief modelling and deformation evidences	Apalachian relief, Hanging synclines	Mestrazgo, Villuercas, Las Loras.	Badlands Viewpoints	Erosional processes of the Armorican Quartzite and Hanging synclines.
The cenozoic and intermountain basins	Guadix baza basin and El Ebro basin.	Catalonia Central, Granada	Montserrat Mountains, Glacis surfaces in granada	Endorheic sea extinction and the betic cordillera uplifting
Volcanism	Different volcanic eruptions (Explosive, basaltic and monogenetic)	Cabo de Gata-Nijar, el Hierro, Lanzarote and Archipielago Islands	El Faro-Orchilla geozone; Calderas Quemadas and Mar de Lavas de Timanfaya; Volcán de los Frailes	Different types of volcanism
The landscapes from glaciations and karstification	Active glaciers, endokarsts and exokarsts.	Sobrarbe-Pyrenees, and others.	Monte Perdido, Cueva de los franceses in Las Loras UGGp (etc).	Actual Glaciar landscape, Valleys and karstification.

Presentation and visual support

When planning how to present the information, it should be considered that the previously mentioned episodes can follow a chronological timeline or thematics. Both approaches are outlined in this work and can be used interchangeably.

It is worth proposing that in order for the narrative to be sufficiently engaging, it should consider the plots and the emotional focus. This means including elements that address cause-and-effect, genesis, emergence, destruction, metamorphosis, convergence, divergence, and oscillation (Phillips, 2012). It is a practical guide for approaching geology in a more dynamic way. The language used in this case should be tailored to the audience, aiming to create a narrative with emotional elements that promote appreciation and conservation of the areas.

In addition to the above, the use of visual tools is crucial for conveying this narrative, which contains some complex processes and features. For a format like the web, it would be interesting to use interactive maps, similar to what some geoparks have developed to visualise the territory, for example, the interactive touristic map developed by Origens [25], in which there is participation from the audience to follow up the sites and routes.

The role of scientific illustration is also crucial for conveying the narrative. The table above (Table 9) summarises the basic visual support proposed to explain key episodes. Although this aspect may vary, the illustration should follow a didactic approach in two aspects: dynamic processes (e.g., tectonics) and reconstructions (e.g., paleo-environments and paleoart). Static landscapes and objects usually are the most common and they should be less used to convey the dynamic geological evolution.

5.1.4.The Channel and Products

Finally, the channels and products will depend on the specific project or initiative that will carry out the communication of the storytelling, but here is proposed that a national committee of geoparks could be focused on to achieve this objective.

Building upon the principles discussed earlier, the goal is to create the final narrative with illustrated visual support. The website proposal outlined in this work aims to be presented after continuous collaboration with the geoparks and scientific coordinators. A second proposal example involves the development of interactive maps (Storytelling maps) (e.g Antoniou et al., 2023), taking advantage of the opportunity to generate content on the official website of the Spanish Geoparks Network. A few examples were developed (See ANNEX 3) , which considered the main interconnected

[25] https://www.geoparcorigens.cat/

contents to incorporate in this approach: The geological domain, Main geological events, Representative sites, Map with a legend based on the main events of the national geological evolution.

In both cases, it is suggested to use or adapt the key episodes for the dissemination of the geological narrative. Additionally, it is crucial that both approaches can be interactive to some extent, similar to a field notebook, as seen in the Las Loras UGGp example, or an interactive map (see Antoniou et al., 2023). In both scenarios, there is also a proposal to overlay the geological narrative with cultural, tourism, educational, biodiversity, conservation, and other narratives that could be developed in the future.

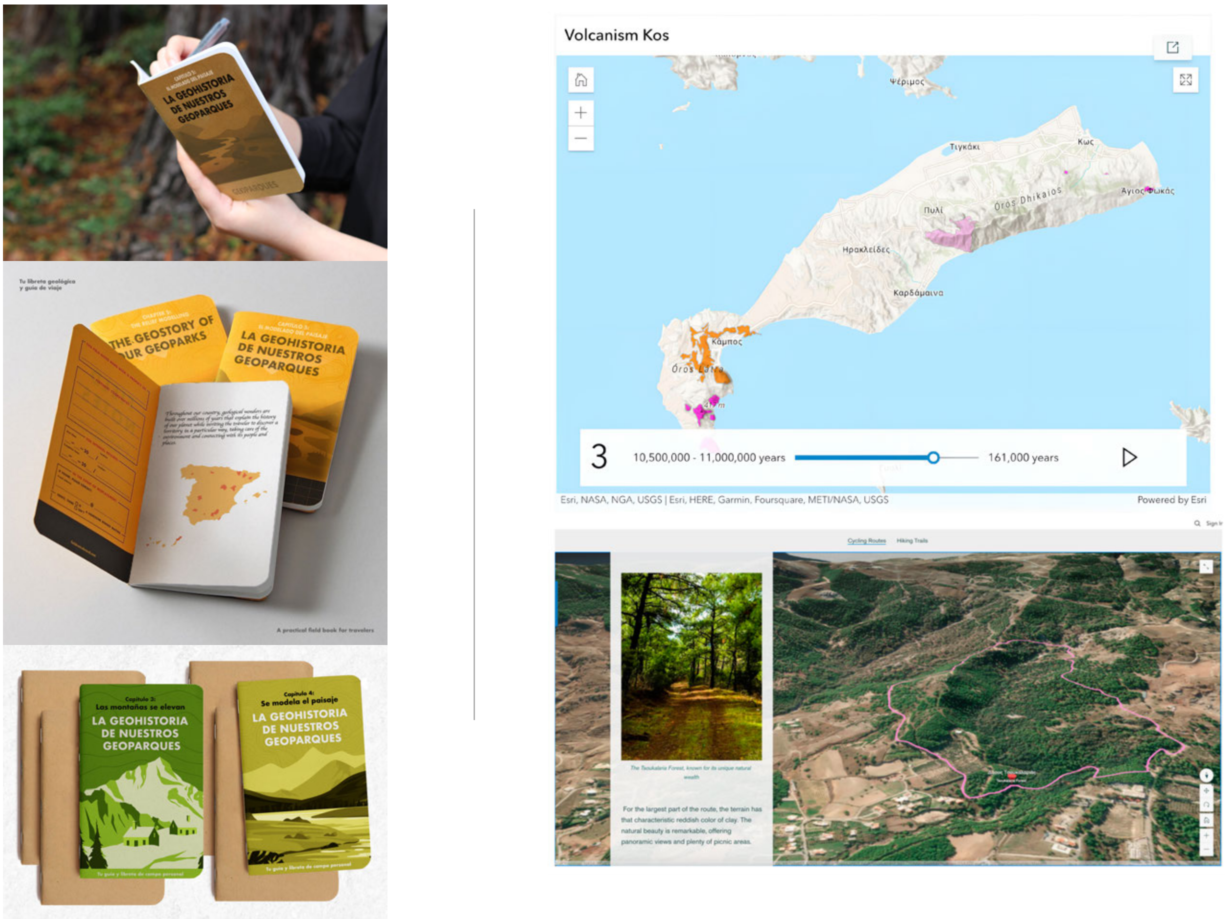

Figure 12: Examples of products. On the left a model of an outreach interactive fieldbook that includes the geological evolution of the Spanish geoparks and the visual support (e.g illustrations and images), inspired from the educative experiences in Las Loras UGGp. On the right, an already developed example for the Kos island, using the interactive storytelling maps to develop the communication of the geological evolution of the island (Antoniou et al., 2023).

