Geological Guide

Granada Geopark

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welcome

The Granada Geopark is one of the most important sustainable development projects carried out in the province in recent years. Over this whole period, many actions have been implemented with the aim of highSGIhting the valuable and important natural and cultural heritage of this wonderful destination. This project is an example of joint work, the efforts of a whole region to conserve its rich heritage, attract visitors and fight depopulation, thereby preserving the values that make it unique.

Now we are going a step further and publishing the Geological Guide to the Granada Geopark, which represents an important milestone for knowledge and dissemination of the most interesting natural resources of this beautiful and distinctive territory. Geological heritage represents one of the cornerstones on which the Geopark rests as a formal entity and entitles the province of Granada to be part of a global network of spaces of great natural and cultural value recognized by UNESCO.

This document is the result of the work of many people who have selflessly involved themselves in this demanding project, offering their time and effort to turn the aspirations of the Geopark and its people into reality. With these words I would also like to convey my admiration and my gratitude for their work and dedication.

With this Geological Guide, both local people and visitors will be able to enjoy unique resources that make this territory incomparable, observing and understanding the nature of the most representative sites of greatest scientific and tourist interest in the Geopark and the processes that formed them, and to appreciate their true value in situ.

José Entrena Ávila
President of the Granada Geopark

preface

For a territory to be considered a UNESCO Global Geopark it has to have exceptional geological features that make it special. Other historical and cultural heritage aspects are also very important. In the Granada Geopark it is easy to understand the close relationship between geology and culture, between earth and history.

In this territory, geology brings an added value to all the fascinating historical and cultural features that attract so many visitors. The aim of this Geological Guide is therefore to help everyone who is interested to understand the most significant geological aspects of the Granada Geopark. Our intention is to enable the Geopark's visitors, local residents, teachers and students, as well as people professionally linked to this natural heritage, to know how the Granada Geopark was formed. With this knowledge, all of us together will be able to protect and preserve this wonderful territory.

The authors of this guide have made a great effort to explain the geology without sacrificing scientific accuracy. We are conscious of having oversimplified some issues at times so that everyone can understand them. However, we will not always have succeeded, owing to the technical characteristics of scientific language. We are also aware that we have not covered all the geological sites and issues of interest in the Granada Geopark. This first edition of the guide therefore starts out with the aim of improving and being revised and expanded in the future.

I had the good fortune to be born in a cave excavated in the bowels of the Quaternary continental sediments of the Granada Geopark. I have also been lucky enough to live and work for decades investigating various geological aspects of this territory. Now I have had the opportunity to coordinate this guide, which is intended as a starting point for many people to get to know the remarkable geological features of this spectacular land. As a geologist I feel privileged to have been born and to have worked in this place, and also to have worked with people who have made it possible to produce this guide, to whom I am deeply grateful for their commitment and confidence in me.

To my family, whose support has been vital for me to be able to pursue my professional life in this territory, and especially in memory of my father, Juan García Domingo, who was unable to see the Granada Geopark become a reality. He taught me to understand and love the Earth and I will always be grateful to him. This guide is dedicated to him and to everyone that loves this territory.

Francisco Juan García Tortosa

Geologist and Scientific Director of the Granada Geopark

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how to use this guide

This guide contains **8 chapters** describing the main geological features and issues that characterize the Granada Geopark. The first chapter is introductory, and the last is devoted to some of the best viewpoints in the Geopark. The other chapters consist of two parts:

The first sets out the basic **theoretical** aspects of the chapter and can be read in continuity with the previous chapter, as a textbook explaining the formation and evolution of the territory of the Geopark.

The second part has a more **practical** aim and is devoted to a description of some of the main **Sites of Geological Interest (SGIs)** related to the chapter. Moreover, for each SGI a sketch plan is included showing how to reach it, providing a QR code with which Google Maps will guide you to the vicinity of the SGI on your mobile phone.

NB: The parking areas and routes indicated on the access sketch plans **are for guidance only, and visitors are responsible** for parking and travelling in permitted areas, always respecting both nature and public or private property in all cases.

for study

for field trips

0 Lugares de Interés Geológico del Geoparque de Granada

1 Badlands/Cárcavas del Marchal
2 Badlands/Cárcavas de Fonelas
3 Badlands/Cárcavas de Dehesas de Guadix
4 Badlands/Cárcavas de Gorafe y Bácor-Olivar
5 Badlands/Cárcavas del Negratín
6 Cerro Mencal
7 Cerro Jabalcón
8 Yacimiento paleontológico Fonelas P-1
9 Yacimiento paleontológico Mencal-9
10 Yacimiento paleontológico Fonelas SCC-3
11 Yacimiento paleontológico Solana del Zamborino
12 Yacimiento kárstico de Darro
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16 Glacis de la Mesa de Bacaire
17 Tajos de la Carihuela
18 Fluviales de Belerda
19 Depósitos lacustres de Fonelas
20 Travertinos de los Baños de Alicún de las Torres
21 Discordancia angular de Gorafe
22 Cretácico Superior-Eoceno de Alamedilla
23 Lavas almohadilladas de Alamedilla
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27 Cerro de La Lancha
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62 Yacimiento paleontológico Barranco León-5
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65 Peña de Castril y cerrada del río Castril
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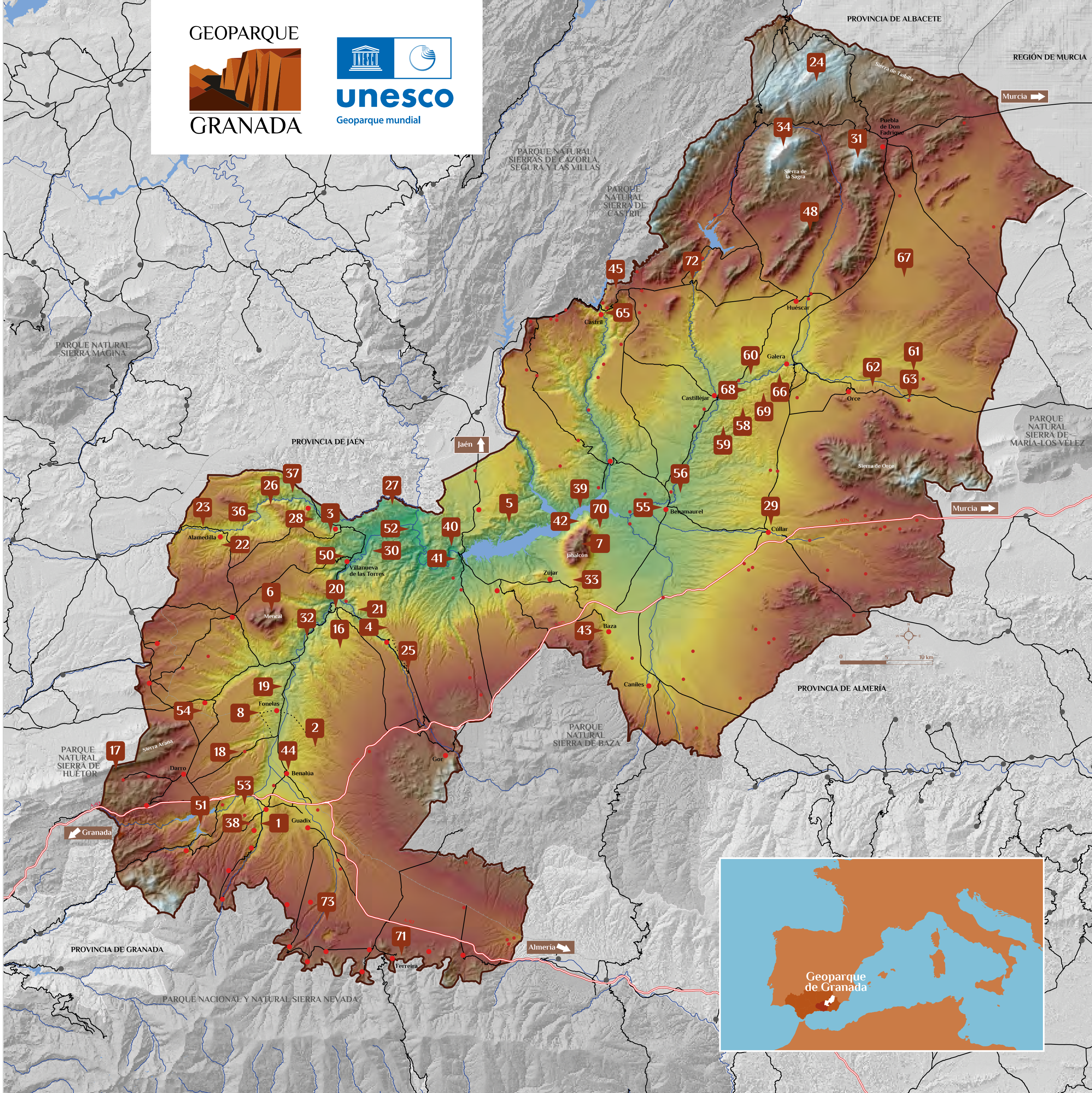
67 Cuenca endorreica de Bugéjar
68 Rambla de los Pilares
69 Sismitas de Galera
70 Falla de Baza
71 Falla de Ferreira (despegue extensional de Mecina)
72 Nacimiento y Valle del río Guardal
73 Minas del Marquesado



1

INTRODUCTION TO THE GRANADA GEOPARK

Panoramic view of the Granada Geopark from the west (Mencal) towards the east, with the Sierra de La Sagra in the background

One of the features that will surprise visitors is the conservation of the extensive territory containing the Granada Geopark in terms of landscape and nature.

Panoramic view of the badlands in the western sector (Desierto de los Coloraos or "Red Desert", Gorafe) with the snow-covered mountains of the Sierra de Cazorla in the background.

The Granada Geopark encompasses an area of 4,700 km^2 in western Andalusia. Its geological characteristics have marked the cultural development of its inhabitants since ancient times. Geology, geomorphology, prehistory and culture merge into an inseparable whole, in a territory with some of the oldest human remains in Europe, shaping an exceptional framework that is very useful for understanding the spirit of what a Geopark in the UNESCO Global Network represents.

The arid nature of the region, with sparse plant cover on the sides of its valleys and ravines, makes it easier to observe the main geological features that distinguish and characterize it. With the aid of this guide, the visitor will

Geomorphology plays a vital role in the Granada Geopark, not only in shaping its spectacular landscape, but because the characteristics of its relief are the gateway that provides access to the other exceptional geological values of the terrain.

Panoramic view of the badlands of the eastern sector (Castilléjar-Galera)

learn to appreciate sediments, rocks, fossils, strata, badlands, travertines, faults and folds. The Geopark's "language of rocks" conveys a fascinating history, of millions of years, that will enable visitors to enjoy its spectacular landscape to the full.

This great expanse of land in the Geopark all belongs to the same geographical unit, the drainage basin of the Guadiana Menor, and the same geological domain, the Guadix-Baza continental basin, giving the Granada Geopark a strong territorial identity (the Guadix and Baza depressions). Its territory is drained by a main watercourse, the River Guadiana Menor, a tributary of the Guadalquivir, which flows into the Atlantic Ocean, so its waters (and the sediments they carry) make a journey of hundreds of kilometres to that ocean.

Most of the Granada Geopark's Sites of Geological Interest lie within the river valleys downcut into this collection of sediments and continental rocks.

Panoramic view of the Gorafe Angular Unconformity (River Gor Valley)

Alamedilla pillow lavas. The geological periods from the Triassic to the Quaternary are represented in the valleys of the Granada Geopark. The basement rocks show us remains of the ancient supercontinent Pangaea; they chronicle the evolution of the Mesozoic seas, with traces of ancient ocean floors where submarine volcanoes generated pillow lavas which now form mountains within the Geopark, and also enable us to recognize remnants of Cenozoic seas, with rocks containing milestones in the history of the planet, such as the Palaeocene-Eocene thermal maximum. In addition, they provide us with information on the last marine stage before the continentalization of the territory, with rocks rich in marine fossils and unconformities that mark the beginning of the continental stage (Chapters 3 and 4).

The eroded sediments in the Guadix-Baza Basin are transported by the local river to the Guadiana Menor, and then to the Guadalquivir, which finally carries them to the Atlantic Ocean.

But until only half a million years ago, this territory had no connection to the sea (it was an endorheic basin), becoming a "trap for sediments and remains of organisms of the past", which **represents one of the best continental records for the Quaternary period** (the past 2.58 million years) on the entire planet.

The river valleys of the Granada Geopark give us access to geological information with very unusual features that extend beyond the Quaternary period, described in the various chapters of this guide.

The erosion by the rivers and their vertical downcutting have made it possible for the more ancient rocks, those that have acted as the substrate or basement of this basin, to be observed at the bottom of the valleys and under the more recent sedimentary rocks (from the last 5 million years), enabling us to tell **a story that goes back more than 250 million years**.

Galera seismites

The more recent rocks contain striking structures that constitute unique examples of seismites, of international importance. These structures show us ancient earthquakes that occurred during the Pleistocene (Chapter 5), like a gigantic seismogram drawn in the rocks.

This guide tells the geological history of the Granada Geopark through six chapters which describe the main events recorded in the sediments, rocks and fossils to which we have access from the valleys. Each chapter contains a first part with a synthesis of the geological history of each of its stages, and a second part describing some of the most important *Sites of Geological Interest* (SGIs) accessible to visitors.

Although the Granada Geopark tells a history of more than 250 million years from the bottom of its valleys, the leading geological actors in the story of the Geopark were an ancient river and an ancient lake. For some 6 million years, when the basin had no outlet to the sea (Chapter 4), they produced an exceptional record of sediments from the Pliocene and Pleistocene epochs. In these sediments the most territorially and chronologically extensive set of palaeontological deposits of continental vertebrates of the Quaternary period

Interior of the River Fardes Valley Palaeontological Station (Fonelas P-1 Palaeontological Site)

There are hundreds of known palaeontological deposits in the Granada Geopark, with thousands of fossil remains studied so far, which speak to us of primitive mammalian ecosystems with the presence of strange and unexpected species ("lost worlds" at the start of the Quaternary).

in Europe has been uncovered, most notably those that appear in Lower Pleistocene sediments, which are especially rich in skeletal remains of large vertebrates, with over 150 locations identified (Chapter 6).

The last great geological event, still in progress, which is the exorheic stage with the erosion of sediments and the downcutting of valleys, as well as revealing these pages of the recent history of our planet, has shaped an impressive landscape of badlands, which is the main hallmark of the territory.

The last chapter of the guide (Chapter 8) is devoted to the Viewpoints of the Granada Geopark. These offer us a visual summary of the various geological and geomorphological aspects of the Geopark's geological history. From these viewpoints, people can, if they prefer, enjoy a quick, convenient and direct way of appreciating the main values that make this territory a UNESCO Global Geopark.

The erosional action of river courses during the last half million years has produced spectacular fluvial landforms in this territory. The outstanding feature is its badlands landscape, which can be considered the primary element of the Geopark's territory from a geomorphological point of view. It also contains many other values, not only geological and geomorphological, but also prehistoric, historical, cultural and biodiversity-related.

Badlands landscape in the western sector (Guadix district)

Barranco León-5 archaeo-palaeontological site

The Early Pleistocene fossils include those that currently represent some of the oldest known human remains in Europe. Along with other types of large vertebrates, such as sabre-toothed cats and mammoths, they are presented in Chapter 6.

Toril aqueduct

In the vicinity of the Alicún de las Torres Spa, the thermal waters have produced rock formations called travertines. The most remarkable of these are the ones that have formed the Toril aqueduct (Chapter 7).

Gorafe dolmen no. 404 (upper photo) and Castellón Alto archaeological site in Galera (lower photo)

In the Granada Geopark geology and archaeology inseparably merge. Magnificent examples of this symbiosis are the Gorafe dolmens and the Argaric site of Castellón Alto. The type of sediments and rocks, as well as the geomorphology of the two areas, determined and made possible the creation of these important sites.

Upper photo: Gorge of the River Guardal (Huéscar).

Lower photo: Jabalcón Viewpoint (Zújar).

The shaping action of water has been responsible for the present landscape of the Granada Geopark. The river valleys are its leading players, not only because of the landscape they offer us, but also because they are a window on a rich geological heritage.

The most characteristic type of accommodation in this area is cave-houses, ancient dwellings excavated directly in the Pliocene-Quaternary sediments of the Guadix-Baza Basin. Many of them have been converted into tourist accommodation. They are places to enjoy a unique experience of relaxing in an environment where silence and withdrawal are the order of the day and whose relationship to geology is obvious.

The landscape of the Granada Geopark as a whole recalls some famous and much-visited locations in other continents on the planet. However, unlike those places, people have lived continuously in the territory of this Geopark for millennia and have preserved the landscape intact for hundreds of generations.

A magnificent example of that relationship between people, landscape and geology is the development, over centuries, of original dwellings excavated in the sedimentary rocks of the Geopark that have now been converted into a wide range of rural accommodation. These dwellings are known in the territory of the Granada Geopark as **caves** and **cave-houses**.

Gorafe Angular Unconformity

2

THE GRANADA GEOPARK: MORE THAN 250 MILLION YEARS OF HISTORY

The geological history of the Granada Geopark involves travelling back in time to the Triassic period, some 250 Ma (million years ago). But this is also a journey in space, which begins on the last supercontinent that existed on Earth and continues through ancient seas and oceans, now extinct, whose remains within the Granada Geopark tell us of the main geological events that made its great geodiversity and extraordinary heritage possible.

Rivers and saltwater lagoons in the Pangaea supercontinent

The history of the Granada Geopark begins in the Triassic, a special period in the Earth's history when there was a single supercontinent known as ***Pangaea*** (Fig. 1). During the Late Triassic (230–200 Ma), the Earth's climate was arid. Pangaea contained large rivers that deposited reddish clays, silts, sands and conglomerates. The coasts of this great supercontinent were surrounded by shallow seas and coastal lagoons where large accumulations of evaporites (gypsum and halite) and carbonate rocks (limestones and dolomites) formed. In the Geopark we find vestiges of these rocks of Triassic age in various places, including magnificent outcrops in the Fardes and Guadiana Menor river valleys. The latter contains notable outcrops downstream of the Negratín Reservoir.

Towards the end of the Triassic Period, Pangaea began to break up and separate into several fragments, which ended up forming new continents and tectonic plates. Some of those fragments are key to the history of the Granada Geopark, such as those that eventually became Iberia, Africa and a small third continent whose rocks now adjoin Iberia and Africa.

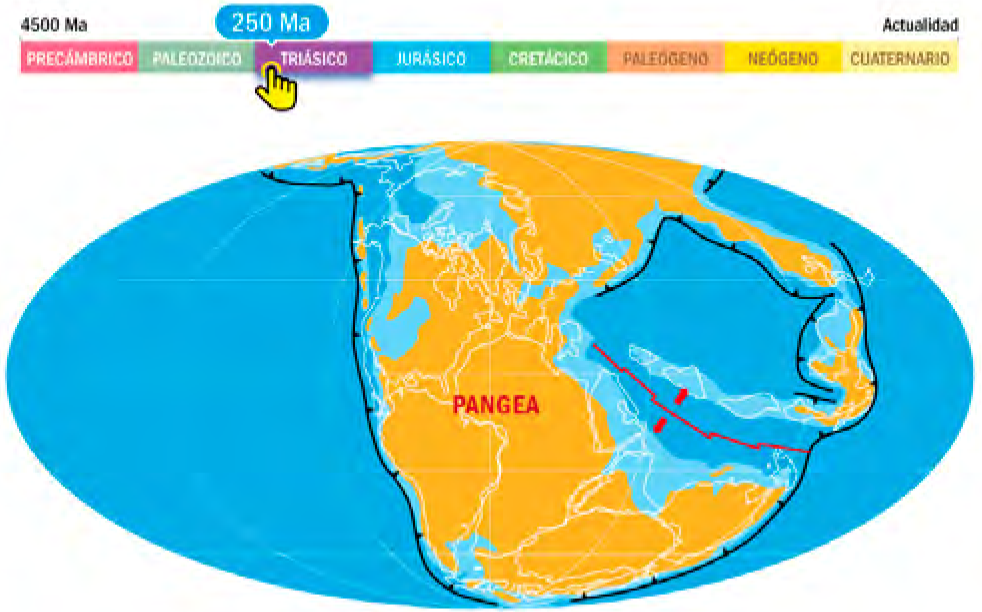


Figure 1. Palaeogeographical map of the Earth during the Triassic Period, 250 million years ago (Ma). Pangaea was the single great continent emerging from the waters at that time.