6. Discussion

Spanish geoparks have been working diligently to disseminate their geological heritage to the local community and developing formal or informal education for its residents, highlighting their utility as a tool for sustainable development. It is essential to consider that a geopark does not primarily aim to convey geological information but rather to utilise the territory as a driver of local development. Moreover, each geopark operates with different resources and guidelines concerning their local outreach strategy, therefore the outreach materials on each one of them are different. This information includes the inherent values of the sites but is also influenced by the point of view of the geoparks management bodies. In this context, a significant diversity and heterogeneity in the information provided by geoparks has been observed, whether through their inventories, informative publications, community activities, or even the accessibility to such information.

The reviewed publications were constrained to those available online and the ones obtained during the fieldwork. This first stage was crucial to comprehend that to build the body of knowledge and to homogenise the information, written summaries of the geological evolution of each area were needed as the baseline for the upcoming stages. As the selected sites were also based on their current informative publications and inventories it is suggested that a more in-depth analysis could be conducted, specifically in the geoparks not visited during this work.

The selection of the elements that construct the general geological framework was made considering that they should represent the large-scale geological evolution of the country by periods. After this selection, the chronological evolution was divided into episodes. These episodes represent the principal large-scale geological processes, chosen due to common attributes identified across geoparks. Specifically, the different episodes, and thus the selection of representative geoparks, were developed by comparing their geological evolution and how these can be grouped by common attributes.

These episodes were constructed based on the geological evidence, nevertheless, they should not be constricted to the chronological boundaries (shown in Figure 10), but more like frameworks of the named events happening during that approximate time.

The method to select the proposed episodes to convey considered that: (i) they must be relevant for the national geological evolution, (ii) their evidence can be observed in the geoparks and its global or national relevant sites, and (iii) they are aligned with the present or future management team efforts to communicate these features. For instance, the Cretaceous period is widely represented in various geoparks, nevertheless, Maestrazgo UGGp is well known by the paleontological records, extensively communicated in their museums, thus this geopark was considered to represent this geological period nationwide along with Las Loras and Basque Coast due to the broad presence in the area. It is expected that new geoparks projects will enter the UNESCO Global Geopark designation and this logical approach could be used to differentiate them and at the same time create connections between geoparks with respect to their geology.

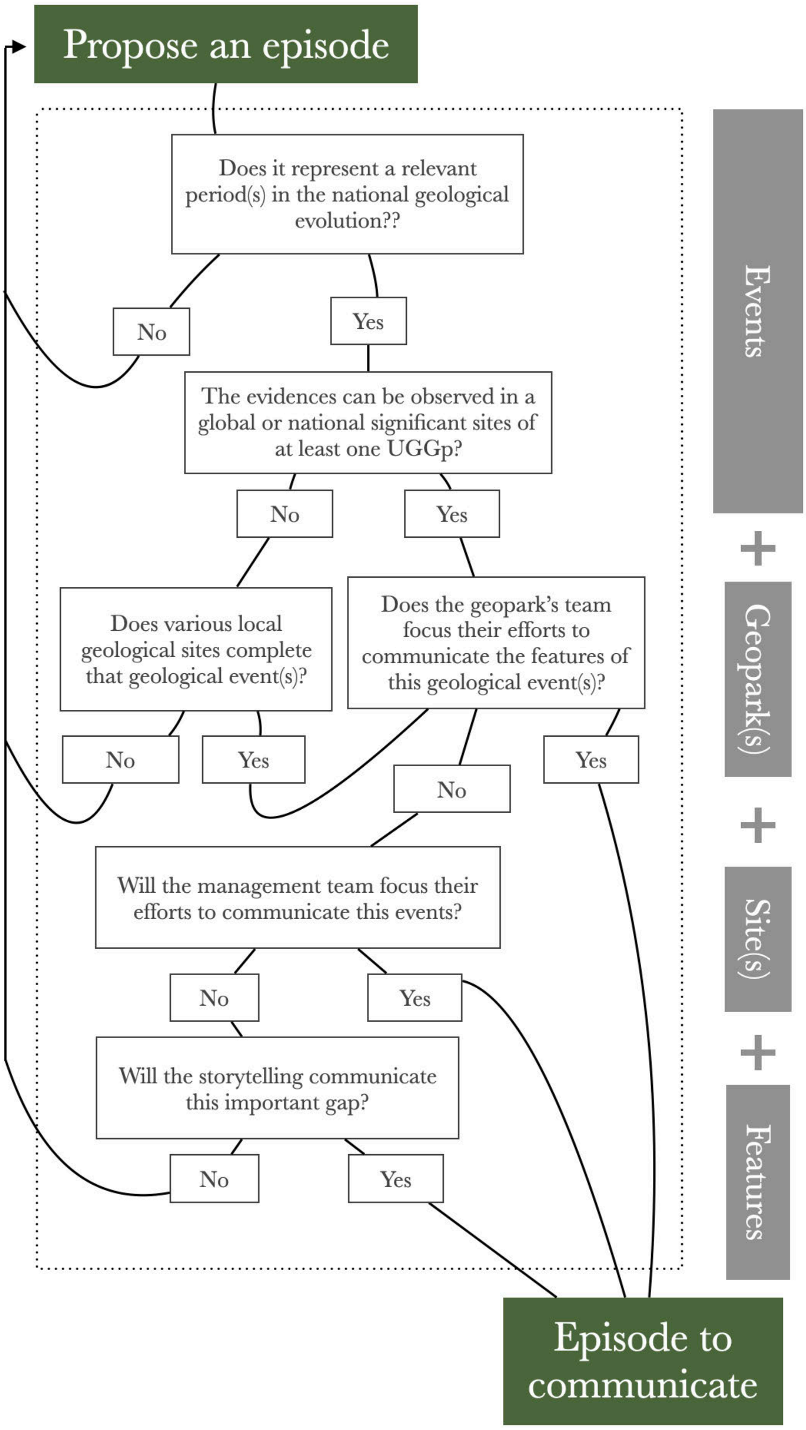

Figure 13: Thought process when proposing Episodes to communicate, that clearly represents the national geological evolution. Each episode includes relevant geological events, representative geoparks, geological sites and geological features.

The logic for constructing episodes is shown in Figure 13. While not a strict diagram, it can serve as a guide. As mentioned, the diagram emphasises that considering the communication strategy of geoparks is relevant when building a geological evolution framework for the country. However, if the goal is to create a more rigorous framework regarding geology and geological heritage, this stage can be skipped. Nevertheless, for the purpose of communication, it is suggested to consider this analysis since it aims to contribute to the communicative work carried out by geoparks over the years. The inclusion of this step contributes to aligning the efforts within the network. Furthermore, if geological heritage were only selected based on the geological significance, the outcome would resemble Table 6 in this study, and from there, another type of framework could be created. Based on the latter, the representative elements were selected based on their ability to exhibit each geological episode with high scientific and educational value sites. Therefore, the selection process considers their potential for visitation and promotion.

There are a few pieces of evidence regarding the Cadomian Orogeny in Spanish geoparks, most of the relevant sites are not centred around this event but it left structural evidence in various geoparks located in the Iberian massif and this orogeny is included as an episode to communicate.