The new continents move apart

Although Pangaea had begun to break up at the end of the Triassic, it was in the Jurassic that the effects of its fragmentation began to have significant consequences (Fig. 2). The Atlantic Ocean began to open up. During the Jurassic Period and part of the Cretaceous, Iberia gradually separated from Africa. Between these emerged territories an ocean, known as Tethys, opened up. Marine sediments deposited in this new ocean are now part of the mountains of the Geopark (such as Mencal, Jabalcón, La Sagra and the Sierra de Baza).

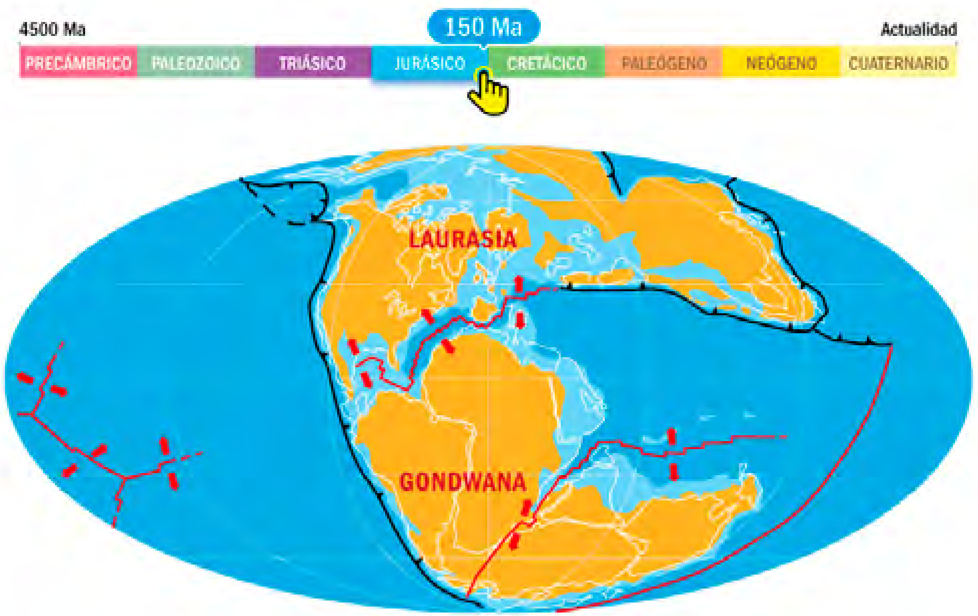


Figure 2. Above: Palaeogeographic reconstruction of the Earth at the end of the Jurassic Period (150 Ma)

Below: During the Cretaceous Period (100 Ma) the African and Eurasian plates were moving apart, producing the Tethys Ocean.

Although all these mountains are now very close together, the sediments that gave rise to them accumulated in two large areas which were very far apart. The sedimentary rocks which make up the group of mountains that form the northern edge of the Geopark, as well as Mencal, were laid down southeast of Iberia. These rocks, mostly marine sedimentary rocks, form what we now call the **External Zone** of the Betic Cordillera. On the other hand, the rocks of Jabalcón and most of those that form the mountains in the southern part of the Geopark were deposited much further away to the east, in the region of the Tethys Ocean that was to become part of the **Alboran plate** millions of years later. The rocks that belonged to this small Alboran tectonic plate form part of what is now known as the **Internal Zone** of the Betic Cordillera. Later on we will see how they reached their current position.

In this context in which the plates were moving apart, the Earth's crust fractured, and numerous normal faults formed in southern Iberia, creating a stepped relief of the seabed. From then on there were two distinct major domains southeast of Iberia: (1) a very shallow sea on its southern coast (future Pre-Betic) and (2) a pelagic sea further away from Iberia characterized by furrows and sills, with large steps like piano keys in the seabed (future Sub-Betic) (Fig. 3).

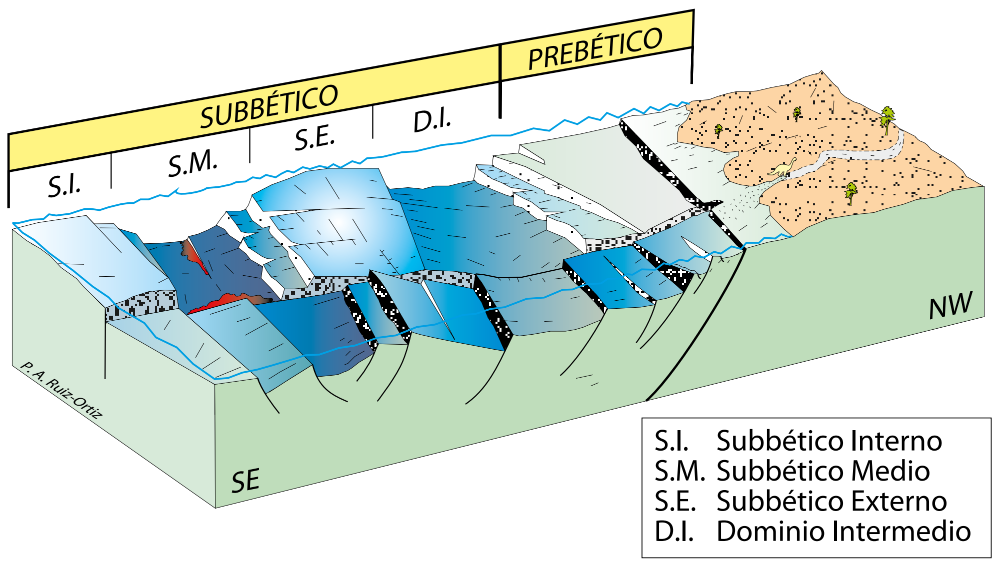


Figure 3. Palaeogeographic reconstruction of the Pre-Betic and Sub-Betic domains of the future External Zone of the Betic Cordillera. Taken from Ruiz Ortiz, P.A.

DID YOU KNOW...?

About 6 km south of the Alicún de las Torres Spa in the direction of Fonelas (km 3.5 on the GR-5103 road, parallel to the River Fardes, next to Cortijo de Victoriano) there are some dark greenish Cretaceous marls and clays, very rich in a type of clay called BENTONITES. These belong to what is called the Fardes Formation and are formed by minerals that increase in volume by trapping water molecules in wet periods and return to their original volume when they lose that water in periods of drought. For that reason, minerals of this kind are known as expansive clays. Their origin is partly related to volcanic rocks formed at the bottom of the ancient Tethys Ocean, south of Iberia. After their formation these rocks underwent a major chemical change and were mixed with marine sediments. The landscape formed by these clays has practically no vegetation, as they are so crumbly that plants find it difficult to fix their roots. The setting in which they appear is a place of great scenic beauty, which we will examine in more detail in Chapter 8 (Cerrada de la Lava Viewpoint in the River Fardes valley).

Outcrop of bentonites in the vicinity of Cortijo de Victoriano (SGI 32).

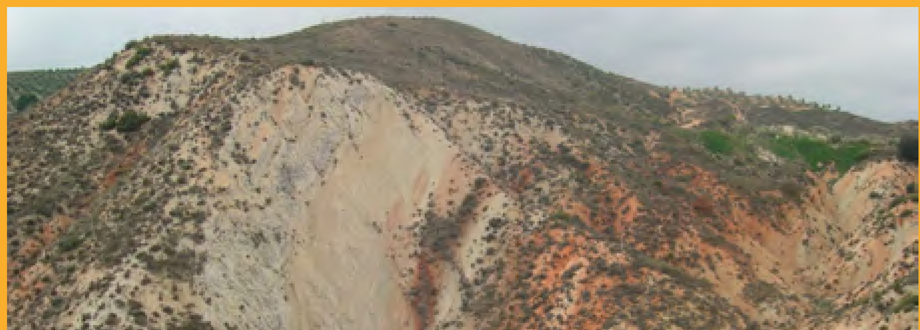
A change in plate tectonics: the convergence of Iberia and Africa

Approximately 70 million years ago a radical change took place in the movement of the tectonic plates. Eurasia and Africa began to move closer together, and several million years later the Iberian plate became part of the Eurasian plate. As a result of the convergence of Africa and Eurasia, the Tethys Ocean gradually began to close up. Meanwhile, some of the sediments that gave rise later to the Tertiary rocks were deposited. We can now find them in many places in the Granada Geopark and the mountains that surround it. As we will see later, both these Tertiary rocks and the more ancient ones (Triassic, Jurassic and Cretaceous) are found not only in the mountains but also at the bottom of the valleys of the Geopark. This enables us to tell this whole amazing geological story from the bottom of our valleys (Fig. 4).

Figure 4. Dominated by the Mencal peak, the River Fardes valley and its rocks contain much of the geological history that gave rise to the territory of the Granada Geopark.

DID YOU KNOW...?

In the rocks of the Alamedilla sector, in the northwestern part of the Granada Geopark, there are traces of one of the most important climatic events in the Earth's history, known as the PALAEOCENE-EOCENE THERMAL MAXIMUM. Fifty-six million years ago, the average temperature of the Earth increased by 6 °C, which caused a considerable rise in sea level and a warming of the oceans, abruptly altering the oceanic and atmospheric circulation. The consequences for life on the planet were devastating. It resulted in the extinction of a host of marine organisms and led to great changes in terrestrial mammals, marking the appearance of current lineages.



Stratigraphic sequence with the thermal maximum.

A collision between continents: the origin of the Betic Cordillera and the Guadix-Baza Basin

About 25 million years ago, a small tectonic plate in the western Mediterranean acquired an individual identity: the ***Alboran plate*** (Fig. 5). Some of the rocks in this plate had undergone intense deformation processes, with high pressures and temperatures which transformed them into metamorphic rocks.

As the two large plates of Eurasia and Nubia (Africa) moved closer together, the Alboran plate shifted westward. Its journey ended when it collided with the south of Iberia and the north of Africa (Figs 5 and 6). The collision began just over 20 million years ago and lasted for several million years more, causing the rocks deposited in southern Iberia (which form what we now call the External Zone) to begin to fold and fracture.

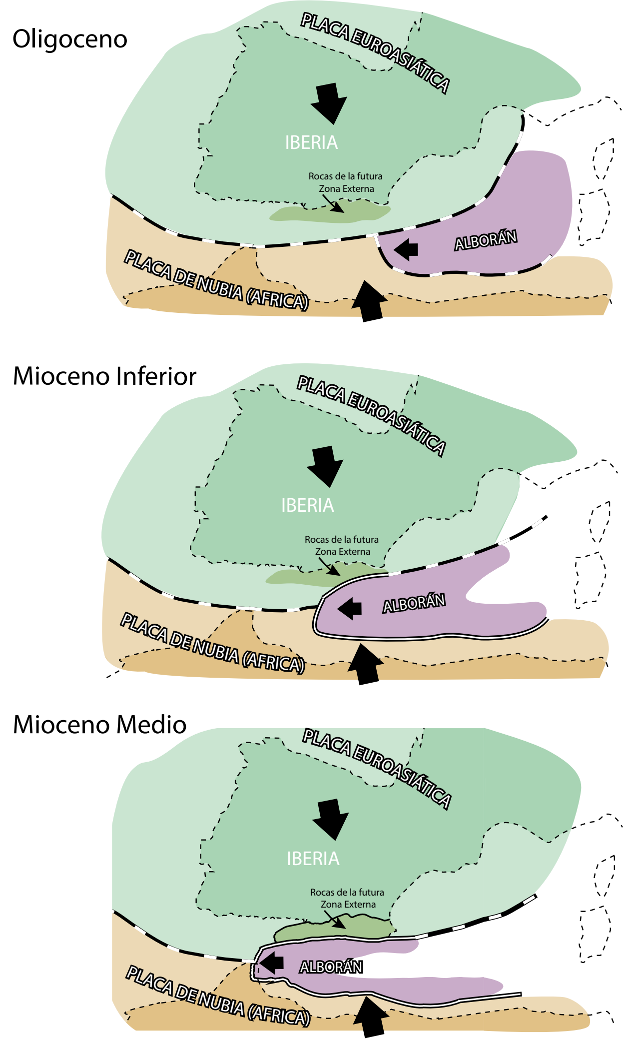


Figure 5. Palaeogeographic evolution of the Alboran plate, compressed during the convergence of the Nubian and Eurasian plates.

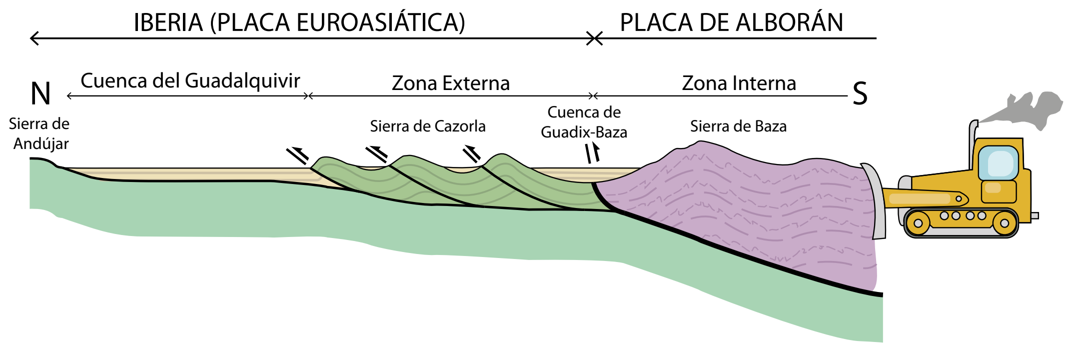


Figure 6. Schematic N-S geological cross-section of the Betic Cordillera. The approach of the Alboran plate produced raised areas together with intramontane depressions. One of the latter was to be the Guadix-Baza Basin, where the Granada Geopark is located.

The ***Betic Cordillera*** had begun to form. Collision and deformation started to raise the seabed, so that small reliefs began to emerge. At that time, the landscape was characterized by small islands separated by marine corridors, where sediments accumulated. One of these corridors was to be the origin of the Guadix-Baza Basin (Fig. 8).

Therefore, the collision between these tectonic plates gave rise to a configuration in which rocks of the External Zone and of the Internal Zone, which had originally formed in places very far apart in the Tethys Ocean (some even in pre-Tethys times), appeared adjacent. The sedimentary rocks of the Guadix-Baza Basin were subsequently deposited on top of these rocks of different origins, in a stage of the geological history that we describe below.

In other words, the rocks of the External Zone and of the Internal Zone form part of the **basement** of the Guadix-Baza Basin. That is to say, they are the substrate or "vessel" on which the more recent sediments of the Granada Geopark were deposited (Figs 7 and 9).

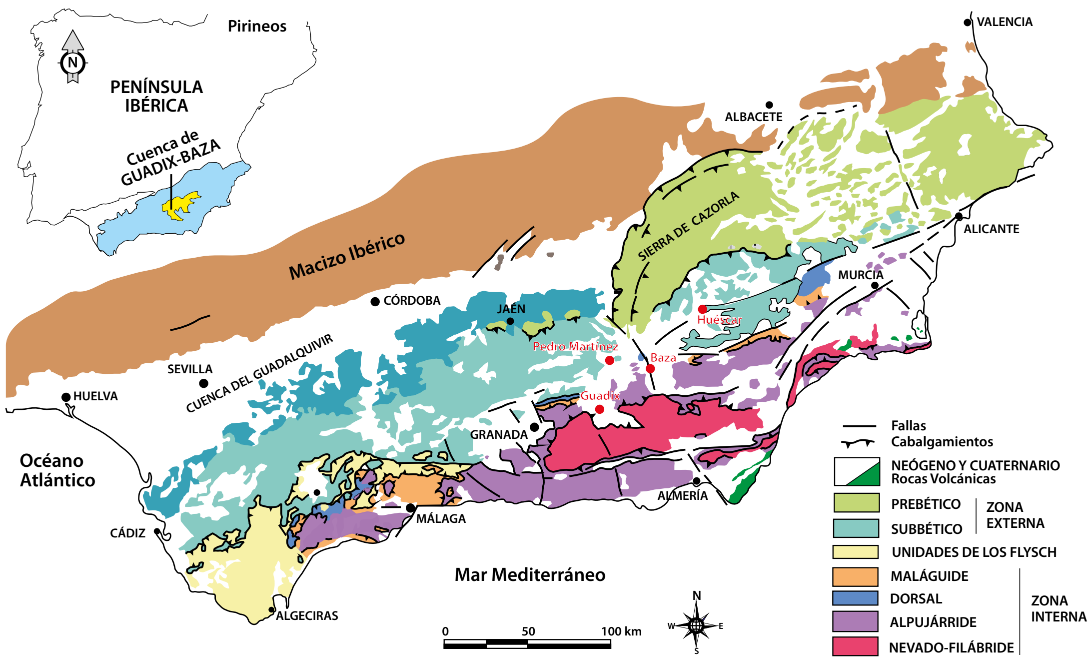


Fig. 7. Geological map of the Betic Cordillera. Modified from Carlos Sanz de Galdeano.

The formation of the Guadix-Baza Basin

In the Late Miocene, approximately 8 million years ago, the elevation of the reliefs that emerged due to the plate collision began to be significant, both to the north (elevation of the Cazorla and Segura, Castril and Huéscar ranges, etc.) and to the south (elevation of Sierra Nevada and the Baza and Filabres ranges, among others). At that time, the Guadix-Baza Basin acquired a profile similar to the one it has now. This is when it can be said that its history as a sedimentary basin started (Fig. 8).

The Guadix-Baza Basin provided the last oceanic connection between the Mediterranean and the Atlantic. This adds a special importance to the study of the basin's marine infill, both for its implications from a palaeoecological point of view, associated with the interaction between two water masses, and for helping us to discover in detail how the total or partial isolation of the Mediterranean Sea occurred.

Sea regression in the Guadix-Baza Basin: the endorheic continental stage

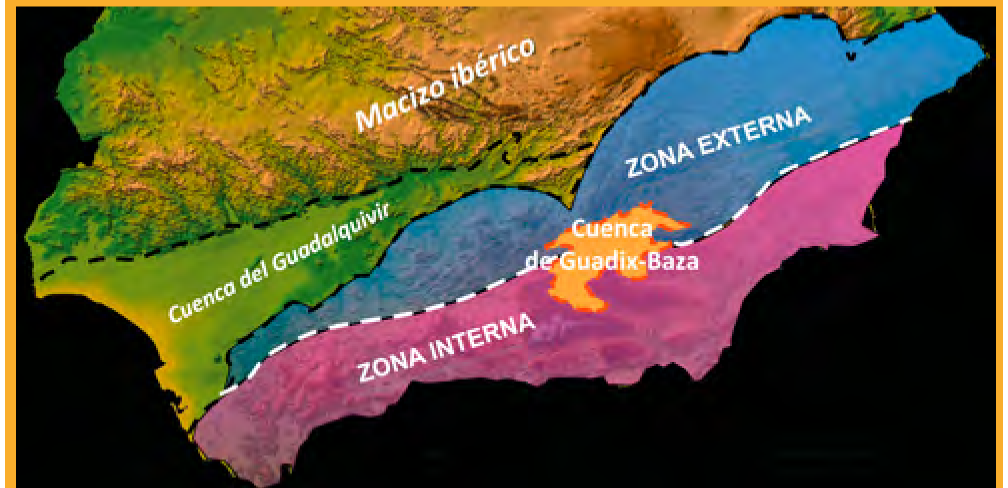
Collision between tectonic plates is a process that lasts several million years. This situation, over a prolonged period, caused a continued rising of the territory of the Guadix-Baza Basin, as well as of the Betic Cordillera as a whole. At a certain point, at the end of the Late Miocene epoch (about 7 million years ago), the basin rose so high that it was above sea level and was disconnected from the Mediterranean and the Atlantic. At that point, the Guadix-Baza Basin was left isolated and surrounded by mountains with a relief very similar to the present one. The basin became ***endorheic***, that is, an emerged territory in which the rivers had no outlet to the sea. In the case of this basin, they flowed into a large lake located in the eastern half of the Granada Geopark: the ***Baza palaeolake*** (Fig. 8).