The recently incorporated Cabo Ortegal UGGp, offers a distinct episode in the national geological evolution, providing insights into allochthonous terrains during the Variscan Orogeny. Many sites within this geopark can represent these episodes, or the entire geopark area can be promoted within these topics.

Sierra Norte de Sevilla UGGp is a unique location that holds significant importance in the study of ancient forest trees. The fossil records found here provide an episode that fills a gap in this framework during the Permian and Triassic. Furthermore, this geopark represents the oldest rocks and the origins of life, along with the Ediacaran fauna in Villuercas-Ibores Jara UGGp.

The Jurassic and Cretaceous periods are the most extensive episodes, and they are well represented in many geoparks. However, it is expected that these episodes can be divided in a more representative manner. Currently, the Cretaceous period is represented by three geoparks: Maestrazgo, Las Loras, and Basque Coast. Meanwhile, the Jurassic period is mainly represented by the Sierras Subbéticas and the evolution of its marine environments. The Jurassic successions can be disseminated also from Maestrazgo and Las Loras UGGps sites and evidence (e.g. Aguilar de Campo Formation).

In the case of the Canary Islands. Although they do not exhibit the same type of volcanism as Cabo de Gata UGGp, they could be disseminated within the same theme, explaining the different types of volcanism.

Some episodes encompass more than one geological event or geopark. For instance, 'relief modelling', which includes the folds of Las Loras UGGp and the Appalachian relief in Villuercas Ibores-Jara UGGp. It is expected that within this same episode, various geomorphological elements shaping the landscape during the Cenozoic, including the effects of tectonic and post-tectonic deformation resulting from the Alpine orogeny, can be included. Or this episode can be subdivided.

Regarding the glaciations and the fluvial and karst systems, it is more challenging to subdivide these episodes due to their relevance to all geoparks, much like the common occurrence of Keuper Facies outcrops. The karst systems are well represented in many geoparks, but the glaciation theme could be promoted based on the active glaciers in Sobrarbe-Pirineos UGGp.

Sobrarbe-Pirineos, Central Catalonia, and Granada UGGps represent key episodes in geological evolution, such as the formation of the Pyrenees and the Cenozoic basins. In these instances, the episodes encompass the entirety of the geopark, featuring numerous representative sites.

Lastly, the remarkable events associated with dinosaurs have been consolidated into a single episode to include the dinosaur fauna and life before their extinction. This episode selection was influenced by the communicative strategy implemented in Basque Coast and Origens UGGps territories.

Finally, to contextualise the written descriptions of the framework, it includes the general paleogeographical situation of the Iberian Peninsula and paleoenvironmental interpretations, information provided from the publications of the geoparks.

The themes presented in the framework respond to the main topic of the evidence that represents the geological episode and each geopark accurately represents the episodes and focuses on a particular theme. Some episodes can represent more than one theme, for instance, the western region of the Iberian Peninsula has the oldest rocks, with significant metamorphic evidence. However, the primary theme presented is paleontological, with a focus on the origins of life, given the extensive geoheritage related to the first fossil records of the early Paleozoic.

As the storytelling can be complemented with more information in the future, the rest of the thematics identified in the publications of the geoparks can be used when adding episodes or sites (e.g. geological risks, soils, resources, etc.). For example, the origins of the mineral or oil resources such as the remarkable oil reservoirs in Las Loras UGGp, could be included.

The core proposal of this research was to provide a general dissemination tool for the geopark network. Although it does not attempt to cover all the geological aspects that could be considered, it presents a useful and systematic compilation and methodology for consulting these attributes and adapting them to desired communication objectives.

As a general recommendation, it is proposed to develop products using these themes and titles. If the necessary interest and the funding of a collaborative project are available it could be a good opportunity to communicate and raise awareness of the geological formation of these geoparks. For this purpose, the geological storytelling product can develop a cohesive written narrative using this model.

Spain, with its abundance of geoparks, offers a unique opportunity for strategic dissemination through these active management teams. This proposal to unify a common narrative is an initial step in developing more unified communication that could be replicated in other countries once their number of geoparks accurately represents their national geology (Asier Hilario, personal communication, 2023). Notably, recent efforts have been made to disseminate the geoheritage of all the geoparks, such as publications about the karsts “Las Cuevas y el Karst: un viaje a través de los Geoparques Españoles” or the "Discovering the Spanish Geoparks" magazine. Moreover, the presence of education on the UGGps websites is a key factor in promoting all the activities that these territories organise throughout the year and demonstrating their effectiveness as sustainable and safe educational alternatives (Aires et al.,2014), therefore the modelled products in this work propose the website of the network as the main channel.

Communication and education strategies are not restricted to follow these models, but to use them as tools. Therefore, future collaborations and decisions from the geopark network, as well as active participation from experts in other geoparks could improve it. This would also foster network collaboration and more effective planning in the dissemination of the geological formation of these areas nationwide.

Finally, considering that "A UNESCO Global Geopark must demonstrate the geological heritage of international significance, but the purpose of a UNESCO Global Geopark is to explore, develop, and celebrate the links between that geological heritage and all other aspects of the area's natural, cultural, and intangible heritages," it is crucial to complement this narrative with other cultural and natural stories to convey the message of national geoconservation more effectively or to similarly create narrowed down storytelling about these topics.

7. Conclusion

The geology of a country can be complex, and explaining scientific concepts to both the public and other scientists can be a challenge. Considering these challenges, the objective of this dissertation has been set to present a framework that contextualises the geology of Spanish geoparks. Furthermore, this work is aware of the complexity and geological contents unfamiliar to the general public. A fundamental part of this effort is based on transferring complex general geological concepts into accessible and appealing elements for the public, thus promoting an appreciation of the rich geological heritage.

In this dissertation, the objective of synthesising fundamental elements to create a useful geological evolution framework is achieved. It encapsulates the unique characteristics of Spanish geoparks, considering the geological heritage and communicative work developed by these projects. The complex evolution has been systematically subdivided with a methodology based on scientific and popular science publications for each of them.

As part of the methodology, the geological evolution framework includes the geological processes, sites and values of each geopark that play a relevant role in the national geological evolution, presented by episodes. The framework also aims to be representative of the complete geochronological scale and national geological units. Fieldwork was carried out in five geoparks to calibrate this model and create a participatory strategy with experts. During this fieldwork, along with the bibliographic review, it was observed how geology is communicated, and it was concluded that the geological communication worked on in each territory does not always coincide with the events or sites that may be relevant in the context of national geological evolution. Therefore, this work to develop a custom framework with the key elements to communicate becomes even more valuable.

A framework diagram and a summarised chronologically written description were developed, presenting the fundamental elements that the geological evolution should include in terms of its form and content (Figure 10). In general, key items are established to create the framework: episodes, events, features, and geoheritage sites; supplemented with geological interpretations. In terms of contents, a first approach assigns concise names to these events or episodes and their approximate position on the geochronological scale, to be representative of almost the entire geological evolution of the country, along with descriptions of their characteristics and exemplary evidence. In this preliminary proposal, the geological evolution framework comprises 19 episodes from the Neoproterozoic until the Quaternary. Each one of them is also presented with a thematic approach to exhibit and exemplify the geodiversity of these areas. The model is open to be adjusted, especially for the geoparks not visited by the author. The areas of improvement are the writing of an extended geological storytelling based on an adjusted framework. Currently, the practical relevance lies in the potential to be the first unified effort for organised consultation and reference to develop popular geoscience and educational initiatives within the network of geoparks outside its borders. The study also includes guidelines for the methodology and potential products to disseminate the general geological evolution of geoparks. These guidelines aim to foster popular geoscience and educational initiatives.

Once enough geoparks are established and they contain significant geoheritage in the national geological configuration, it is expected that unified strategies for disseminating any country's geological evolution will be formulated. However, in order to effectively communicate the values of the geopark in the national geological context, a solid communication strategy must also be developed in these territories.

Finally, these initiatives aim to promote the geoparks as significant repositories of Earth's evolutionary history. It addresses the task of improving geographical literacy, and if a product is materialised, it can promote responsible behaviours in these areas, emphasising their intrinsic geological value. Ultimately, the work seeks to highlight the importance of geoparks in understanding our past, inspiring current conservation efforts, and guiding future sustainable interactions with these relevant geological areas.

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ANNEXES:

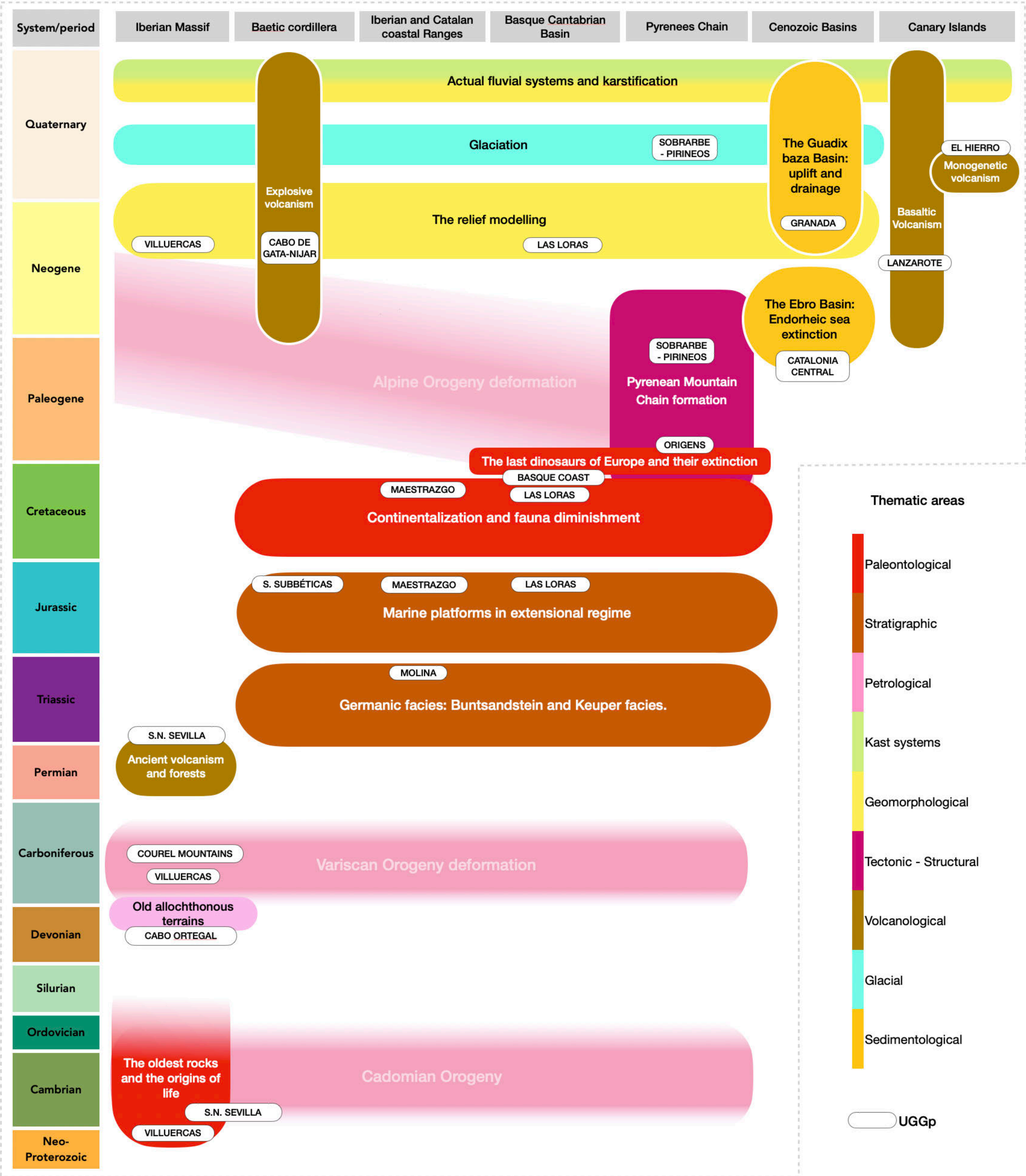
ANNEX 1: Geological evolution framework diagram

ANNEX 2:Fieldwork Visited Sites

ANNEX 2: Storytelling maps model, as product proposal

ANNEX 3: Relevant mentioned publications of the geoparks

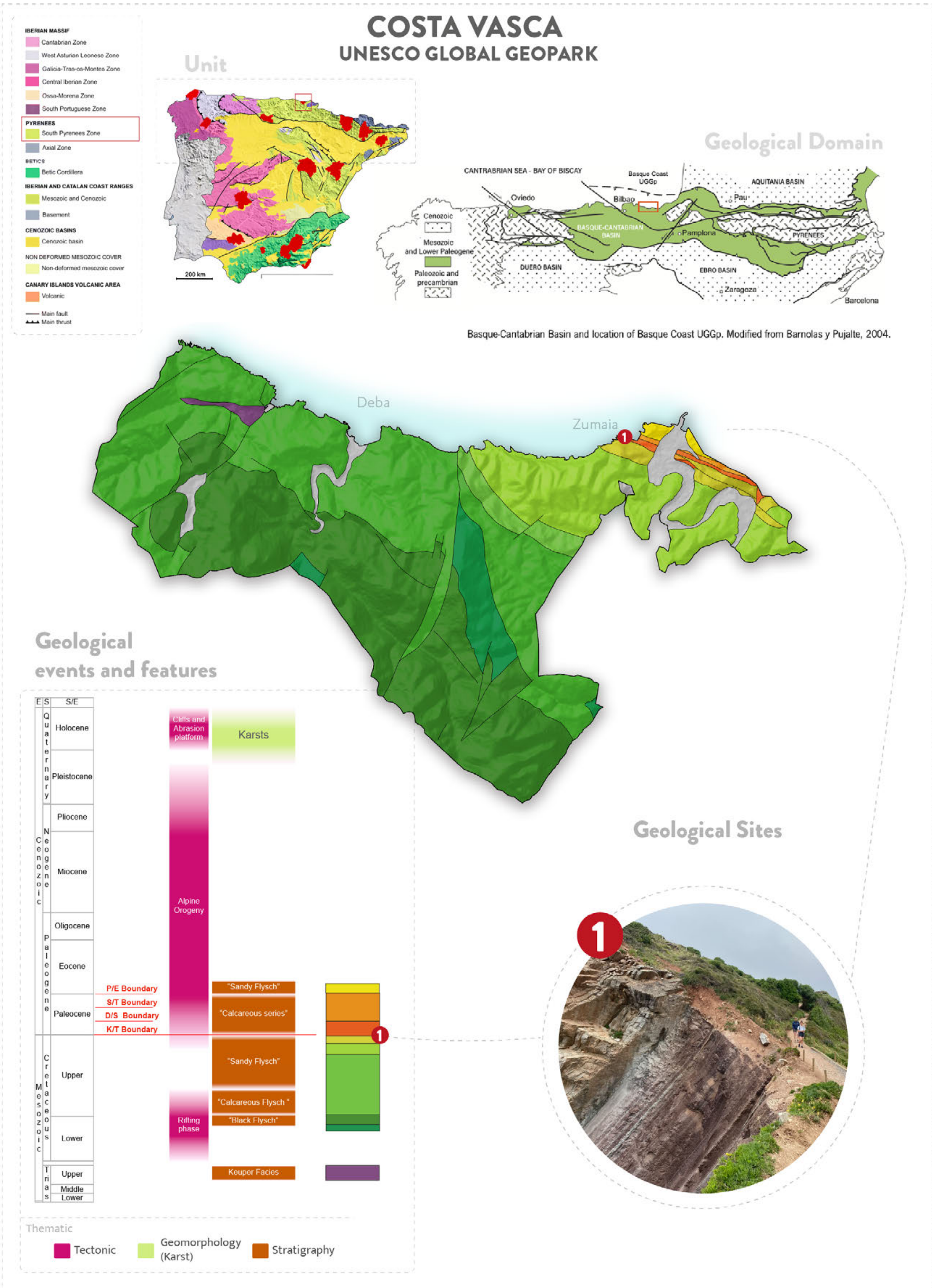
ANNEX 1: Geological evolution framework diagram