In the western half, for the most part, fluvial systems with detrital sedimentation developed, draining their waters to the east via a main river, the ***palaeo-Fardes***, flowing into the Baza palaeolake. Significant accumulations of carbonate and evaporitic sediments were deposited in this lake. These sediments constitute one of the best continental stratigraphic records in the world for the Quaternary, especially for the Pleistocene.

The continental stage lasted more than 6 million years. During that time, the landscape of the territory was dominated by a glacis, that is, an extensive plain, with the palaeo-Fardes river running across it and the Baza palaeolake in the eastern part. Large mammal fauna lived together on the banks of the river and the shores of the lake (see Chapter 6), forming a landscape very similar to the African savanna today.

DID YOU KNOW...?

The Granada Geopark includes an ancient PLATE BOUNDARY. The northern part (External Zone) belongs to the rocks that were deposited southeast of Iberia, whereas the southern part (Internal Zone) consists of metamorphic rocks from the Alboran plate. This plate boundary ceased to be active a few million years ago and is currently covered by the most recent sediments that have filled the Guadix-Baza Basin.



Geological context of the Betic Cordillera. The Guadix-Baza Basin is an intramontane depression in the centre of the cordillera, just above an old tectonic plate boundary.

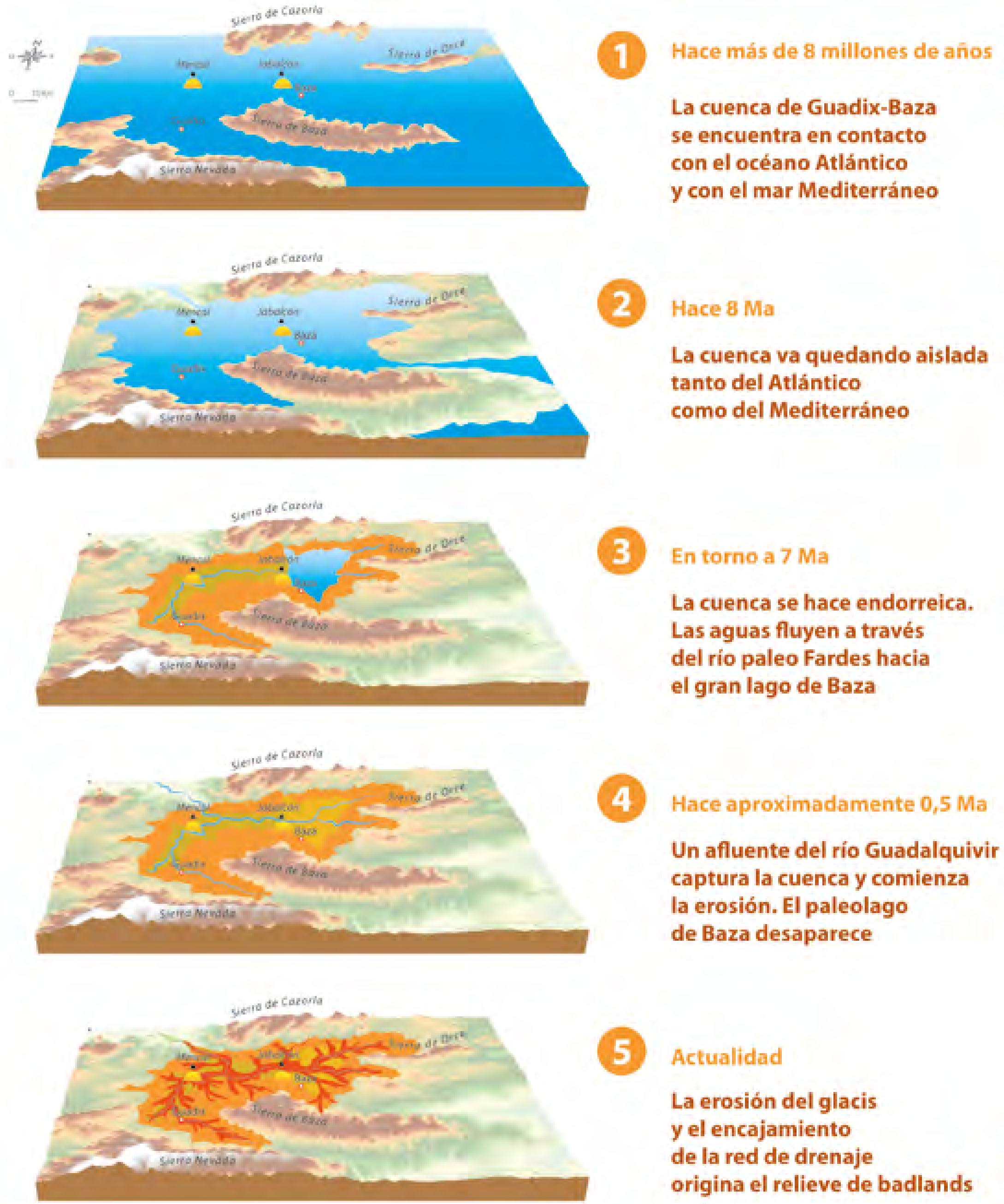


Figure 8. Palaeogeographic evolution of the Guadix-Baza Basin over the last 8 million years.

Initially connected to the open sea, it became an endorheic continental basin, with no outlet to the sea, for some 6 million years. Later, approximately 0.5 million years ago, it came to form part of the drainage basin of the River Guadalquivir and flow into the Atlantic Ocean.

Erosion and emptying of the basin: the current landscape

The last stage of the geological history of the Geopark began approximately half a million years ago, in the Middle Pleistocene. To the north of the Guadix-Baza Basin runs the Guadalquivir. This great river and its tributaries gradually eroded the valleys through which they flowed, making them deeper and longer. The drainage basin of one of the tributaries of the Guadalquivir (now called the Guadiana Menor) grew to the point that it reached the Guadix-Baza Basin. The effect of this process, known as river capture, was that the basin came to have an outlet to the sea. In other words, it ceased to be endorheic and became exorheic. The high average altitude of the depression in which the Granada Geopark lies, the semiarid climate and the high erodibility of the materials that make up the sedimentary infill have facilitated the deep downcutting of the current river network: up to more than 200 m in some valleys.

As soon as the capture occurred, erosion gained the upper hand over sedimentation in the basin. The break-up of the glacis began, resulting in the development of a still active landform of badlands and the formation of the river valleys and terraces that characterize this territory. In these terraces we can discover and read the last chapters of this geological history, which is directly linked to the history and culture of the people of the Granada Geopark.

This current erosion process is key for the Granada Geopark, because it has exposed its rich and varied geological heritage to us, highlighting the great palaeontological sites and the spectacular landscape of badlands, both of which are hallmarks of this territory. And the most exciting aspect is that the relief is still active, tectonics is still at work owing to the current convergence between the Eurasian and Nubian (African) plates (see Chapter 5), and the downcutting of the valleys is following its course (see Chapter 7).

THE STORY CONTINUES...

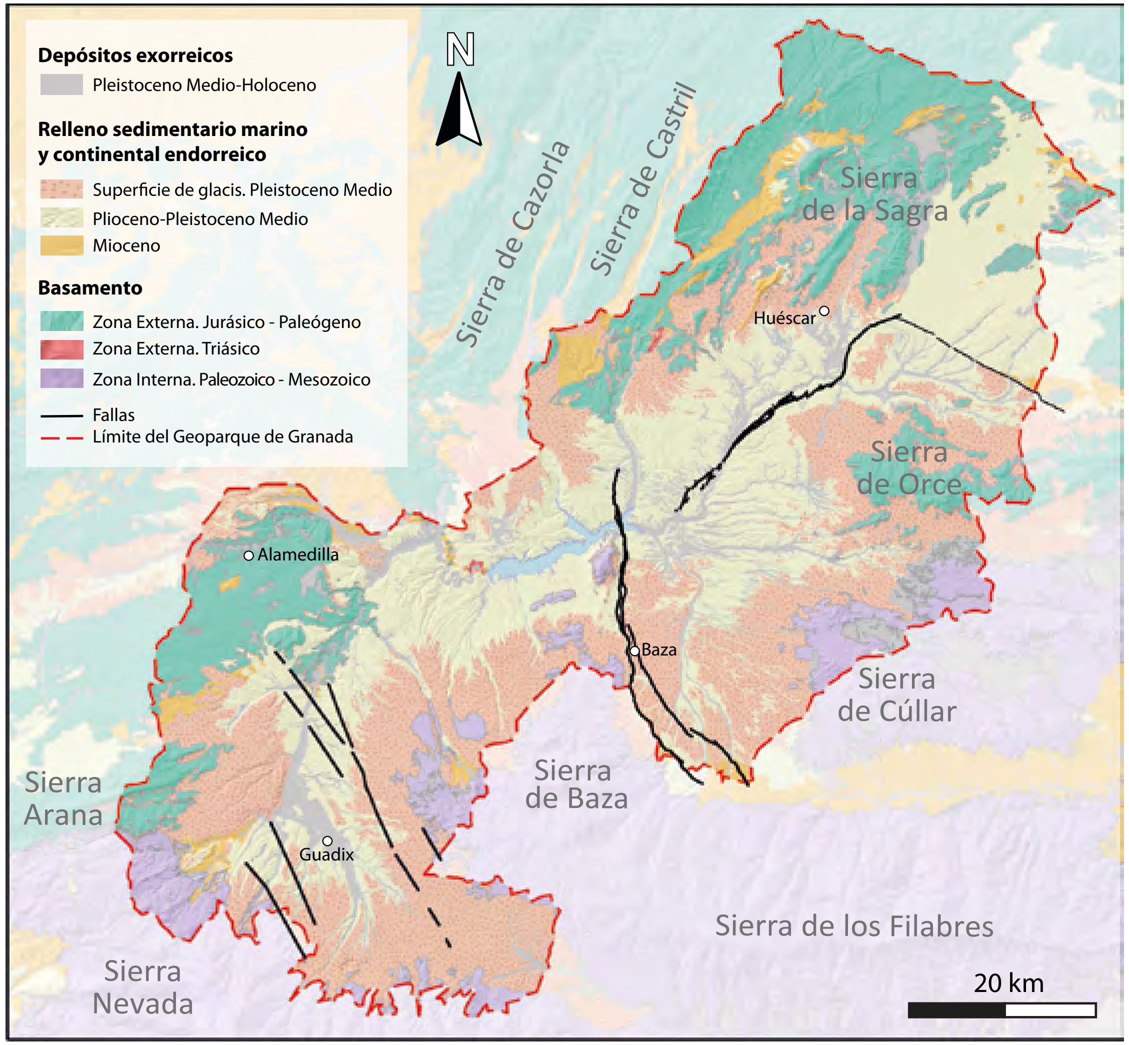


Figure 9. Geological map of the Granada Geopark.

Geology determines the three landscapes that characterize the Geopark:

1. **The mountain ranges**. The basement consists of the rocks of the Internal Zone of the Betic Cordillera, to the south, and of the External Zone, to the north.

2. **The great plain**. The glacis extends from the foot of the mountains and covers a large area.

3. **The river valleys**. The area highlighted in a yellowish colour is being eroded and gives rise to the unique landscape of badlands.

THE TRIASSIC OF THE GUADIANA MENOR

SGI 40

Figure 1. Negratín outcrop of Triassic materials (lutites, sandstones and gypsums).

In the valley of the River Guadiana Menor, downstream of the Negratín Reservoir, there is an exceptional outcrop of Triassic rocks. It is made up of gypsum, clays of intense colours, red, yellow and green, and layers of limestone and dolostone (Fig. 1). Among the Triassic rocks, enclaves of volcanic rocks (basalts) and subvolcanic rocks (ophites, Fig. 2) with *sill* and *dyke* geometries can also be observed.

The rock assemblage that appears in this outcrop has been classified as an ***olistostrome***. This is defined as a sedimentary deposit that consists of a chaotic mass of rocks composed of large blocks of more ancient material embedded among more recent materials. The origin of olistostromes is generally associated with large submarine landslides, which produce a mixture of older and younger rocks. However, this particular outcrop does not show the arrangement just described, and the Triassic materials lie underneath a substantial pile of sedimentary rocks in which more recent ones can be seen (from the Jurassic, Cretaceous and Tertiary Periods).

In other nearby outcrops in the Guadiana Menor valley, the Triassic rocks that appear are associated with diapiric processes. These are processes of extrusion of materials due to differences in density and mechanical behaviour compared to those around them (Fig. 3). The Triassic materials, with abundant clays and gypsum, have a lower density than the rocks positioned above them (a pile of rocks of between Jurassic and Tertiary age) and are capable of flowing when subjected to stresses.

In this region, the stresses produced by the collision between the Eurasian, Alboran and Nubian (African) plates caused these Triassic clays and gypsums to rise along numerous fractures.

Figure 2. Outcrop of subvolcanic rocks (ophites) intruded between Triassic clays and gypsum.

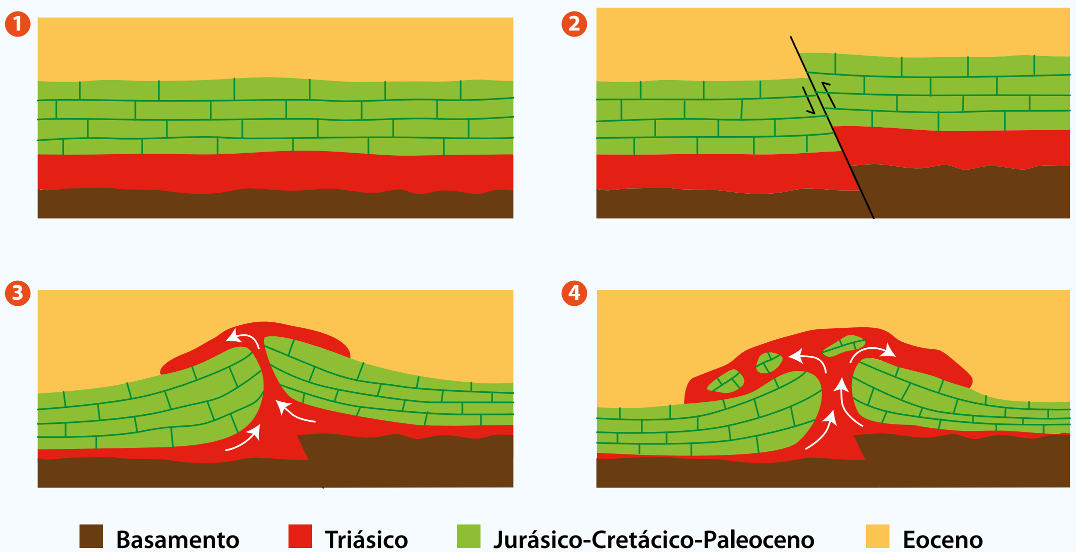


Figure 3. How a diapir associated with reverse faults works.
The less dense materials, such as gypsum and clays (in red), rise along the fractures, passing through the denser and more resistant upper materials.

MENCAL AND JABALCÓN: TWO ICONIC MOUNTAINS IN THE GRANADA GEOPARK

SGI 06, 07

Mencal and **Jabalcón** are two iconic mountains that tower over the predominant relief of the Granada Geopark, the great plain or glacis, at an average altitude of around 1,000 metres (Fig. 1).

With a maximum height of nearly 1,500 metres, their summits offer magnificent views of the Geopark. Indeed, one of the most spectacular viewpoints in the whole territory is on Jabalcón.

Both mountains are composed mainly of Jurassic limestone. However, despite their current proximity and similarity, most geologists who have studied their rocks believe that they have very distant origins within the Tethys Ocean. Mencal's sediments were deposited in southeast Iberia, relatively close to their present position. By contrast, those of Jabalcón were laid down many kilometres away to the southeast. The present position of Jabalcón's rocks is connected to the long westward journey of the Alboran plate until it collided with Iberia.

One of the most interesting aspects of Mencal and Jabalcón is that they have both been inselbergs or "island mountains" for millions of years. At first, they were two mountains in the last sea that existed within the Geopark. Subsequently, when the basin became continental, both of them continued to stand out in the territory (Fig. 2). The products of their erosion also form part of the Pliocene and Pleistocene sediments of the Granada Geopark.

Figure 1. Above. Panoramic view of Cerro del Mencal (1449 m) taken from the southeast.
Below. Panoramic view of Jabalcón (1494 m) taken from Mencal (west).

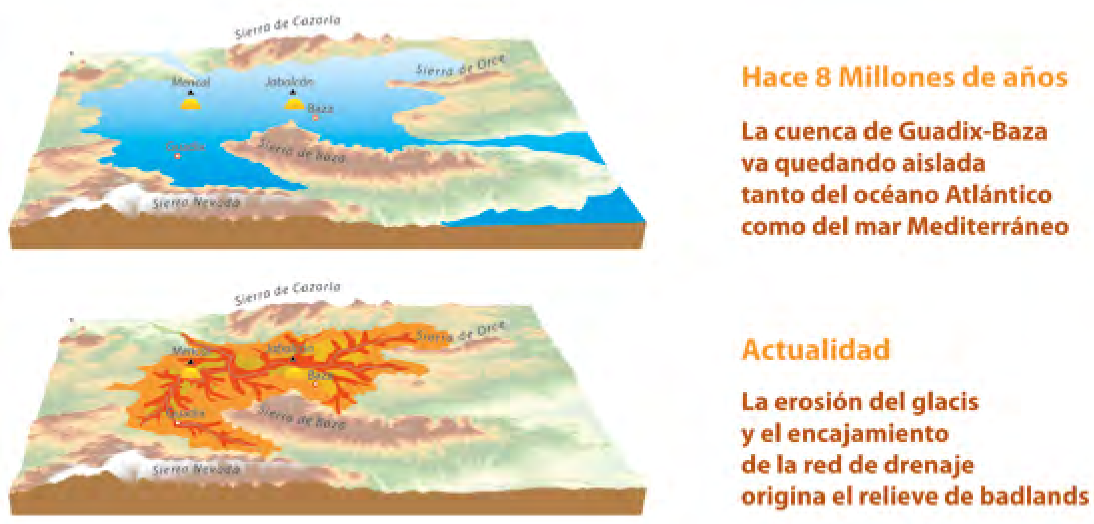


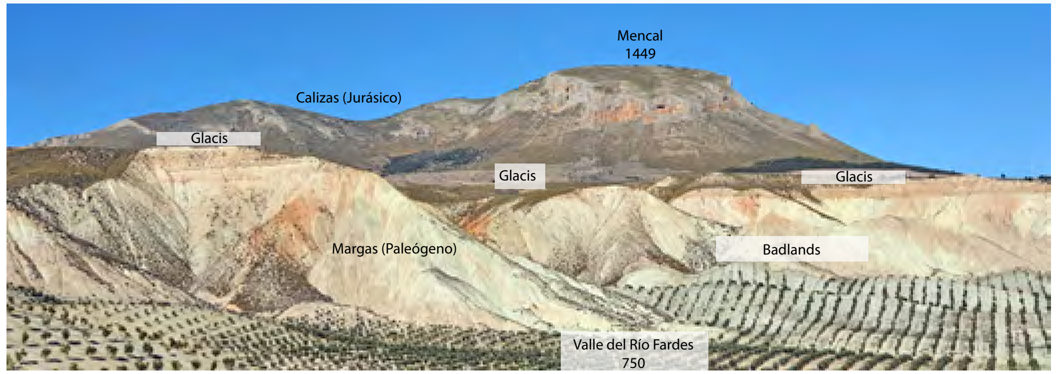
Figure 2. Palaeogeography of the Guadix-Baza Basin showing the position of the two inselbergs or "island mountains", Mencal and Jabalcón.

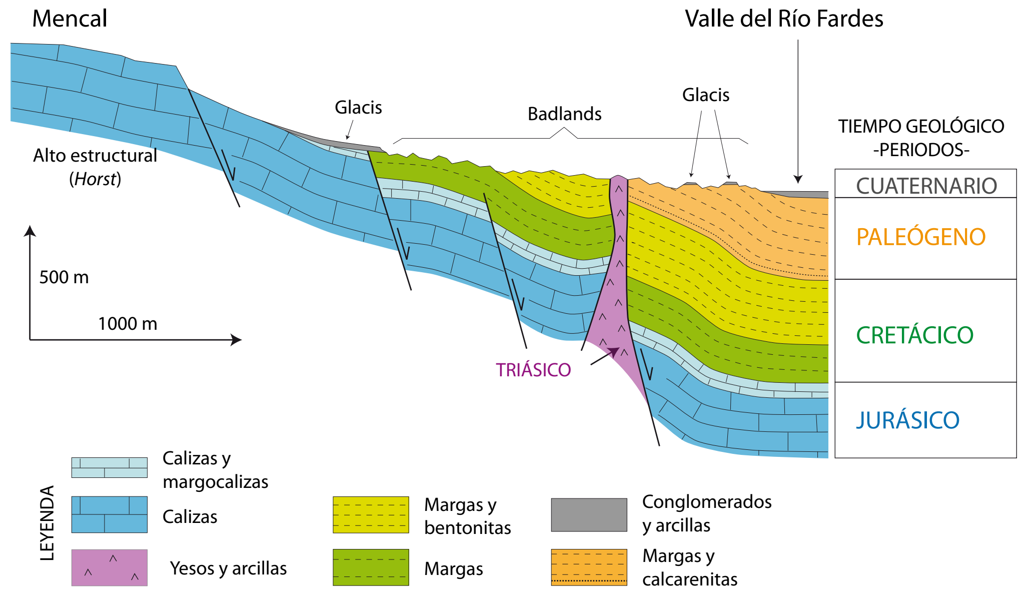
MENCAL

Main geological features

Cerro Mencal is composed of white limestone with a thickness of more than 300 metres, deposited in a shallow sea during the Early Jurassic epoch. Marly limestones, marls and pelagic radiolarites, with ages ranging from Lower Jurassic to Upper Cretaceous, were deposited on top of this white limestone (Fig. 3), on a sea with an irregular bottom. These rocks show us a complex history with stages of deposition, emergence, erosion and fracturing during the Jurassic and the Cretaceous, due to the opening-up of the Tethys Ocean and rising and falling sea levels.

Figure 3 (next page). Between Mencal and the River Fardes there is a magnificent continuous sequence of rock layers from the Jurassic, Cretaceous and Palaeogene (from 200 million to 23 million years ago). Cerro Mencal stands out in the landscape thanks to normal faults which produce a stepped structure called a horst. On the slopes of Mencal the badlands develop in much older rocks than in most of the Geopark, where they usually erode rocks from the Pliocene and Pleistocene epochs.





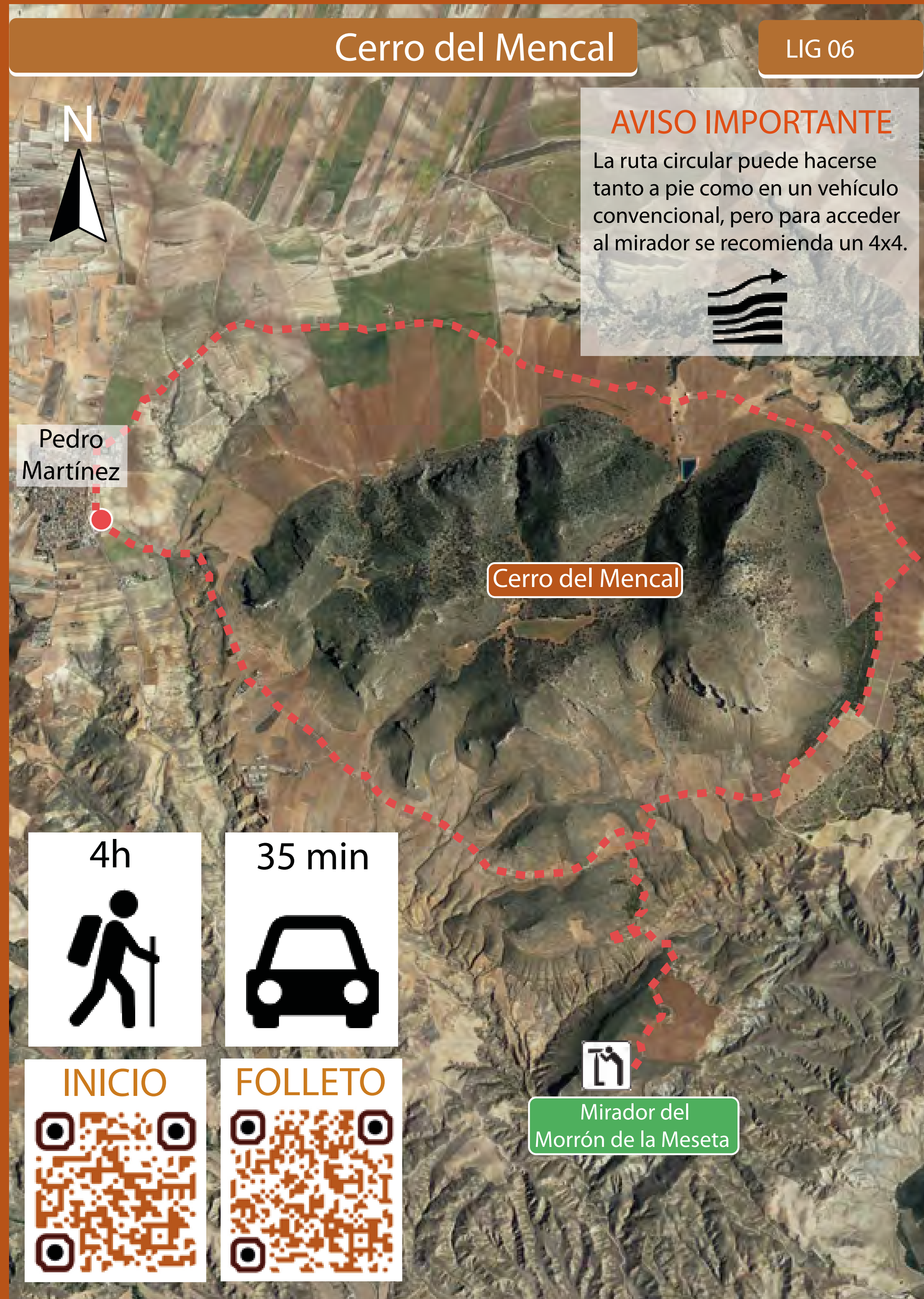
JABALCÓN

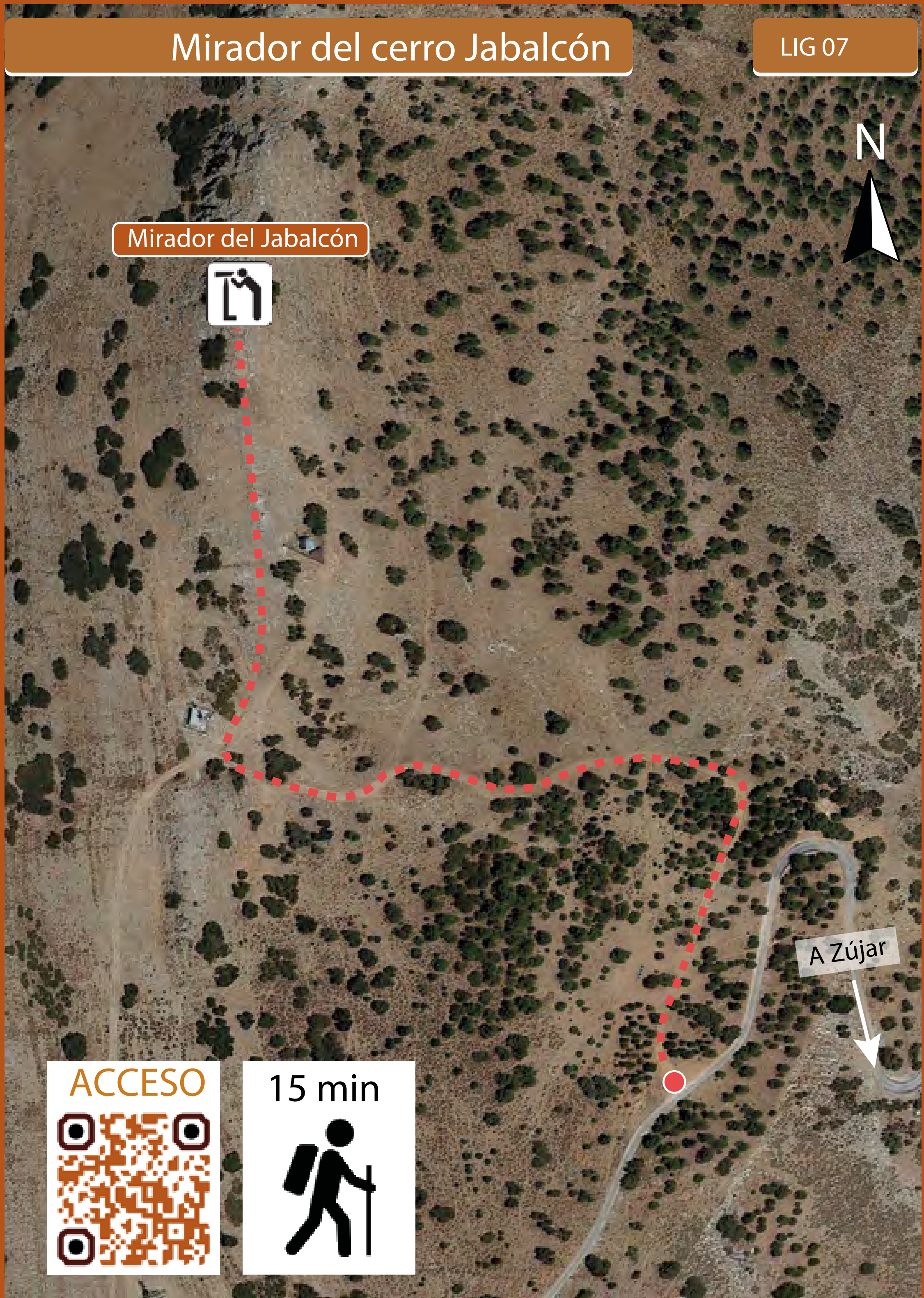
Main geological features

Cerro del Jabalcón is mainly composed of Early Jurassic limestones and dolostones. The dolostones, dark grey in colour and at least 150 metres thick, outcrop at its northern end, in the vicinity of the Zújar Thermal Baths. Overlying the dolostones are more than 450 metres of white or grey limestones, which constitute most of the mountain. These rocks, like the more ancient ones of Mencal, were also formed in a shallow sea, but in a position further from Iberia. In the upper part of this set of layers, the limestones have some nodules and banks of black flint. On the summit of Jabalcón and the slope that descends from the Virgen de la Cabeza hermitage towards the south, pinkish nodular limestone of Late Jurassic age can also be distinguished.

Figure 4. Upper photo: Horro de la Heredad.
Below: Negratín Reservoir from the Peña del Baño.

There is a path leading from the town of Zújar to the summit of Jabalcón and running right round the mountain halfway up. It provides magnificent panoramic views of the Geopark, and you can reach *La Horadada*, also called *Ojo* and *Horro de la Heredad* (Fig. 4). This is an arch several metres high, naturally formed in the limestone rock by erosion and dissolution processes. You can also get to the Peña del Baño, right on the northern slope, which offers wonderful views of the Negratín Reservoir. At the top of the mountain, near its triangulation station, is the Jabalcón viewpoint, with one of the best views of the Geopark (Chapter 8).





ALAMEDILLA PILLOW LAVAS

TAKE THE PLUNGE TO AN ANCIENT SEA FLOOR

SGI 23, 26, 36

Some rocks in the Granada Geopark are vestiges of the volcanic activity associated with the break-up of Pangaea and the formation of certain sea floors. These include the **Alamedilla pillow lavas**.

In the area around Alamedilla there are marine sedimentary rocks aged between 200 million years (Early Jurassic) and 34 million years (Eocene), with volcanic rocks dating mostly from the Jurassic and Cretaceous periods. Several outcrops included in the Granada Geopark's catalogue of sites of geological interest are concentrated in a small area: Cerro Méndez Jurassic Limestones (SGI 35), Alamedilla Late Cretaceous-Eocene (SGI 22), Loma de la Solana-El Peñón (SGI 26), Alcaide Ravine (SGI 36) and the Alamedilla Pillow Lavas (SGI 23).

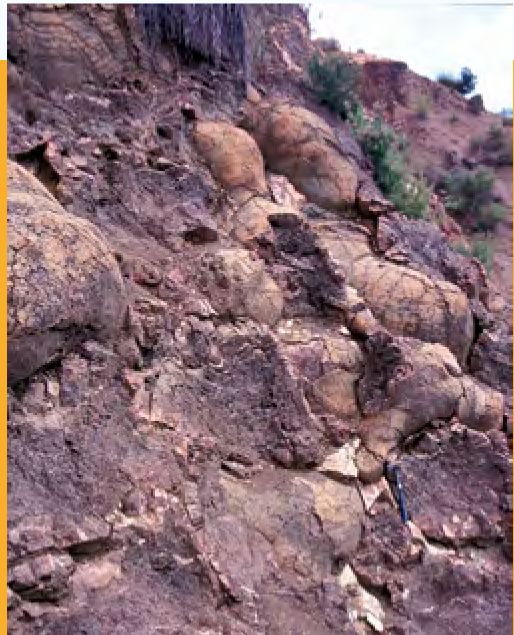
Outstanding among these sites of interest are the Alamedilla pillow lavas. These are submarine volcanic rocks that are interlayered between Jurassic and, to a lesser extent, Cretaceous sedimentary rocks. They are mainly volcanic rocks of the basalt group which have a pillow-shaped morphology. Magnificent examples can be seen on the road from Guadahortuna to Alamedilla (Figs 1 and 2).

This type of lava forms at the bottom of the sea when magma comes into contact with seawater. Each "pillow" has an inner core of volcanic rock with a more crystalline appearance, and a thin outer layer of volcanic glass due to the rapid cooling they undergo. This glassy layer gives pillow lavas a very distinctive appearance, similar to elephant skin.

Figure 1. Pillow lavas interlayered with Upper Cretaceous materials in the vicinity of Alamedilla. The light-coloured sediment (**S**) fills the gaps left by the darker pillow lavas (**PL**).

DID YOU KNOW...?

The highly characteristic pillow-shaped morphology of these lavas shows us that they formed on the sea bottom. The hydrostatic pressure of the water helped the lava to acquire this lobed shape. The ones in Alamedilla are textbook examples, as the expression goes. On platforms such as YouTube you can see recordings of these lavas using the keywords "underwater pillow lavas".



Lobed appearance of the Alamedilla lavas

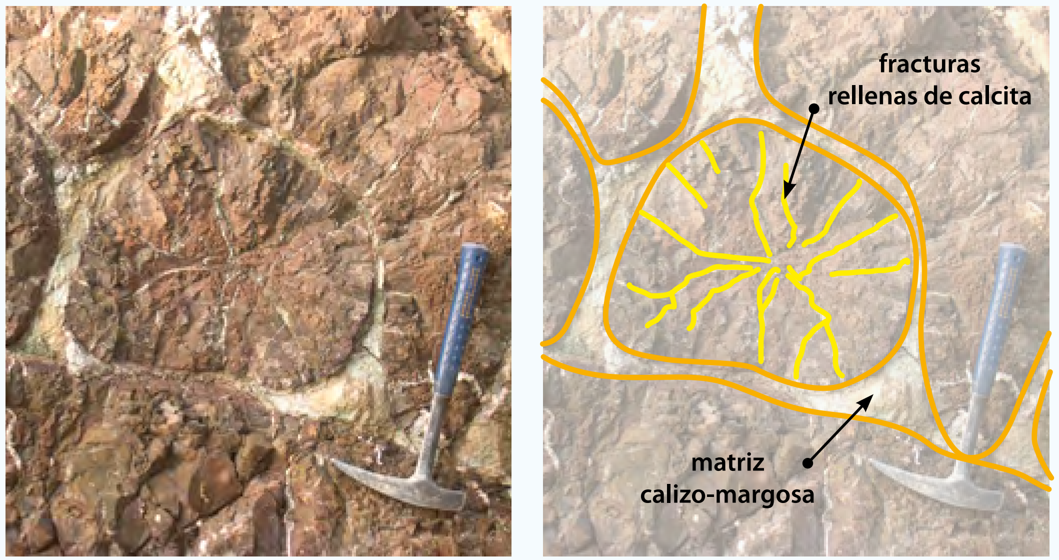


Figure 2. Another very characteristic feature of pillow lavas is the presence of radial fractures, which form abruptly due to the thermal contrast between the hot lava and the cold seawater, causing the lava to break in this highly distinctive way.

Most of the Alamedilla lava flows are arranged in tabular bodies parallel to the stratification. In some sectors, such as Alcaide Ravine, more than ten lava flows can be observed overlaid with batches of strata mostly from the Middle Jurassic, creating accumulated thicknesses of up to 700 m, one of the largest in the entire Betic Cordillera.

Scientists have identified lavas from the Early Jurassic (about 185 Ma) to the Late Cretaceous (about 85 Ma), with the stage of greatest activity being the Middle Jurassic (between 175 and 161 Ma) (Fig. 3). It has been possible to obtain this information thanks to radiometric dating and the study of nannofossils present in sedimentary rocks.

Overlying these lava flows are carbonate shelf rocks that were deposited in a shallow sea. This type of construction, composed of a volcanic edifice topped by limestone deposited on an isolated carbonate shelf, is called a guyot (Fig. 4). These are underwater mountains that rise above the sea floor and are surrounded by steep slopes where gravitational landslides are common.