ANNEX 2: Fieldwork Visited Sites

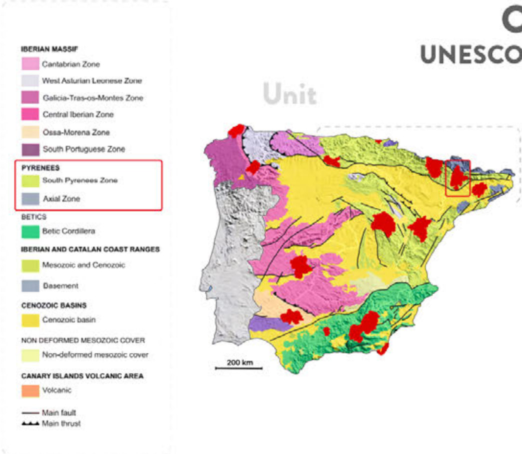
Geopark	Visited Sites	Information Gathered
Origens Geopark	Epicentre Geopark Visitor Centre, Gerri de la Sal Museum, Conca Dellà Museum, Vilanova de Meià Museum, Key sites along Georutes 1, 7, 2, and 4	Communication strategy regarding geological history, Collaborative fieldtrip observations with the scientific coordinator
Catalonia Central	Montserrat Mountain viewpoint, Temporary exhibition at the library in Manresa	Observations related to geopark communication strategy, Information on geological history
Sobrarbe-Pyrenees	Castillo de Aínsa Interpretation Center	Data collection and collaboration with the scientific coordinator
Basque Coast Geopark	Complete Flysch sequence by boat, GR 121 hiking route from Zumaia to Deba, "The Valley of Prehistory" route	Observation of geological formations and features, Exploration of new interpretation product
Las Loras Geopark	Interpretation Center in Villadiego, Petroleum Museum, Valle del Sedano, Covalagua Natural Monument, Aguilar Formation in Aguilar de Campoo, Olleros de Pisuerga, Rebolledo de la Torre geological sites	Observation of various geological sites and features, Collaborative fieldtrip observations with the scientific coordinator