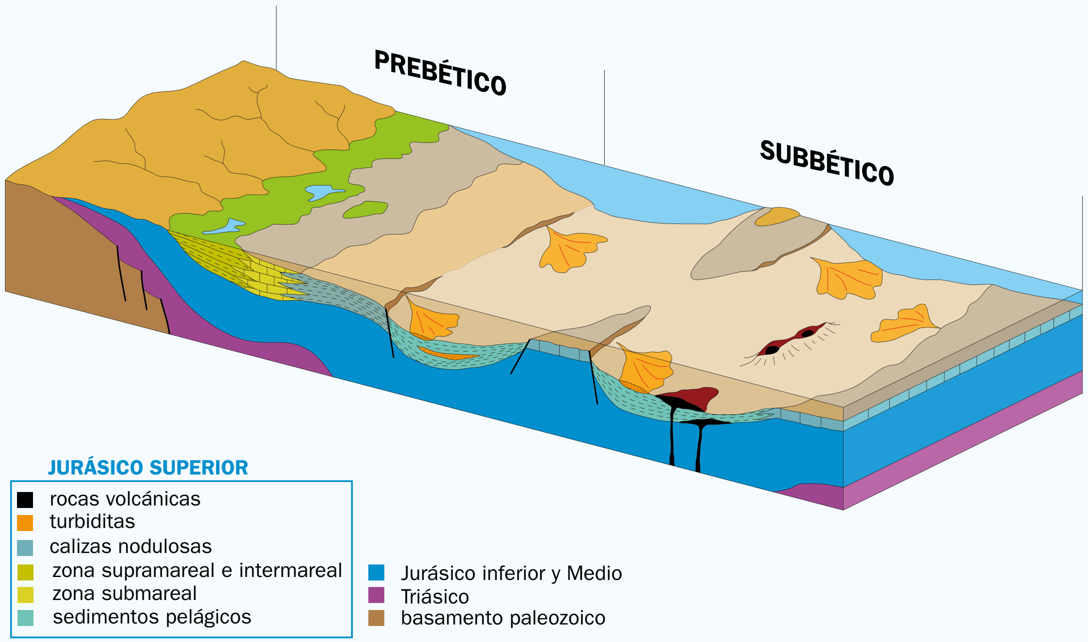


Figure 3. The magma that formed the pillow lavas reached the seabed through the faults that formed southeast of Iberia due to the expansion that the whole region was undergoing. In the Jurassic and Cretaceous periods, the Atlantic Ocean and the Tethys Ocean were opening up.

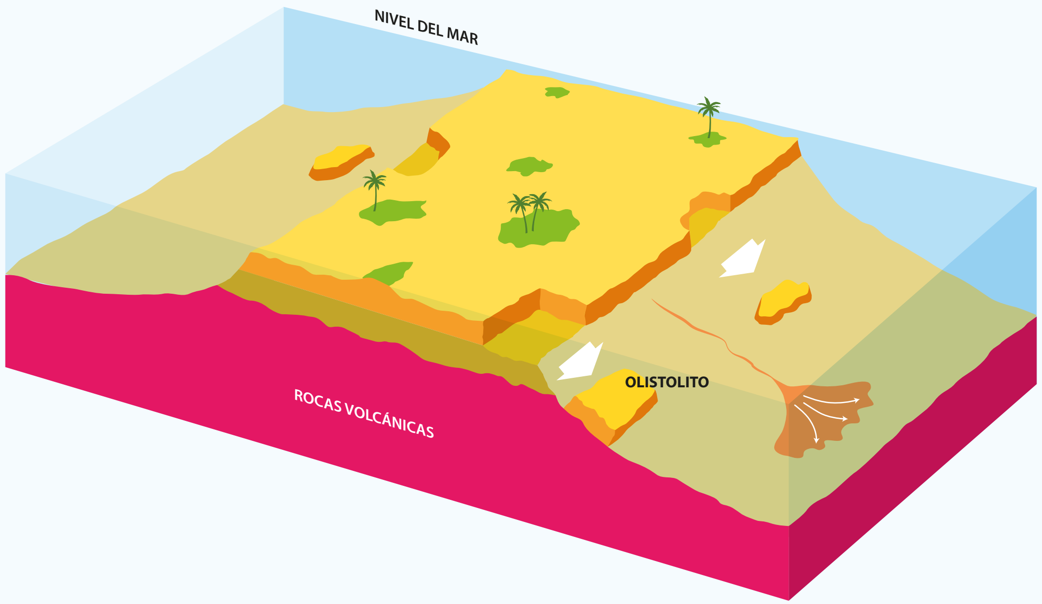


Figure 4. Diagram of a *guyot* or seamount, built of volcanic rocks (pillow lavas) with sedimentary rocks deposited in a shallow sea. At Alamedilla we can immerse ourselves in this Tethys Ocean and enjoy a remarkable geological heritage.

GEOPARQUE GRANADA

PEÑA DE CASTRIL AND THE RIVER CASTRIL GORGE

SGI 65

Under normal conditions, the strata or layers of sedimentary rocks are arranged horizontally and parallel to each other, one on top of another. However, those of the limestones of **Peña de Castril** (Fig. 1) do not follow this pattern, but appear in a progressive unconformity. In other words, they form a fan-shaped structure in section, in which those occupying lower positions are more steeply inclined than the higher ones. Progressive unconformities are created when strata are being deformed while they are deposited (Fig. 2). In the case of Peña de Castril, this deformation is related to the collision between tectonic plates that gave rise to the formation of the Betic Cordillera. In other words, the progressive unconformity of Peña de Castril helps us to discover the moment in geological time when the collision was occurring.

Figure 1. The materials of which Peña de Castril is composed are mainly bioclastic limestones formed during the Late Miocene epoch. These limestones have a particular arrangement that enables us to explore a crucial event in the geological history of the Geopark.

Figure 2. Panoramic view of Peña de Castril and Cerro de la Henchura from the north. Process of formation of a *progressive angular unconformity*

River Castril Gorge

The River Castril is fed by the karst aquifers of the Sierra de Castril and the Sierra Seca. The water that flows through it is of great purity, low mineralization and cold temperature. Consequently, it has a great ability to dissolve rocks made of calcium carbonate. When the river reaches the village of Castril it finds a promontory of limestone rocks that it has to pass. Initially, the river would have run across the highest part of these carbonates, into which it gradually downcut, owing to its erosive capacity and especially the chemical attack of its waters on these carbonate rocks. This downcutting was aided by the progressive uplift of the entire mountain system. Gradually, the river made its way through, producing a narrow gorge almost 150 m deep in its most downcut part.

In view of the great beauty of the surroundings, the gorge has been equipped for visits with walkways that enable visitors to traverse the whole length of it (Fig. 3).

Figure 3. River Castril Gorge Walk

As it passes through Castril de la Peña, the river cuts deep into the limestone rock, producing one of the most spectacular fluviokarst gorges in the Granada Geopark. Even though the valley walls are vertical, it is possible to visit and enjoy this spectacular stretch of the river safely and easily, thanks to wooden walkways, a large 70-metre suspension bridge and a tunnel excavated in the rock, with an opening that offers a magnificent balcony from which to see a waterfall.

GEOPARQUE GRANADA

FERREIRA FAULT

THE MECINA EXTENSIONAL DÉCOLLEMENT

SGI 71

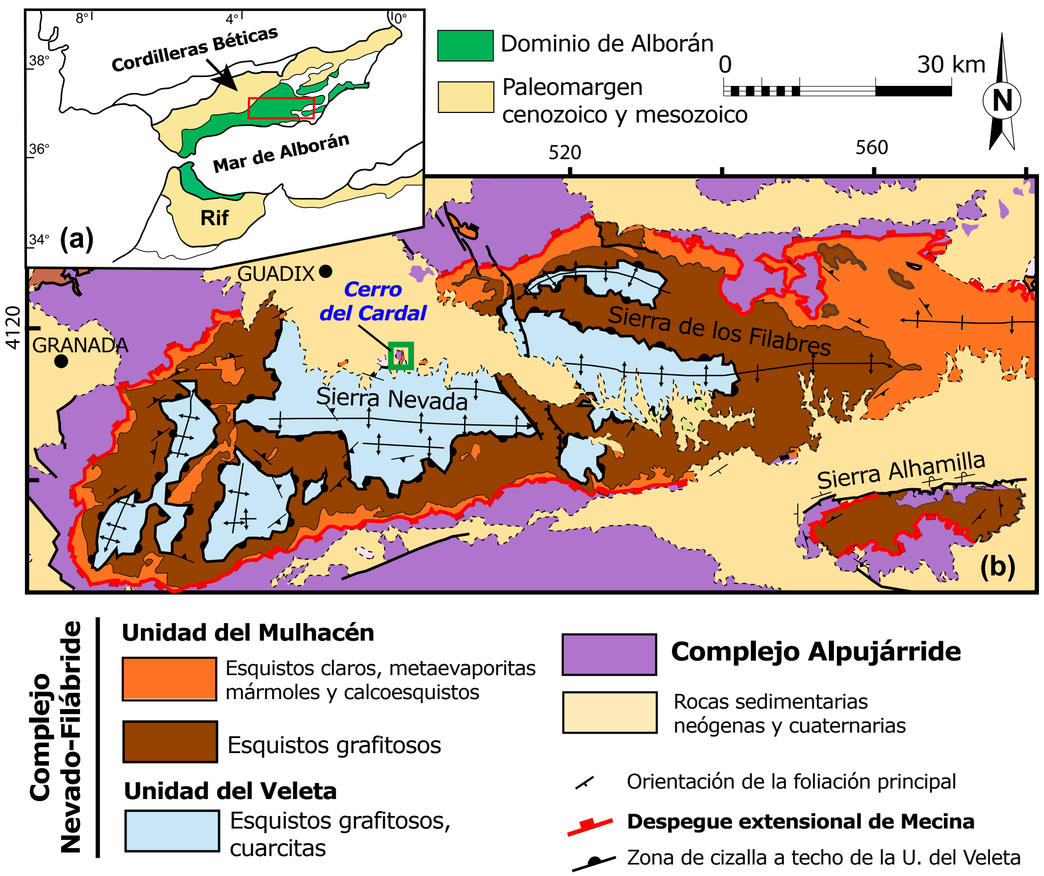
On the **Cerro del Cardal** and **Cerro Jazmín** hills, at the southern boundary of the Granada Geopark, we can see and touch some of the rocks that make up the great contours of the Sierra Nevada, to the south (Fig. 1).

The Sierra Nevada is mainly composed of a set of rocks belonging to what is called the Nevado-Filábride Complex. On the edges of the range, and on top of the Nevado-Filábride rocks, another sequence of rocks called the Alpujárride Complex can be found (Fig. 1).

These Sierra Nevada rocks, like those of the Filabres and Baza mountains, form part of the Internal Zone of the Betic Cordillera and are therefore related to the Alboran plate. On their journey to their present position, many of these rocks were located many kilometres deep within the Earth's crust and were subjected to high pressures and temperatures which turned them into metamorphic rocks. Whereas the Nevado-Filábride rocks were able to reach temperatures of over 650 °C (at depths of more than 40 kilometres), the Alpujárride rocks in this sector did not exceed 450 °C (implying a much lesser depth).

In order for us to be able to touch them on the surface today, these rocks must have subsequently undergone a process of ascent, which we call exhumation. This process is usually driven by the action of large faults: fractures along whose surfaces (fault planes) some rock sequences have been displaced relative to others.

The contact between the Nevado-Filábride and Alpujárride complexes is a large fault with a very shallow-dipping plane, known as the **Mecina Décollement** or **Mecina Fault**. This structure allowed the large column of Alpujárride rocks to become thinner, facilitating the ascent of the Nevado-Filábride rocks to levels close to the surface. Subsequently, the erosion generated by landform-shaping agents, such as rainwater, made it possible for these rocks to have been completely exhumed. Indeed, much of the sedimentary infill of the Guadix-Baza Basin comes from that erosion and we can find pebbles of all kinds of metamorphic rocks forming part of that infill.



FFigure 1. Geological map of the Nevado-Filábride omplex with the course (thick red line) of the Mecina décollement in contact with the Alpujárride Complex and the location of the Cerro del Cardal (small green box).

The Mecina Fault emerges in many places along the western and southern edges of the Sierra Nevada, but one of the most spectacular is the outcrop between Cerro del Cardal and Cerro Jazmín (Fig. 1).

At this site very detailed observations can be made on the following questions:

I. The **rock sequence of the Nevado-Filábride Complex**. It lies below the fault and consists mainly of marbles, light mica schists, quartzites and graphite-rich dark mica schists (Figs 2 and 3).

II. The **rock sequence of the Alpujárride Complex**. It is located above the fault and is composed of phyllites, quartzites, and in the upper part, limestones and dolomites (Figs 2 and 3).

III. The **fault rocks** associated with the Mecina Fault, mainly affecting the Nevado-Filábride marbles and the Alpujárride phyllites (Figs 3 and 4). Moreover, along the tectonic contact iron oxide-rich mineralization was formed, giving the rocks a striking brown and yellowish colour.

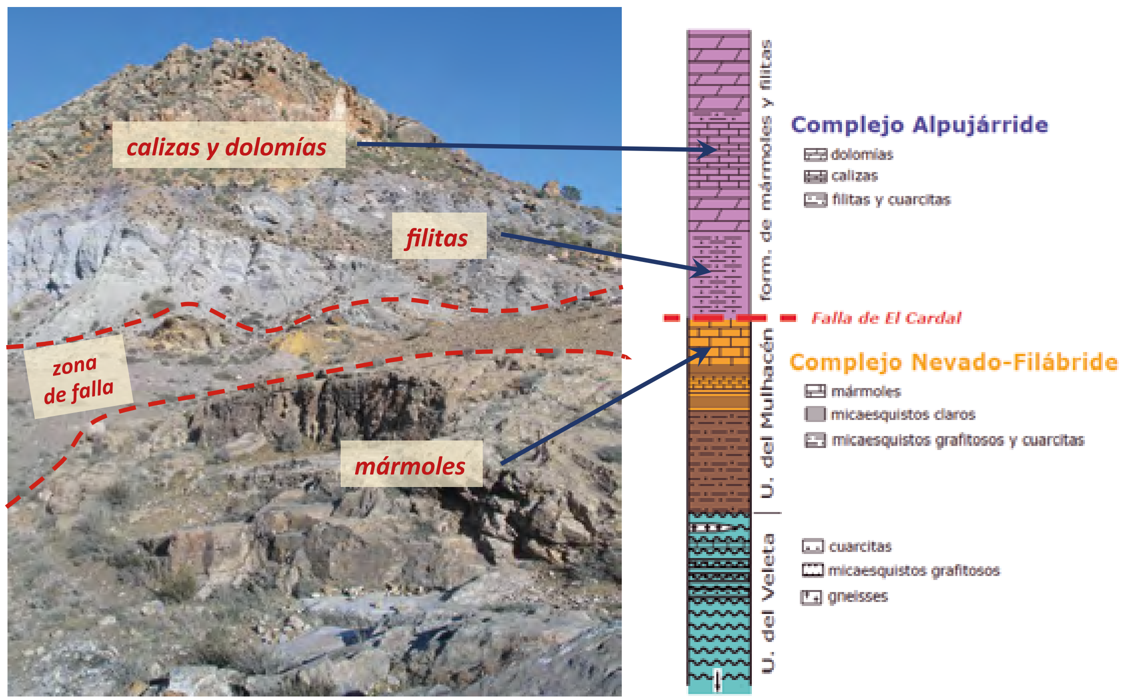


Figure 2. Panoramic photo of Cerro Jazmín (northward continuation of Cerro del Cardal) showing the location of the fault zone at the point of contact between the marbles of the Nevado-Filábride Complex and the sequence consisting of phyllites, limestones and dolomites of the Alpujárride Complex. The lithological column on the right shows the complete sequence of rocks that outcrop in the area.

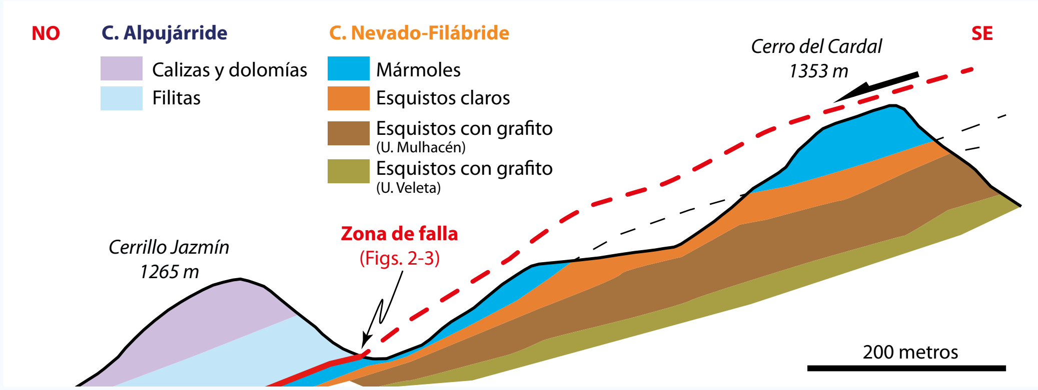


Figure 3. Detailed geological cross-section showing the position of the fault (red line) between the rock sequences of the Nevado-Filábride and Alpujárride complexes and their westward direction of movement. The action of this fault favoured the exhumation of the Nevado-Filabrides rocks near the surface.

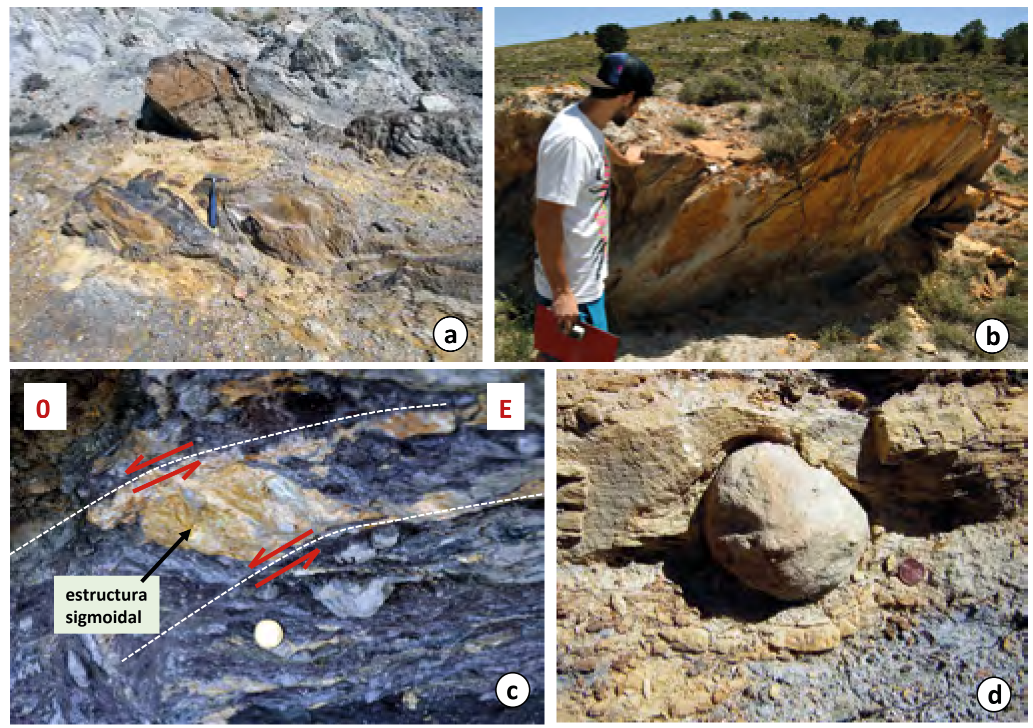


Figure 4. Characteristics and structures of the fault zone in the valley between Cerro del Cardal and Cerro Jazmín (Fig. 3). **A**: heterogeneous appearance of the fault zone with a mixture of fragments from different types of rock, including the iron mineralization. **B**: fault plane on which striations can be observed (not visible in the photo). **C**: detail of the sigmoidal deformation structures generated in the Alpujárride phyllites as a result of their westward movement due to the action of the fault. **D**: detail of an almost spherical pebble within the fault zone.

IV. The **characteristic structures** of the fault rocks (Fig. 4). Structure is defined as the new shape a rock acquires due to deformation, in this case rupture deformation. The main structures that can be observed in this fault zone are fault planes, striations caused by abrasion, and sigmoidal structures and deformed pebbles in the Alpujárride phyllites. The orientation of these structures enables us to deduce the fault movement: in this case, the hanging wall (the upper block, consisting of the Alpujárride complex) was displaced to the west relative to the footwall (the lower block, consisting of the Nevado-Filábride complex) (Figs 3 and 4c).

V. The **style of deformation** of each of the sequences (the structures they display) before the action of the fault. Away from the fault zone, more ductile structures are observed in the case of rocks from the Nevado-Filábride complex, due to the fact that they were located at greater depth and temperature (Fig. 5a), and more brittle in the case of the Alpujárride complex, because they were situated closer to the surface (Fig. 5b).

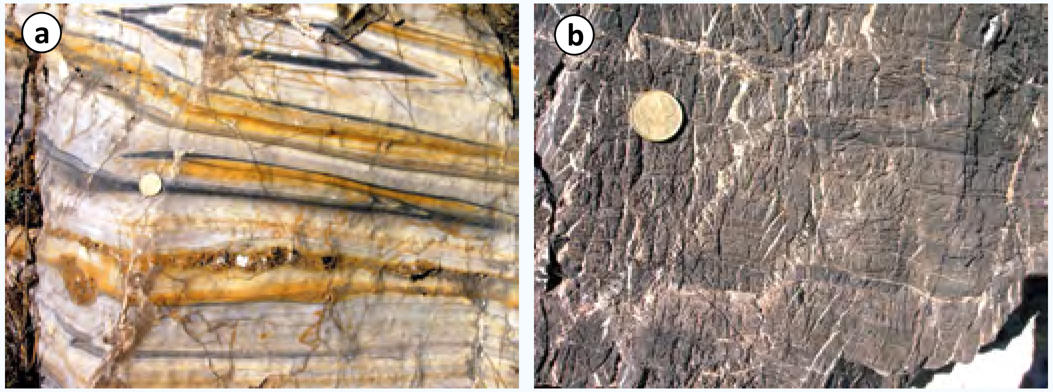


Figure 5. Photographs showing the different style of deformation between a *Nevado-Filábride marble* (**a**), in which we can see very tight folds formed under ductile conditions at great depth, and an *Alpujárride limestone* (**b**), traversed by numerous brittle fractures.

DID YOU KNOW...?

In fault planes not only mechanical effects (such as fracturing and displacement of blocks of rock) take place; there can also be processes of circulation of fluids that are channelled along the fault plane. Precipitation of new minerals can occur from these fluids and the dissolved elements they contain, as in the case of the iron mineralizations observed in the fault zone between Cerro del Cardal and Cerro Jazmín (Fig. 4).

GORAFE ANGULAR UNCONFORMITY

A SUMMARY OF GEOLOGICAL HISTORY

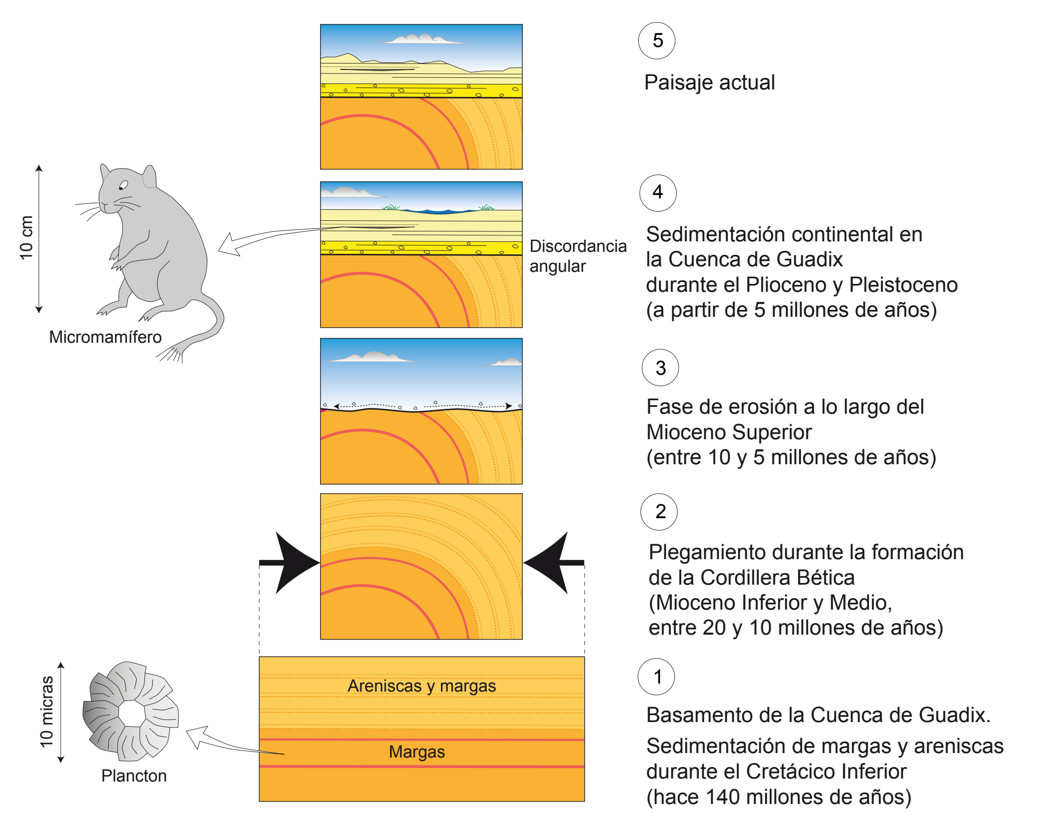
SGI 21

Just 2.5 km from the Alicún de las Torres Thermal Baths, in the direction of Gorafe, there is a magnificent outcrop that enables us to understand various stages of geological history in the Granada Geopark at a glance. This outcrop contains rocks from the basement of the Guadix-Baza Basin (in this case, Cretaceous marls and marly limestones belonging to the External Zone). On top of these rocks we find others from the basin infill (gravels, clays and limestones from the Pliocene and Pleistocene) (Fig. 1).

To understand this landscape, you need to know that most of the strata (layers of sedimentary rocks) were originally arranged horizontally. In this outcrop, however, the only strata that maintain their initial horizontal position are those of the basin infill, while the basement strata below them are almost vertical. This is due to the fact that after being deposited in a horizontal position, the basement strata underwent folding during the Miocene epoch, which ended up leaving them almost vertical (Fig. 2). This deformation also caused the basement rocks to rise to a position above sea level. They were thus exposed to erosional agents, which gradually smoothed the new folded relief to produce a flat surface. Later, during the Pliocene and Pleistocene, gravels, clays and limestones that form the horizontal strata of the upper unit were deposited in the rivers and lakes that occupied the Guadix-Baza Basin.

The arrangement of these two sets of strata and the surface that separates them (called an ***unconformity surface***) are evidence of the collision between tectonic plates that led to the formation of the Betic Cordillera.

Figure 1. Gorafe Angular Unconformity (Gor Stream). The Cretaceous pelagic marine materials are visibly folded and affected by an unconformity surface (US) that cuts across their stratification. On the US the Pliocene-Pleistocene continental materials are laid horizontally.



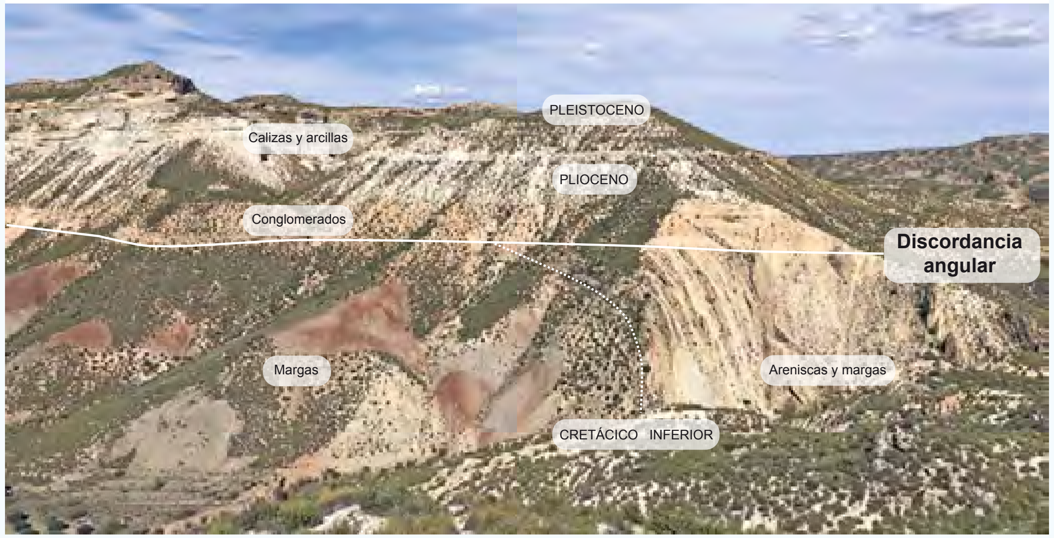


Figure 2. Geological interpretation of the Gorafe unconformity and its evolution from the Cretaceous to the present.

Cerro de La Lancha outcrop (east of Dehesas de Guadix). The Geopark's two most characteristic types of marine rocks can be recognized in the image: marls (lower part) and calcarenites (upper part). Both were deposited during the Upper Miocene (approximately 8.4 to 7.6 million years ago).

3

THE MARINE HISTORY OF THE BASIN

For part of the Late Miocene epoch, during the Tortonian age (approximately 10 to 7.6 million years ago, the Guadix-Baza Basin was a marine sedimentary basin located in the central Betic Cordillera. A great variety of deposits accumulated in this basin, in both shallow and deep water. The marine deposits are located at several points in the Geopark (Fig. 1), where natural erosion has exposed remarkable outcrops which have enabled us to find out what that last sea that occupied the Geopark's territory was like. Some of the most interesting outcrops are the following (Figs 2 to 6): Cerro Molicias and the surroundings of the Francisco Abellán reservoir (La Peza-Lopera), Fonelas, Alicún de Ortega-Dehesas de Guadix, Cerro de la Lancha (Dehesas de Guadix) and Negratín Reservoir (Cuevas del Campo/Bácor-Olivar).

The marine history of the Guadix-Baza Basin begins in the Late Miocene, specifically during the Tortonian. Before this, in the Middle Miocene, the basin did not exist as such; the whole area was part of an extensive marine domain known as the North-betic Strait. It was during the Tortonian, approximately 10 million years ago, that the basin began to acquire a geographical outline somewhat similar to the present one, since what are now the main mountainous reliefs surrounding Granada Geopark began to be uplifted. These notably include the Sierra Nevada and Sierra de Baza to the south, Sierra Arana to the west, Sierra de Segura, Sierra de Castril and Sierra de La Sagra to the north and the Sierra de María, Sierra de Orce and Sierra de Cúllar to the east. During this marine stage the basin was connected to the Atlantic Ocean and the Mediterranean, forming a passage or corridor between the two marine domains (Fig. 7).

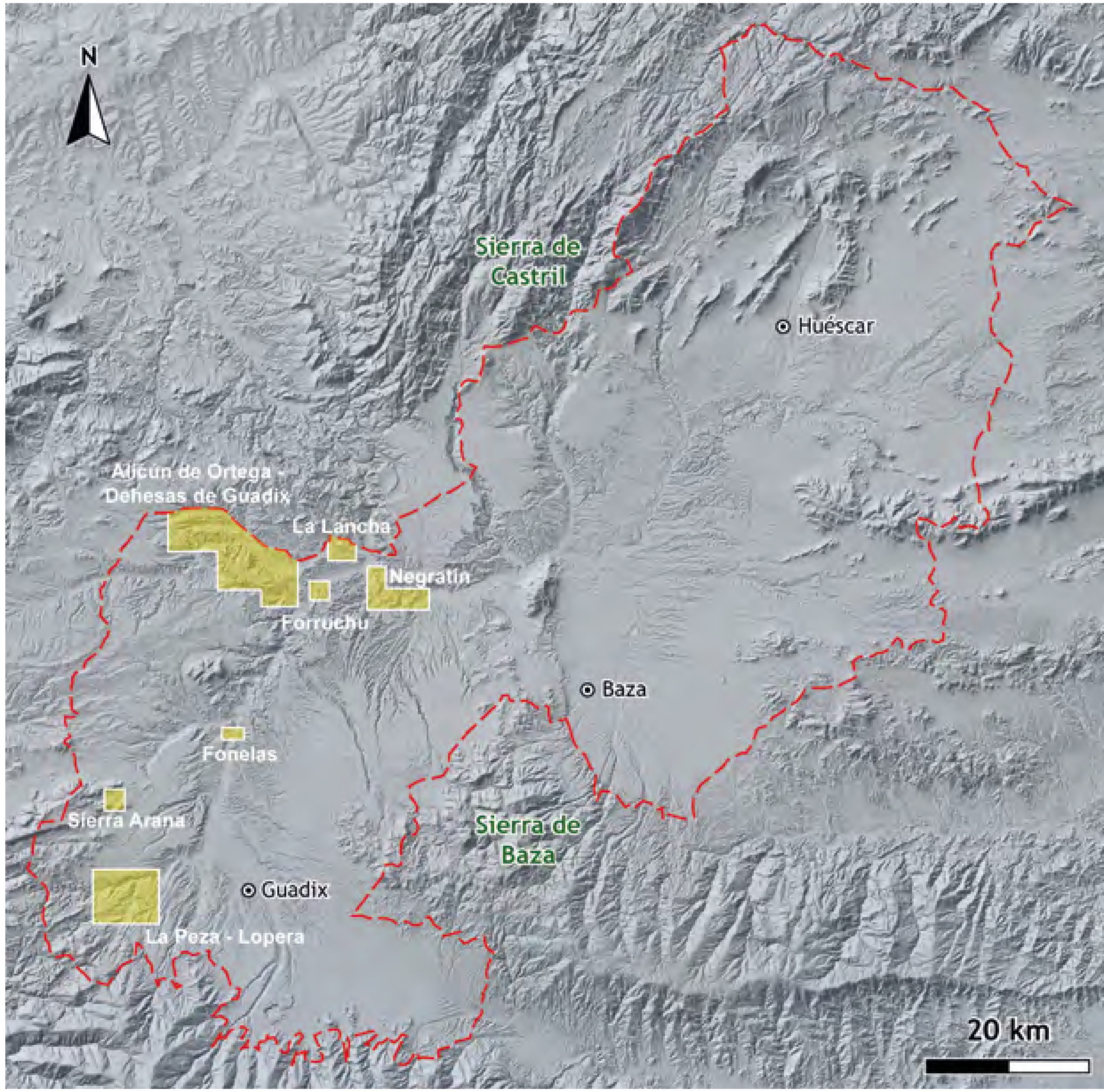


Figure 1. Location of the main marine outcrops described in this chapter (in yellow).

Figure 2. Partial view of outcrops between La Peza and Lopera (district of Cortes and Graena). Two marine units of Tortonian age can be recognized: a lower one of white marls very rich in deep-water microfossils and a higher one of shallow marine calcarenites. Both units are covered by red clays corresponding to the continental infill of the basin.

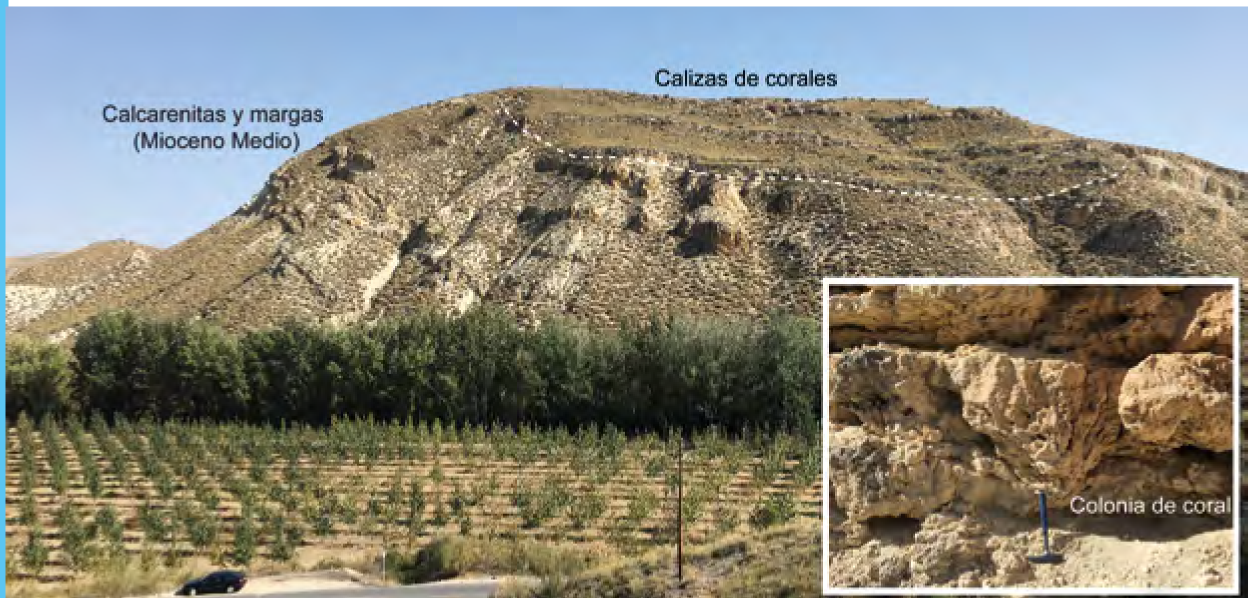


Figure 3. General panoramic view of the Fonelas outcrop. The horizontal strata of coral limestone of Tortonian age (see detail in the lower photo) lie in unconformity on a Middle Miocene (Serravallian) unit of calcarenites and marls, deposited before the configuration of the Guadix-Baza marine basin. These coral limestones are typical of very shallow reef seabeds.

Figure 4. Image of the Alicún de Ortega outcrop showing two marine units of Tortonian age, a lower one of marls with deep-water microfossils and a higher one of very well stratified shallow-water calcarenites.

Figure 5. General stratigraphic sequence of the La Lancha outcrop. The series consists of three units of Tortonian age: a lower one of turbiditic sandstone (deposited by turbidity currents on a deep submarine slope), an intermediate unit of marls with deep-water microfossils and an upper one of very shallow marine calcarenites. These calcarenites mark the end of marine sedimentation in the Guadix-Baza Basin.

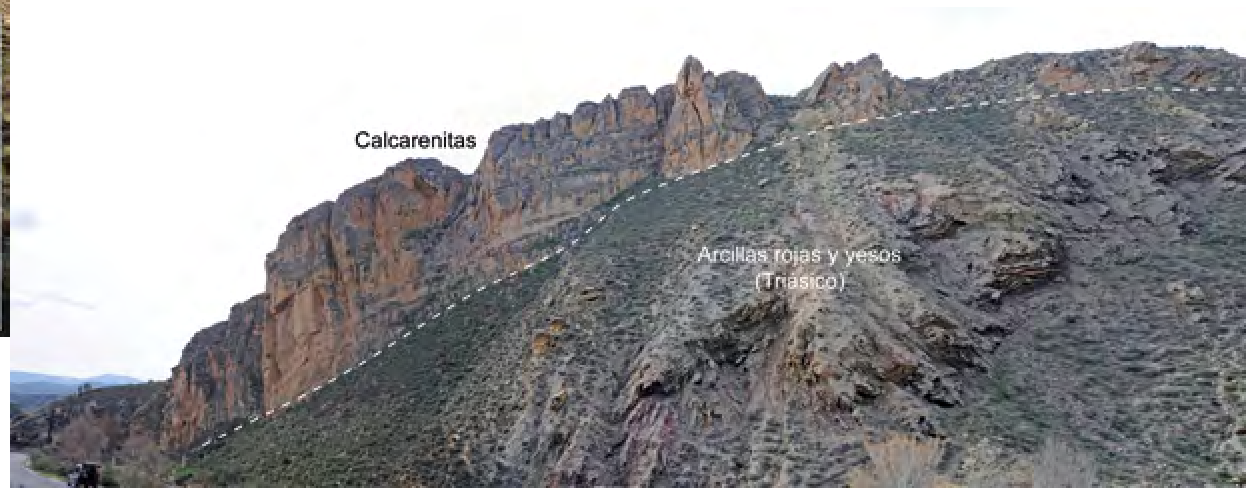


Figure 6. Partial view of the Negratín Reservoir outcrop, showing Tortonian shallow marine calcarenites lying directly on rocks of Triassic age.