ANNEX 3: Storytelling maps model, as product proposal

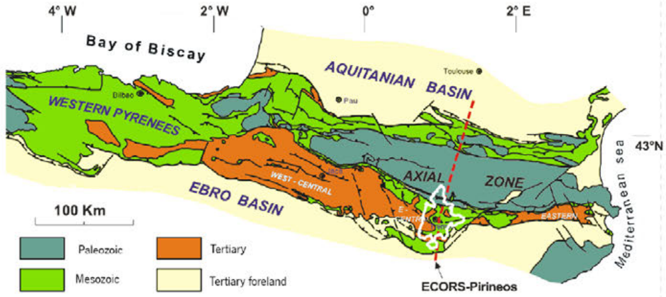


ORIGENS
UNESCO GLOBAL GEOPARK

Unit

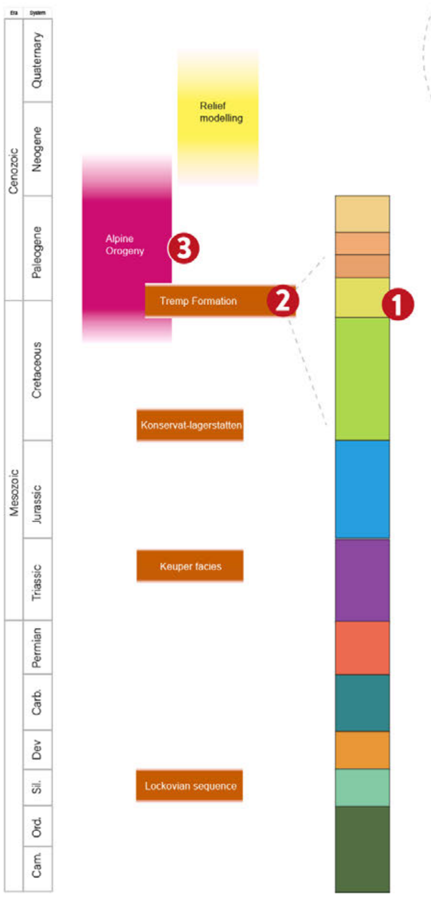


Geological Domain

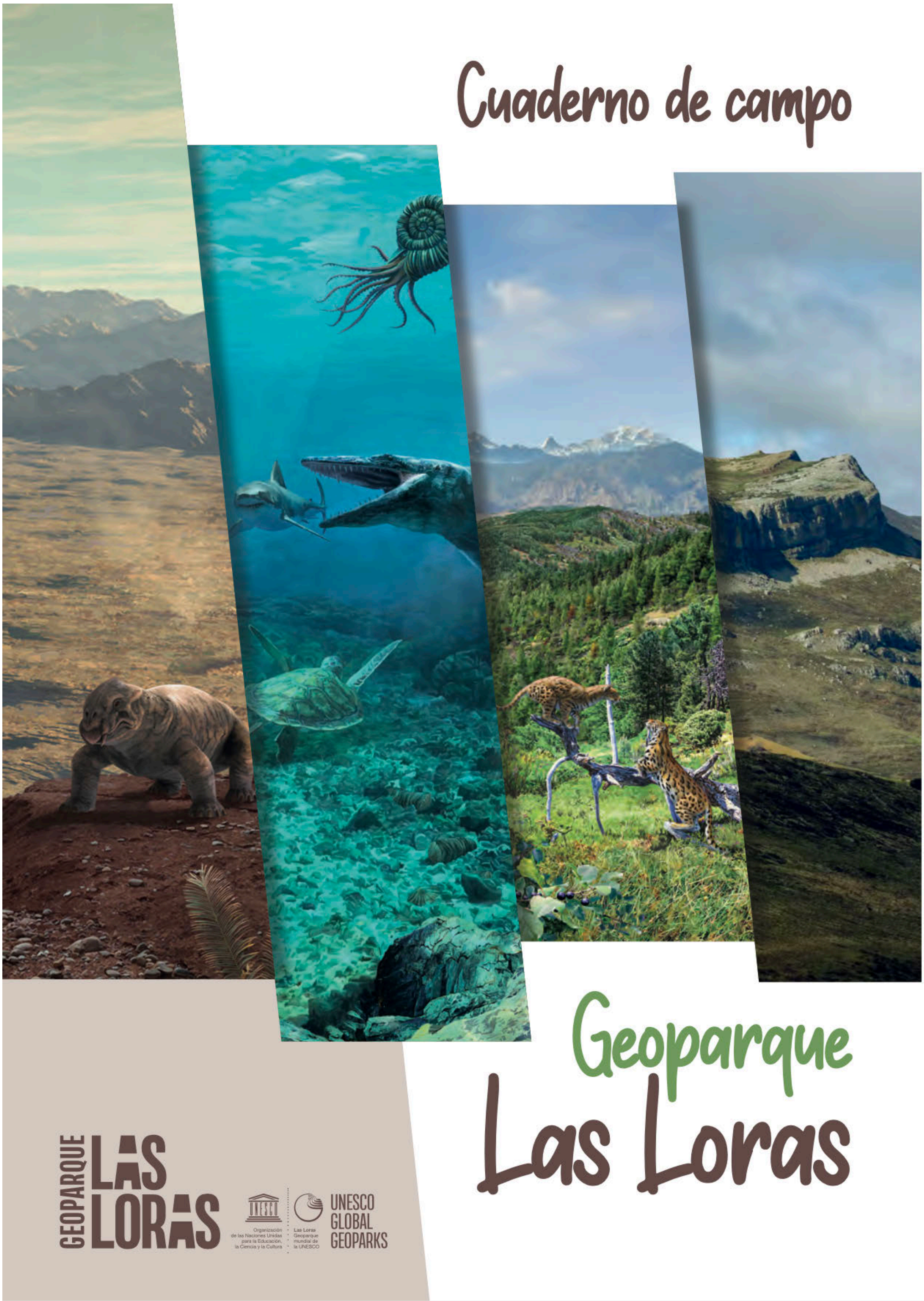


Geological Sites

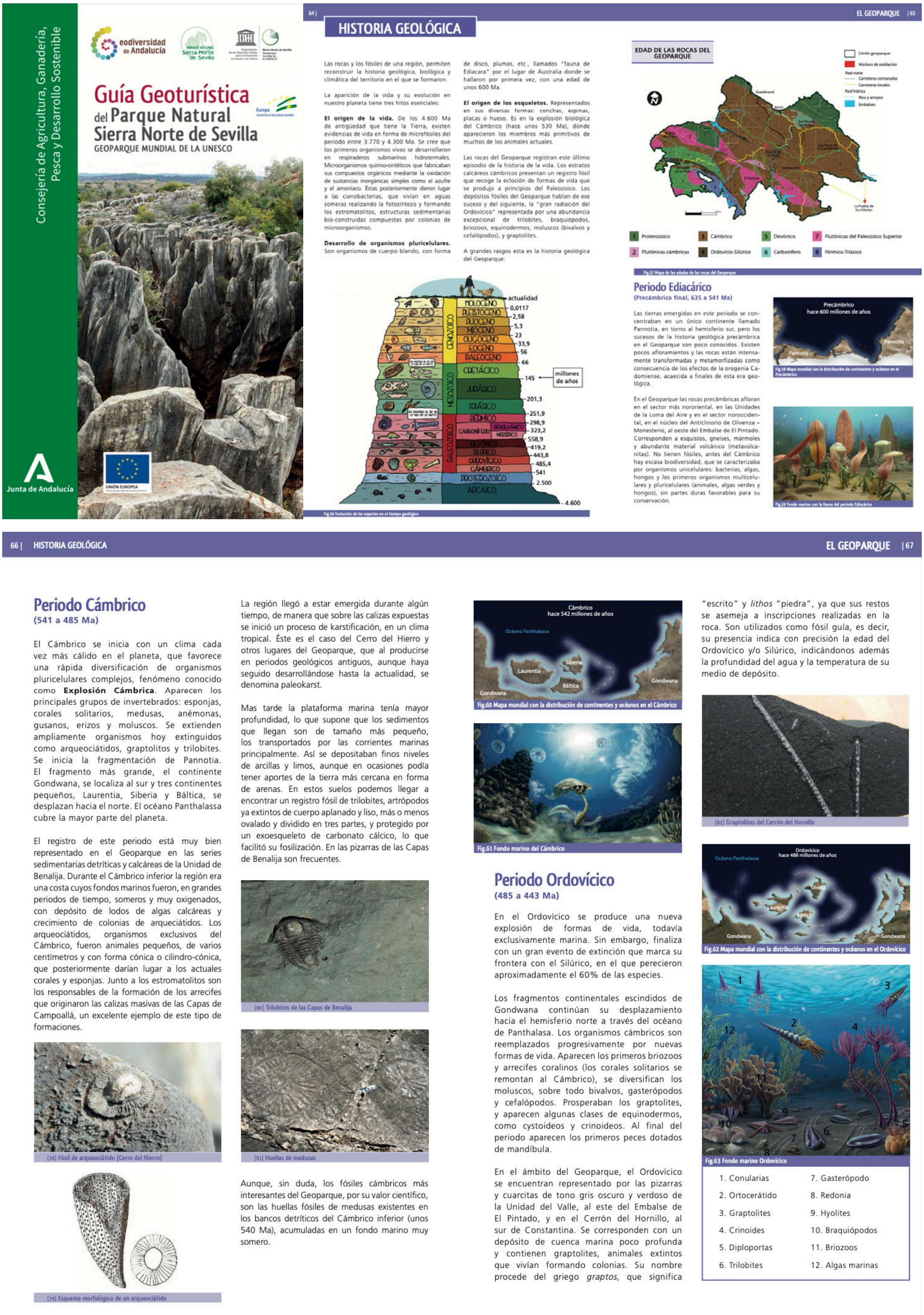
Geological events and features



ANNEX 3: Relevant mentioned publications of the geoparks



Educative fieldbook, including illustrated geological evolution. Las Loras UGGp. (Authors: José Ángel Sánchez Fabián y Karmah Salman)



Guía Geoturística del Parque Natural Sierra Norte de Sevilla

GEOPARQUE MUNDIAL DE LA UNESCO

Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible

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HISTORIA GEOLÓGICA

Las rocas y los fósiles de una región, permiten reconstruir la historia geológica, biológica y climática del territorio en el que se formaron.

La aparición de la vida y su evolución en nuestro planeta tiene tres hitos esenciales:

El origen de la vida. De los 4.600 Ma de antigüedad que tiene la Tierra, existen evidencias de vida en forma de microfósiles del periodo entre 3.770 y 4.300 Ma. Se cree que los primeros organismos vivos se desarrollaron en respiraderos submarinos hidrotermales. Microorganismos quimio-sintéticos que fabricaban sus compuestos orgánicos mediante la oxidación de sustancias inorgánicas simples como el azufre y el amoníaco. Éstas posteriormente dieron lugar a las cianobacterias, que vivían en aguas someras realizando la fotosíntesis y formando los estromatolitos, estructuras sedimentarias bio-construidas compuestas por colonias de microorganismos.