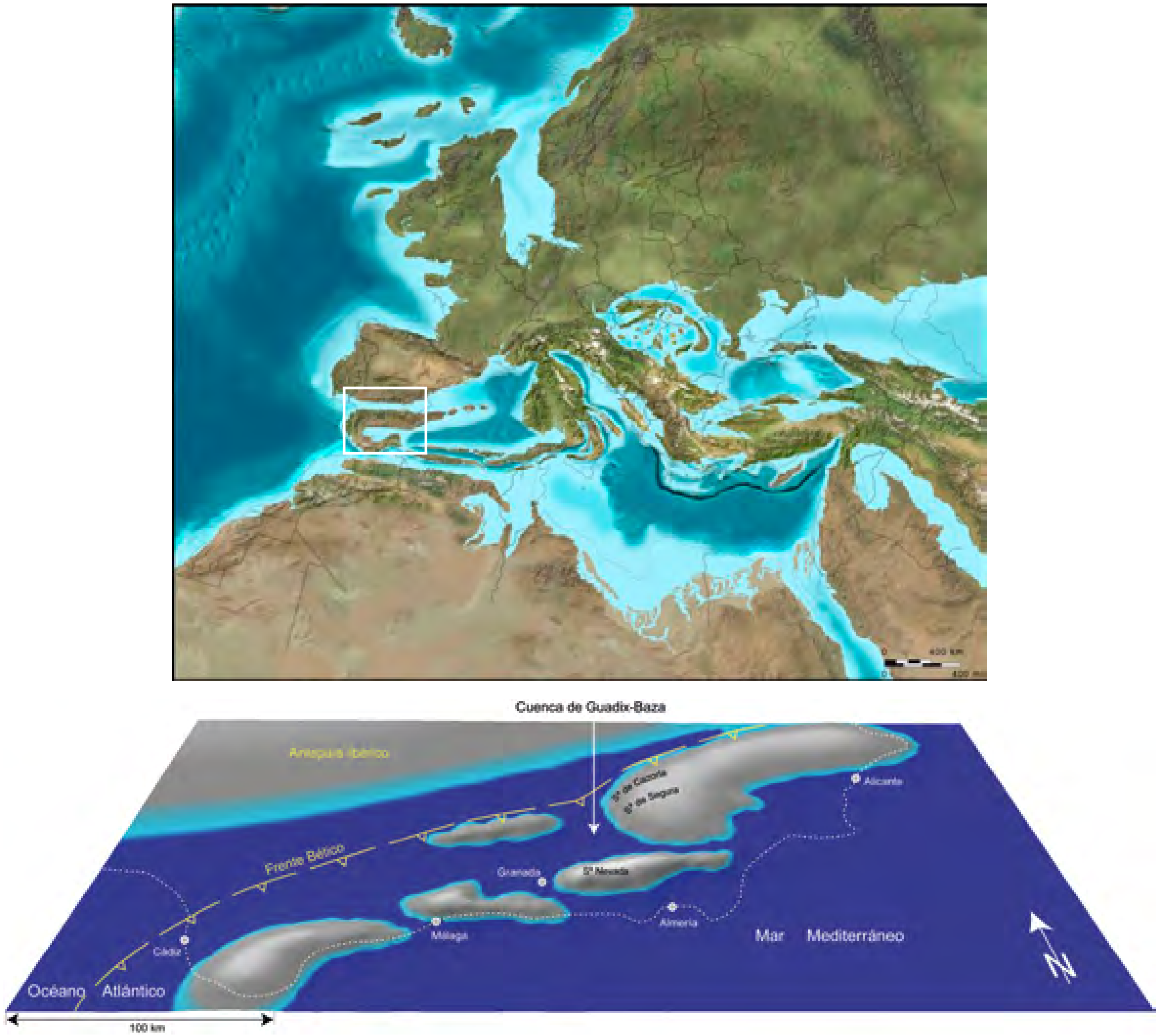


Figure 7. Palaeogeography of the Betic Cordillera region during the Tortonian Age (Miocene).

The age of the marine stage has been established by studying the fossil planktonic foraminifera that appear in the sediments. Many of these microfossils are of biostratigraphic interest; in other words, their temporal distribution interval (from appearance to extinction) over the course of geological time is known. Three species among them can be highlighted: *Neogloboquadrina acostaensis*, *Globigerinoides extremus* and *Globorotalia suterae*. From the distribution of these species in the stratigraphic series of the basin, the age range of the marine sedimentation has been established as between 10 and 7.6 million years (Fig. 8).

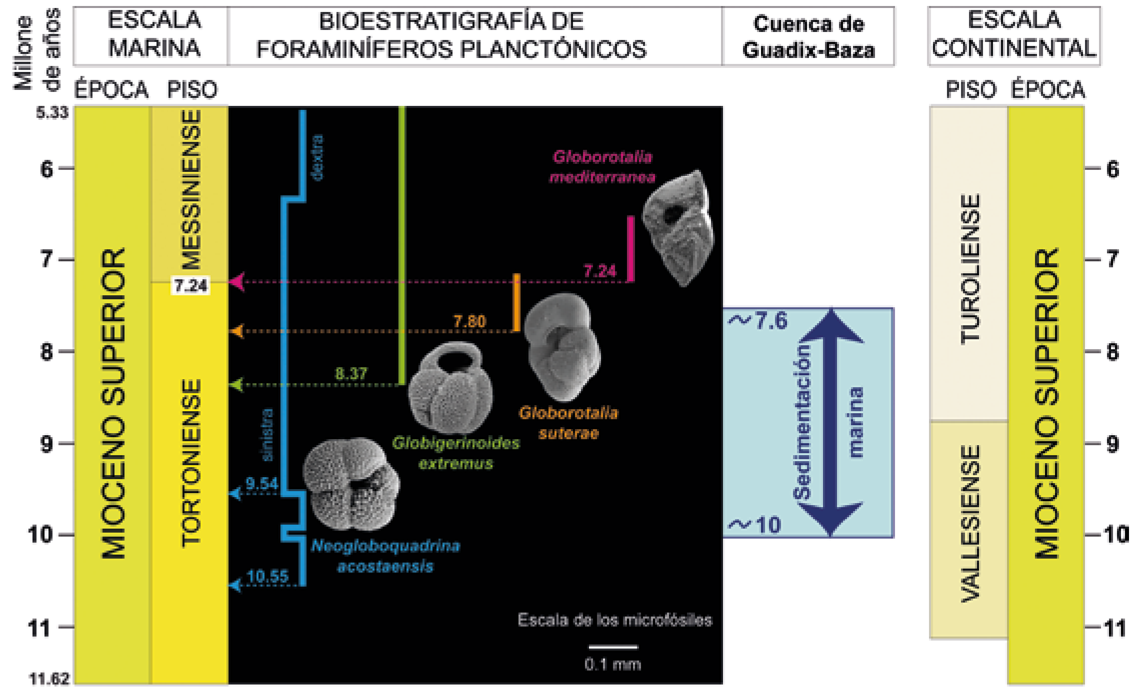


Figure 8. Planktonic foraminiferal biostratigraphy makes it possible to narrow down the age range of the marine sedimentation in the Guadix-Baza Basin during the Tortonian age. The oldest sediments contain dextral (right-coiling) Neogloboquadrina acostaensis (Lower Tortonian, approx. 10 Ma). The most recent contain Globorotalia suterae (Upper Tortonian, approx. 7.6 Ma). The absence of Globorotalia mediterranea indicates that marine sedimentation ended before the Messinian stage.

The right of the table indicates the continental scale stages and their correlation with the marine scale stages.

The most complete marine sedimentary infill in the Guadix-Baza Basin can be identified in the La Peza-Lopera and La Lancha sectors. Here we have stratigraphic sequences that enable us to reconstruct the marine history of the basin. This history consists of four stages, from the start of marine sedimentation to when the sea withdrew and continental sedimentation began (Fig. 9).

FIRST STAGE **began approximately 10 million years ago**

The sea invaded the basin, which rapidly deepened. Large deltaic fans (deposits from mountain rivers entering the sea), composed of gravel, sand and silt, formed at the margins of the basin. Downstream of the deltas, avalanches of sand occurred, produced by turbidity currents (turbidites), down the seabed slope. At the centre of the basin, where the turbidites did not reach, there was a predominance of pelagic sedimentation, represented by marls rich in planktonic microfossils (foraminifera, radiolarians and calcareous nannoplankton).

SECOND STAGE **approximately 8.4 million years ago**

The sea occupied the entire basin. The seabed gently sloped from the edge to the centre of the basin. The margin was a shallow shelf where calcarenites with fossils of red algae, lamellibranchia and bryozoans accumulated. The marine currents moved the bottom sediments, forming underwater dunes with cross-stratification within them. At the centre of the basin there was a predominance of pelagic sediments, consisting of marls with microfossils. These marls contain abundant benthic microfossils, indicating a shallower bottom depth than in the first stage.

THIRD STAGE **approximately 7.6 million years ago**

There was a lowering of the sea level. The whole basin was left in a very shallow condition. Most of the seabed was a shelf where calcarenites with bryozoans, lamellibranchia and brachiopods accumulated. At some points in this shallow basin, Gilbert-type conglomeratic deltas (always on the margins, at river mouths) and small coral reefs formed.

FOURTH STAGE **after 7.6 million years ago**

This marine history ended approximately 7 million years ago, when the sea finally withdrew and continental sedimentation began. This will be described in detail in the next chapter.

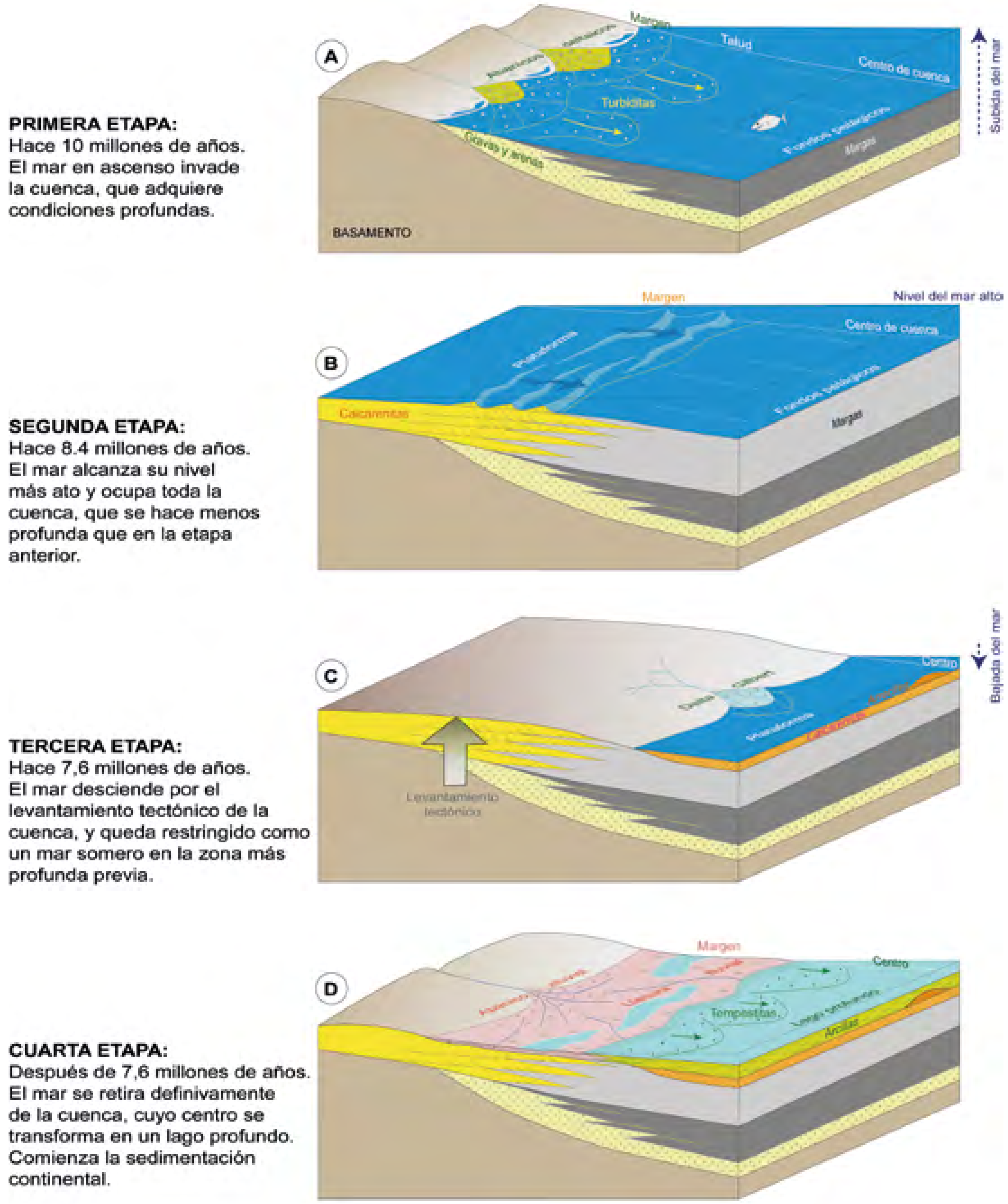


Figure 9. Successive stages of marine infilling (**A**, **B** and **C**) and beginning of continental sedimentation (**D**) in the Guadix-Baza Basin.

THE ALICÚN DE ORTEGA DELTA

SGI 28

Deltas are bodies of sediment that form where a river flows into the sea or into a lake. They have a fan-shaped morphology in their horizontal layout. On the coast of Granada deltas can be seen today, such as the one that formed in the town of La Rábita during the catastrophic flooding of the Rambla de Albuñol ravine between 17 and 19 October 1973 (Fig. 1A). Gilbert-type deltas are a particular case of deltas that arise when a river flows into deep waters. They have three parts: a deltaic plain, a steep slope, and the base of the slope, with a gentle gradient (Fig. 1B). In the internal structure of Gilbert deltas, these three parts are called the topset (uppermost strata), the foreset (body strata) and the bottomset (base strata). Each line running from the topset to the bottomset is known as a clinoform.

In the vicinity of Alicún de Ortega there is an outcrop of conglomerates that shows all the parts of the internal structure of a Gilbert-type delta and is therefore known as the Alicún de Ortega Gilbert delta, or delta of Los Olivillos. It belongs to the third marine stage of the Guadix-Baza Basin (Fig. 2). This delta was deposited on the margin of the basin, at the same time as the third-stage shelf calcarenites and reefs, such as those that can be seen at Forruchu, La Lancha and Negratín (see SGIs 30, 27 and 41).

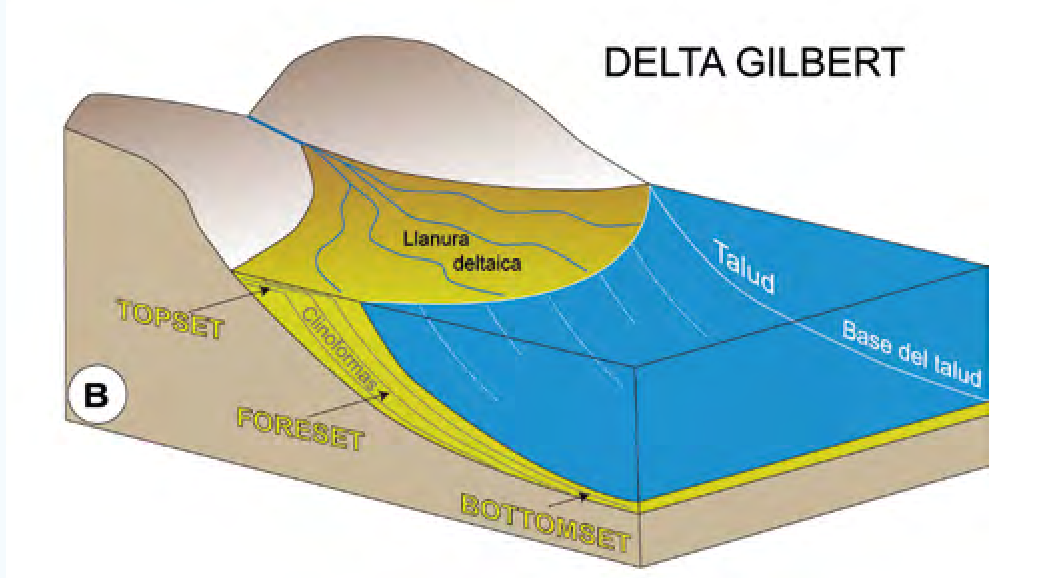


Figure 1. **A**: current delta of La Rábita, showing the typical fan shape.
B: parts and internal structure of a Gilbert delta.

In the Alicún de Ortega Gilbert delta the clinoforms of its internal structure are very clearly recognizable (Fig. 3). The upper part of the clinoforms consists of the almost horizontal strata of the topset. These formed on the deltaic plain and gravel beaches, which received inputs from the river mouth. The intermediate part of the clinoforms corresponds to the foreset. Here the steeply inclined strata were deposited on the delta slope by avalanches of clasts, including some that rolled downslope. The lowest part of the clinoform is the bottomset of the delta, or base of the slope, where the gradient decreases and the clast avalanches stop. The seabed, which does not directly receive inputs from the delta, is the shallow marine shelf. If we measure the distance between the topset and the bottomset-shelf we obtain the depth of the basin. In the case of Alicún de Ortega this depth reached 40 metres.

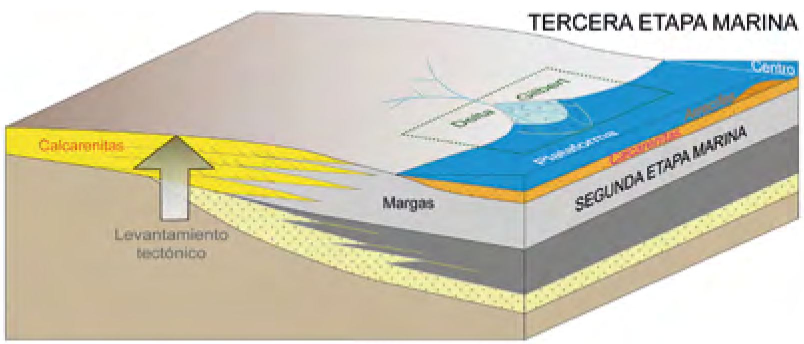
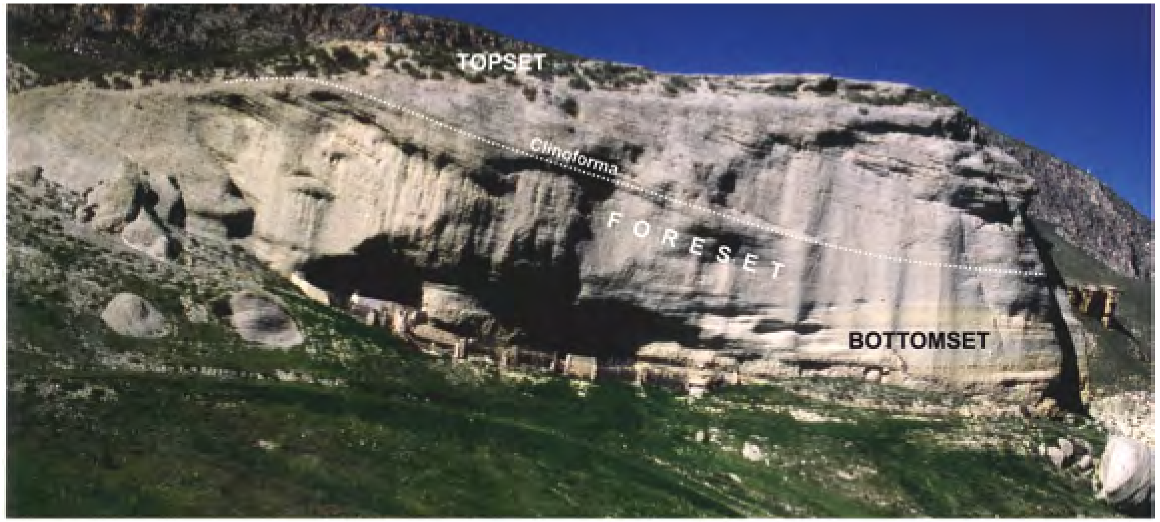


Figure 2. Panoramic view of the Alicún de Ortega Gilbert delta. This is a body of conglomerates clearly resting on the marls (interspersed with calcarenites) of the second marine stage. The inclination that can be seen in the deltaic conglomerates is due to tectonic tilting; in Figure 3 the inclination has been restored to match the original.