Desarrollo de organismos pluricelulares. Son organismos de cuerpo blando, con forma de disco, plumas, etc., llamados "fauna de Ediacara" por el lugar de Australia donde se hallaron por primera vez, con una edad de unos 600 Ma.

El origen de los esqueletos. Representados en sus diversas formas: conchas, espinas, placas o hueso. Es en la explosión biológica del Cámbrico (hace unos 530 Ma), donde aparecieron los miembros más primitivos de muchos de los animales actuales.

Las rocas del Geoparque registran este último episodio de la historia de la vida. Los estratos calcáreos cámbricos presentan un registro fósil que recoge la eclosión de formas de vida que se produjo a principios del Paleozoico. Los depósitos fósiles del Geoparque hablan de ese suceso y del siguiente, la "gran radiación del Ordovícico" representada por una abundancia excepcional de trilobites, braquiópodos, briozoos, equinodermos, moluscos (bivalvos y cefalópodos), y graptolites.

A grandes rasgos esta es la historia geológica del Geoparque:

Fig.56 Evolución de las especies en el tiempo geológico

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EDAD DE LAS ROCAS DEL GEOPARQUE

Fig.57 Mapa de las edades de las rocas del Geoparque

Periodo Ediacárico

(Precámbrico final, 635 a 541 Ma)

Las tierras emergidas en este periodo se concentraban en un único continente llamado Pannotia, en torno al hemisferio sur, pero los sucesos de la historia geológica precámbrica en el Geoparque son poco conocidos. Existen pocos afloramientos y las rocas están intensamente transformadas y metamorfizadas como consecuencia de los efectos de la orogenia Cadomiense, acaecida a finales de esta era geológica.

En el Geoparque las rocas precámbricas afloran en el sector más nororiental, en las Unidades de la Loma del Aire y en el sector noroccidental, en el núcleo del Anticlinorio de Olivenza – Monesterio, al oeste del Embalse de El Pintado. Corresponden a esquistos, gneises, mármoles y abundante material volcánico (metavolcanitas). No tienen fósiles, antes del Cámbrico hay escasa biodiversidad, que se caracterizaba por organismos unicelulares: bacterias, algas, hongos y los primeros organismos multicelulares y pluricelulares (animales, algas verdes y hongos), sin partes duras favorables para su conservación.

Fig.58 Mapa mundial con la distribución de continentes y océanos en el Precámbrico

Fig.59 Fondo marino con la fauna del periodo Ediacárico

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EL GEOPARQUE | 67

Periodo Cámbrico

(541 a 485 Ma)

El Cámbrico se inicia con un clima cada vez más cálido en el planeta, que favorece una rápida diversificación de organismos pluricelulares complejos, fenómeno conocido como **Explosión Cámbrica**. Aparecen los principales grupos de invertebrados: esponjas, corales solitarios, medusas, anémonas, gusanos, erizos y moluscos. Se extienden ampliamente organismos hoy extinguidos como arqueociátidos, graptolitos y trilobites. Se inicia la fragmentación de Pannotia. El fragmento más grande, el continente Gondwana, se localiza al sur y tres continentes pequeños, Laurentia, Siberia y Báltica, se desplazan hacia el norte. El océano Panthalassa cubre la mayor parte del planeta.

El registro de este periodo está muy bien representado en el Geoparque en las series sedimentarias detríticas y calcáreas de la Unidad de Benalija. Durante el Cámbrico inferior la región era una costa cuyos fondos marinos fueron, en grandes periodos de tiempo, someros y muy oxigenados, con depósito de lodos de algas calcáreas y crecimiento de colonias de arqueciátidos. Los arqueociátidos, organismos exclusivos del Cámbrico, fueron animales pequeños, de varios centímetros y con forma cónica o cilindro-cónica, que posteriormente darían lugar a los actuales corales y esponjas. Junto a los estromatolitos son los responsables de la formación de los arrecifes que originaron las calizas masivas de las Capas de Campoallá, un excelente ejemplo de este tipo de formaciones.

[78] Fósil de arqueociátido (Cerro del Hierro)

[79] Esquema morfológico de un arqueociátido

La región llegó a estar emergida durante algún tiempo, de manera que sobre las calizas expuestas se inició un proceso de karstificación, en un clima tropical. Éste es el caso del Cerro del Hierro y otros lugares del Geoparque, que al producirse en periodos geológicos antiguos, aunque haya seguido desarrollándose hasta la actualidad, se denomina paleokarst.

Mas tarde la plataforma marina tenía mayor profundidad, lo que supone que los sedimentos que llegan son de tamaño más pequeño, los transportados por las corrientes marinas principalmente. Así se depositaban finos niveles de arcillas y limos, aunque en ocasiones podía tener aportes de la tierra más cercana en forma de arenas. En estos suelos podemos llegar a encontrar un registro fósil de trilobites, artrópodos ya extintos de cuerpo aplanado y liso, más o menos ovalado y dividido en tres partes, y protegido por un exoesqueleto de carbonato cálcico, lo que facilitó su fosilización. En las pizarras de las Capas de Benalija son frecuentes.

[80] Trilobites de las Capas de Benalija

[81] Huellas de medusas

Aunque, sin duda, los fósiles cámbricos más interesantes del Geoparque, por su valor científico, son las huellas fósiles de medusas existentes en los bancos detríticos del Cámbrico inferior (unos 540 Ma), acumuladas en un fondo marino muy somero.

Fig.60 Mapa mundial con la distribución de continentes y océanos en el Cámbrico

Fig.61 Fondo marino del Cámbrico

Periodo Ordovícico

(485 a 443 Ma)

En el Ordovícico se produce una nueva explosión de formas de vida, todavía exclusivamente marina. Sin embargo, finaliza con un gran evento de extinción que marca su frontera con el Silúrico, en el que perecieron aproximadamente el 60% de las especies.

Los fragmentos continentales escindidos de Gondwana continúan su desplazamiento hacia el hemisferio norte a través del océano de Panthalasa. Los organismos cámbricos son reemplazados progresivamente por nuevas formas de vida. Aparecen los primeros briozoos y arrecifes coralinos (los corales solitarios se remontan al Cámbrico), se diversifican los moluscos, sobre todo bivalvos, gasterópodos y cefalópodos. Prosperaban los graptolites, y aparecen algunas clases de equinodermos, como cystoideos y crinoideos. Al final del periodo aparecen los primeros peces dotados de mandíbula.

En el ámbito del Geoparque, el Ordovícico se encuentran representado por las pizarras y cuarcitas de tono gris oscuro y verdoso de la Unidad del Valle, al este del Embalse de El Pintado, y en el Cerrón del Hornillo, al sur de Constantina. Se corresponden con un depósito de cuenca marina poco profunda y contienen graptolites, animales extintos que vivían formando colonias. Su nombre procede del griego *graptos*, que significa "escrito" y *lithos* "piedra", ya que sus restos se asemeja a inscripciones realizadas en la roca. Son utilizados como fósil guía, es decir, su presencia indica con precisión la edad del Ordovícico y/o Silúrico, indicándonos además la profundidad del agua y la temperatura de su medio de depósito.

[82] Graptolites del Cerrón del Hornillo

Fig.62 Mapa mundial con la distribución de continentes y océanos en el Ordovícico

Fig.63 Fondo marino Ordovícico

1. Conularias	7. Gasterópodo
2. Ortocerátido	8. Redonia
3. Graptolites	9. Hyolites
4. Crinoides	10. Braquiópodos
5. Diploportas	11. Briozoos
6. Trilobites	12. Algas marinas

Geotouristic guide of Sierra Norte de Sevilla UGGp Showing the geological evolution describing the main global events followed by illustrations and evidences in the geopark.

Geo ruta 1 ESPACIO DEL GEOPARQUE DE SOBRARBE

aínsa

CENTRO DE INTERPRETACIÓN DEL GEOPARQUE

RED DE GEO-RUTAS del Geoparque de Sobrarbe

Geoparks · Global Geoparks Network · Sobrarbe Geoparque

HISTORIA GEOLÓGICA DEL GEOPARQUE

La historia geológica del Geoparque de Sobrarbe se remonta más de 500 millones de años en el tiempo. Durante este enorme periodo de tiempo se han sucedido numerosos acontecimientos geológicos que condicionan los paisajes y relieves actuales. La historia geológica de Sobrarbe se puede dividir en 6 episodios diferentes, cada uno de los cuales refleja importantes momentos de su evolución hasta configurar el paisaje geológico actual.

1 EL PASADO MÁS REMOTO
(hace entre 500 y 250 millones de años)

Durante un largo periodo de tiempo del Paleozoico, el territorio que actualmente ocupa Sobrarbe fue un fondo marino en el que se acumularon limos, lodos, arcillas y arenas.

Hoy estos sedimentos se han transformado en las pizarras, areniscas, calizas y cuarcitas que forman las montañas y valles del Norte de la Comarca. Estas rocas se vieron intensamente deformadas por la orogenia Varisca: un episodio de intensa actividad tectónica que afectó a buena parte de Europa y que dio lugar a una enorme cordillera. Numerosos pliegues y fallas atestiguan este pasado, así como los granitos que se formaron en esta época.

Pliegues en rocas paleozoicas

2 SEDIMENTACIÓN MARINA TROPICAL
(hace entre 250 y 50 millones de años)

La gigantesca cordillera formada en la etapa anterior fue intensamente atacada por la erosión, haciéndola desaparecer casi por completo. El relieve prácticamente plano resultante fue cubierto por un mar tropical poco profundo. Se formaron en él arrecifes de coral y se acumularon lodos calcáreos que hoy vemos en forma de calizas, dolomías y margas, muchas de las cuales contienen abundantes fósiles marinos. El mar sufrió diversas fluctuaciones incluyendo numerosas subidas y bajadas, pero prácticamente cubrió la zona durante todo este episodio.

Fósiles de organismos marinos en calizas del Cretácico

3 LA FORMACIÓN DE LOS PIRINEOS
(hace entre 50 y 40 millones de años)

La sedimentación marina continuó durante este episodio, pero en condiciones muy diferentes a las del anterior. Poco a poco se fue cerrando el mar que separaba lo que hoy es la Península Ibérica del resto de Europa. Hace alrededor de 45 millones de años, según se iba estrechando este mar, se producía sedimentación en el fondo marino a miles de metros de profundidad, mientras que en tierra firme la cordillera pirenaica iba creciendo.

Paisaje típico de zonas donde afloran las turbiditas

En Sobrarbe podemos encontrar excepcionales ejemplos de turbiditas, unas rocas formadas en aquel mar que recibía enormes cantidades de sedimentos como resultado de la construcción de la cordillera, al tiempo que las montañas iban creciendo.

PALEOZOICO					
542 m.a. 488 m.a.	443 m.a.	416 m.a.	359 m.a.	299 m.a.	251 m.a.
Cámbrico	Ordovícico	Silúrico	Devónico	Carbonífero	Pérmico

EPISODIOS: 1

4

DE SOBRARBE

4 LOS DELTAS DE SOBRARBE *(hace entre 40 y 25 millones de años)*

La formación de la cordillera provocó el progresivo cierre del mar, cada vez menos profundo y alargado. Hace alrededor de 43 millones de años un sistema de deltas marcó la transición entre la zona emergida y las últimas etapas de ese golfo marino. A pesar de que este periodo fue relativamente breve, se acumularon enormes cantidades de sedimentos que hoy podemos ver en la zona Sur de la Comarca convertidos en margas, calizas y areniscas.

Una vez que el mar se hubo retirado definitivamente de Sobrarbe, el implacable trabajo de la erosión se hizo, si cabe, más intenso. Hace alrededor de 40 millones de años, activos y enérgicos torrentes acumularon enormes cantidades de gravas que, con el tiempo, se convertirían en conglomerados.

Conglomerados: rocas formadas por fragmentos redondeados de otras rocas

5 LAS EDADES DEL HIELO
(últimos 2,5 millones de años)

Una vez construida la cadena montañosa y su piedemonte, la erosión empezó a transformarla. Los valles de los ríos se fueron ensanchando y se fue configurando la actual red fluvial. En diversas ocasiones durante el Cuaternario, fundamentalmente en los últimos 2 millones de años, se sucedieron diversos episodios fríos que cubrieron la cordillera de nieve y hielo.

La última gran glaciación tuvo su punto álgido hace alrededor de 65.000 años. Enormes glaciares cubrieron los valles y montañas, y actuaron como agentes modeladores del paisaje. El paisaje de toda la zona Norte de Sobrarbe está totalmente condicionado por este pasado glaciar.

Glaciares como los actuales de los Alpes cubrieron el Pirineo durante esta época

6 ACTUALIDAD

En la actualidad progresan los procesos erosivos que, poco a poco, van desgastando la cordillera. Esta erosión se produce de muchas maneras: mediante la acción de los ríos, erosión en las laderas, disolución kárstica, etc.

El paisaje que vemos en la actualidad tan sólo es un instante en una larga evolución que sigue en marcha, pero con la participación del Hombre, que modifica su entorno como ningún otro ser vivo es capaz.

Río Cinca, agente modelador actual

MESOZOICO			CENOZOICO		
199 m.a.	145 m.a.	65 m.a.	23 m.a.	2,5 m.a.	
Triásico	Jurásico	Cretácico	Paleógeno	Neógeno	Cuaternario
	2		3 4		5 6

5

EPISODIOS REPRESENTADOS EN LAS GEO-RUTAS

Nº	GEO-RUTA	EPISODIOS					
PN1	Valle de Ordesa		2			5	6
PN2	Monte Perdido		2	3		5	6
PN3	Brecha de Roland		2	3		5	6
PN4	Miradores de las Cutas		2	3		5	6
PN5	La Larri	1		3		5	
PN6	Balcón de Pineta		2	3		5	6
PN7	Cañón de Añisclo (parte baja)		2			5	6
PN8	Cañón de Añisclo (parte alta)		2	3		5	
PN9	Circuito por el Cañón de Añisclo			3			6
PN10	Valle de Escuaín			3			6
PN11	Valle de Otal	1		3		5	6

Episodio 1: Orogenia Varisca - **Episodio 2:** Sedimentación marina tropical -**Episodio 3:** Formación de los Pirineos - **Episodio 4:** Los Deltas del Sobrarbe - **Episodio 5:** Las Edades del Hielo - **Episodio 6:** Actualidad

Sobrarbe-Pirineos UGGp. Example of the geo-route outreach brochures, using the geological history subdivided by episodes.