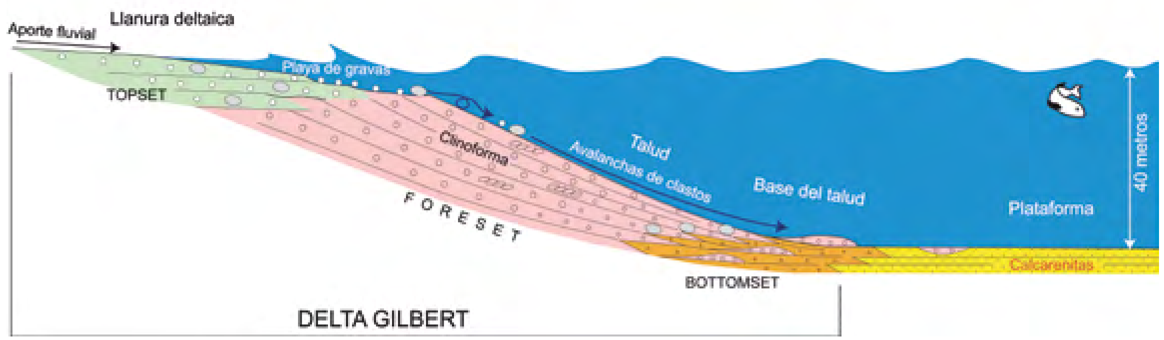


Figure 3. Clinoforms and internal structures of the Alicún de Ortega Gilbert delta.

The diagram below illustrates the processes that act in each part of the delta.

DID YOU KNOW...?

The name *Gilbert delta* is derived from the American geologist Grove Karl Gilbert. When palaeogeographical reconstructions are made, Gilbert deltas are valuable indicators of the exact position of the margin of marine basins.

GEOPARQUE GRANADA

FROM A DEEP SEA TO A SHALLOW SEA: VILLANUEVA DE LAS TORRES CALCARENITES

SGI 30

The change from the second to the third marine stage of the Guadix-Baza Basin is recorded in many places by an abrupt lithological change from marls to calcarenites. This change represents a significant drop in sea level, immediately before the final withdrawal of the sea and the continentalization of the basin. The **Forruchu outcrop in Villanueva de las Torres** (SGI 30 (Fig. 1) is an exceptionally suitable site to illustrate some of the sedimentological and palaeontological criteria that are applied to characterize the change from a deep sea to a shallow sea.

The Forruchu marine stratigraphic series consists of two units: a lower one of **marls with foraminifera**, corresponding to the final part of the second marine stage, and an upper one of **calcarenites with bryozoans**, which represents the whole of the third marine stage (Fig. 2).

The marls were deposited on a deep seabed away from the coast, where 1) planktonic foraminifera predominated over benthic foraminifera, and 2) benthic foraminifera typical of the upper bathyal zone (average depth of 300 metres) lived.

The calcarenites accumulated in a shallow sea (less than 30 metres deep) close to the coast, where 1) the assemblage of organisms consisted mostly of bryozoans, and to a lesser extent lamellibranchia, 2) rock clasts and coal fragments were incorporated from outside the basin, and 3) the seabed was affected by the erosive effect of storms. The fossil bryozoans, as the main biogenic component of the Forruchu calcarenites, are comparable to the bryozoans that currently live on the bottom of Granada's coastal waters (Fig. 3).

In short, the Forruchu outcrop illustrates an abrupt fall in sea level that coincides with the change from the second to the third marine stage of the Guadix-Baza Basin (Fig. 4). This rapid shallowing is one of the most significant events in the marine history of the basin.

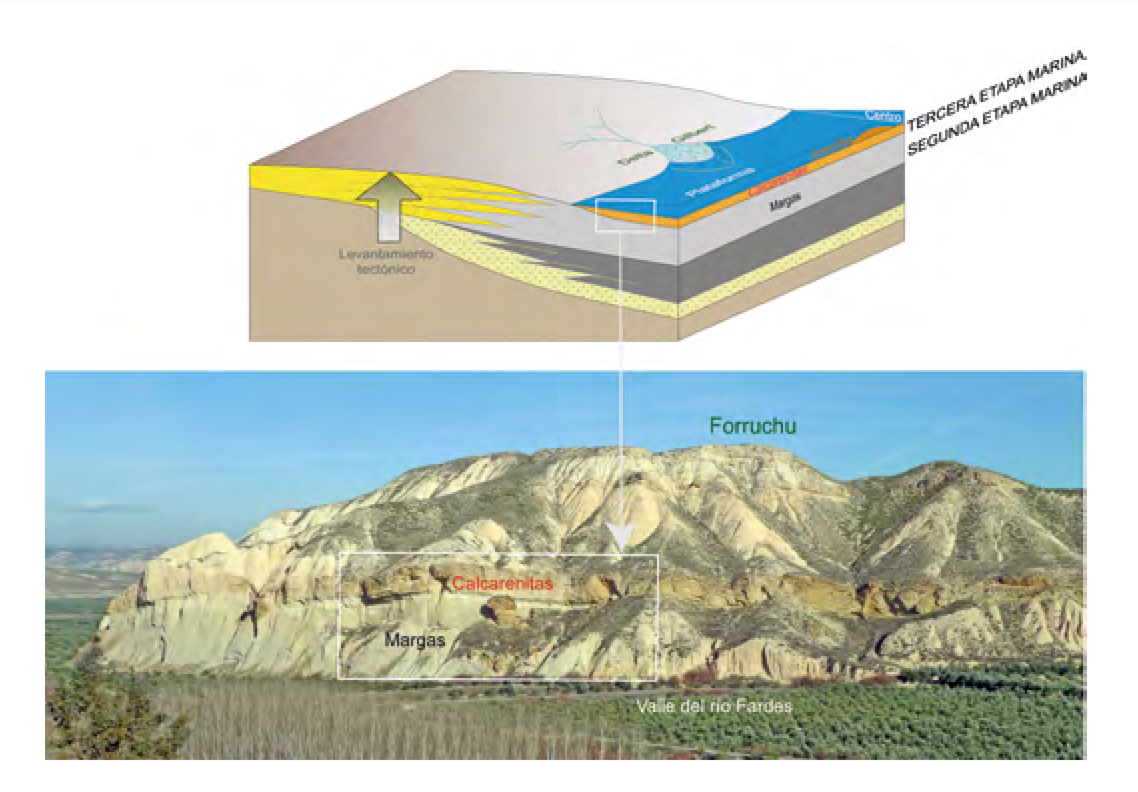


Figure 1. Panoramic view of the Forruchu outcrop, where the calcarenites of the third marine stage stand out, clearly lying on the marls of the second marine stage.

DID YOU KNOW...?

Both the marls and the calcarenites of Forruchu are good examples for applying the principle of actualism in geology. The fossil benthic foraminifera of the marls are the same as those living today in the upper bathyal zone. The same is true of the coastal bryozoans, as illustrated in Figure 3.

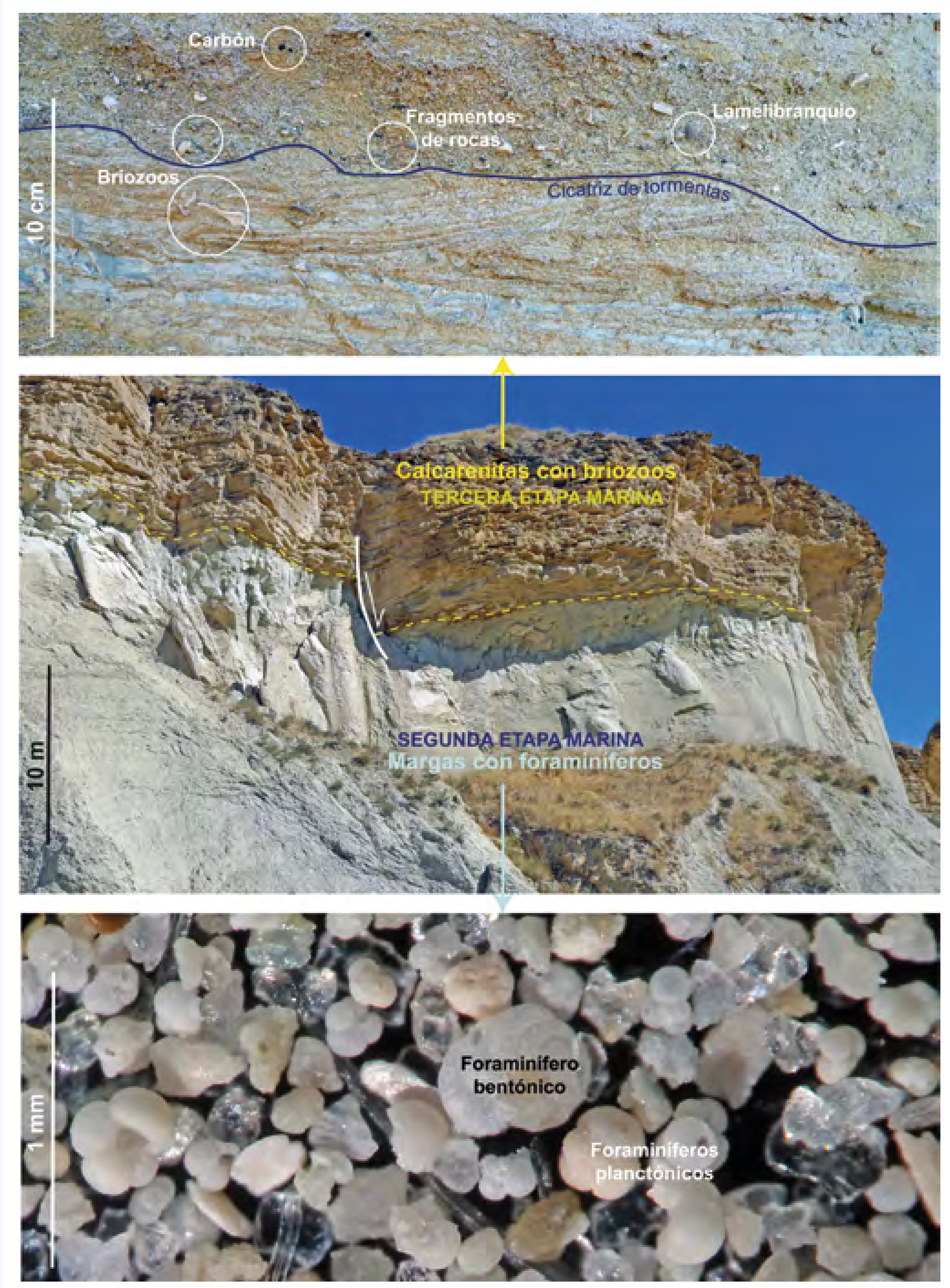


Figure 2. Main components of the marls and calcarenites (bryozoans) of Forruchu, which make it possible to determine the depth at which they were deposited.

Figure 3. Comparison of the Forruchu fossil bryozoans with Mediterranean coastal bryozoans.
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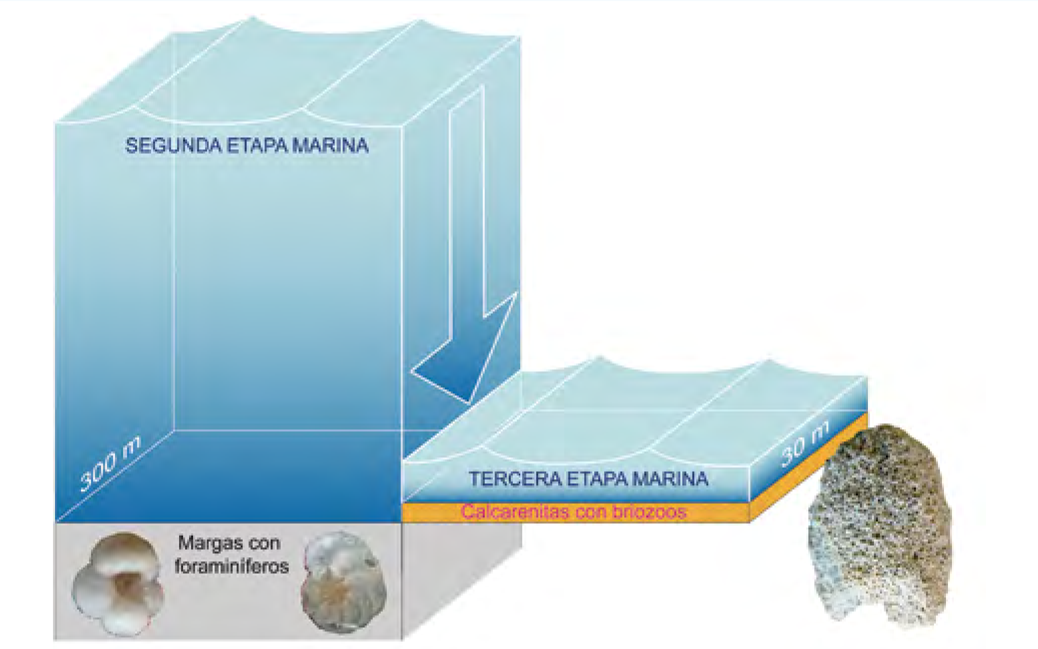


Figure 4. Change from deep basin (second marine stage) to shallow basin (third marine stage).

SEDIMENTARY RHYTHMS AND CLIMATE CYCLES

THE MOLICIAS STRATIGRAPHIC SEQUENCE

SGI 51

Sedimentary rhythms are repetitive alternations of different lithologies within a stratigraphic sequence, which is called a *rhythmic series*. A *rhythm*, or pair of rocks, contains two intervals that differ in their lithological composition (including grain size), fossil assemblages, chemical elements, or combinations of any of these features. Rhythms are caused by changes in conditions in the sedimentary basin. Climate oscillations are a global factor with the capacity to modify conditions cyclically over the entire expanse of a sedimentary basin. That is why rhythmic series are explained by **climate cycles**. The Molicias stratigraphic sequence is a rhythmic series belonging to the second marine stage of the Guadix-Baza Basin (Fig. 1). It is included in the catalogue of the Geopark's sites of geological interest under the name Cerro Molicias Miocene Series (La Peza), SGI 51.

Each rhythm consists of a marl interval and a calcarenite interval (Figs 2A and 2B). The marls are characterized by a high content of planktonic foraminifera (Fig. 2C), dominated by the genera *Globigerina* and *Neogloboquadrina*. These marls were originally deposited on the bottom of the basin as pelagic oozes, in which the microfossils that lived within the seawater column accumulated. The calcarenites show cross-stratification caused by the migration of subaqueous dunes.

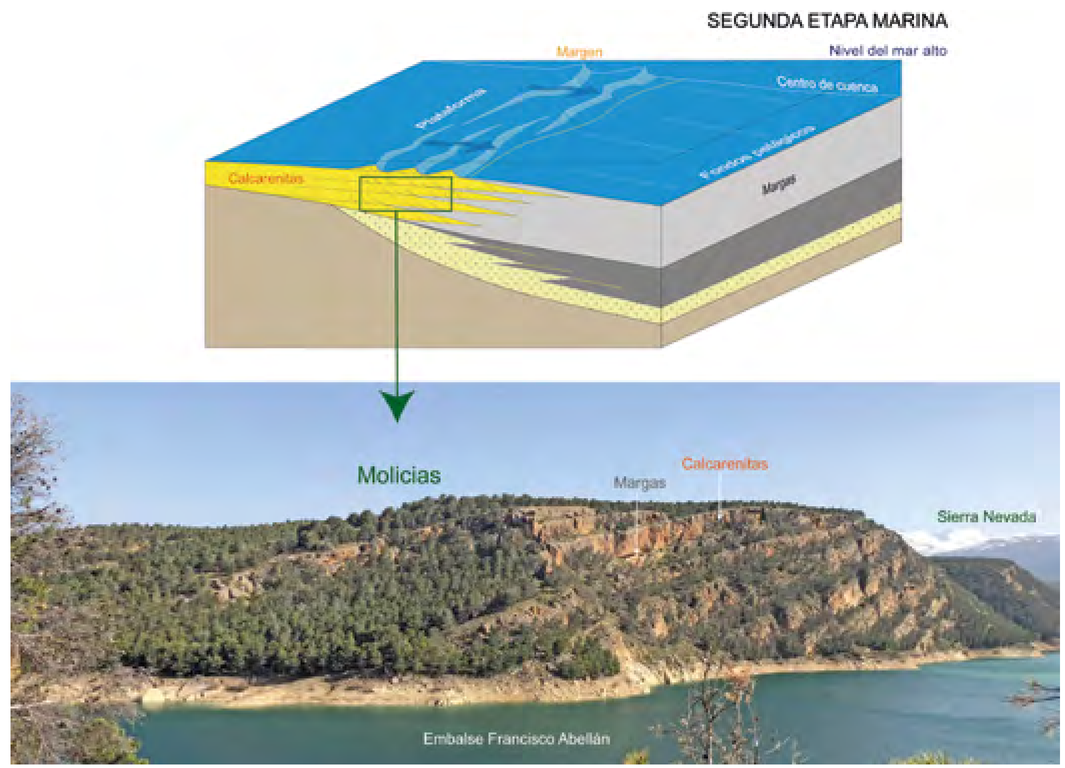


Figure 1. Panoramic view of the Molicias rhythmic series, showing the two intervals (marls and calcarenites) that form the sedimentary rhythms. The inclination that can be seen in the strata is due to tectonic tilting.

The fossil components of the calcarenites are very varied. They notably include lamellibranchia, bryozoans and red algae (*rhodoliths*). This fossil assemblage is typical of a shallow marine shelf. As well as these biogenic components, there are abundant clasts of metamorphic rocks derived from erosion of the Sierra Nevada.

The climatic significance of the sedimentary rhythms has been established by studying the fossil components. In the marl interval, the predominance of *Globigerina* and *Neogloboquadrina* indicates cold conditions at the surface of the water column, coinciding with times of insolation minima (Fig. 3). In the calcarenite interval, the abundance of lamellibranchia, bryozoans and red algae reflects temperate water conditions, coinciding with times of insolation maxima. The most pronounced changes in insolation are caused by the precession cycles of the Earth's axis, which are completed in periods of between 19,000 and 23,000 years (Fig. 3).

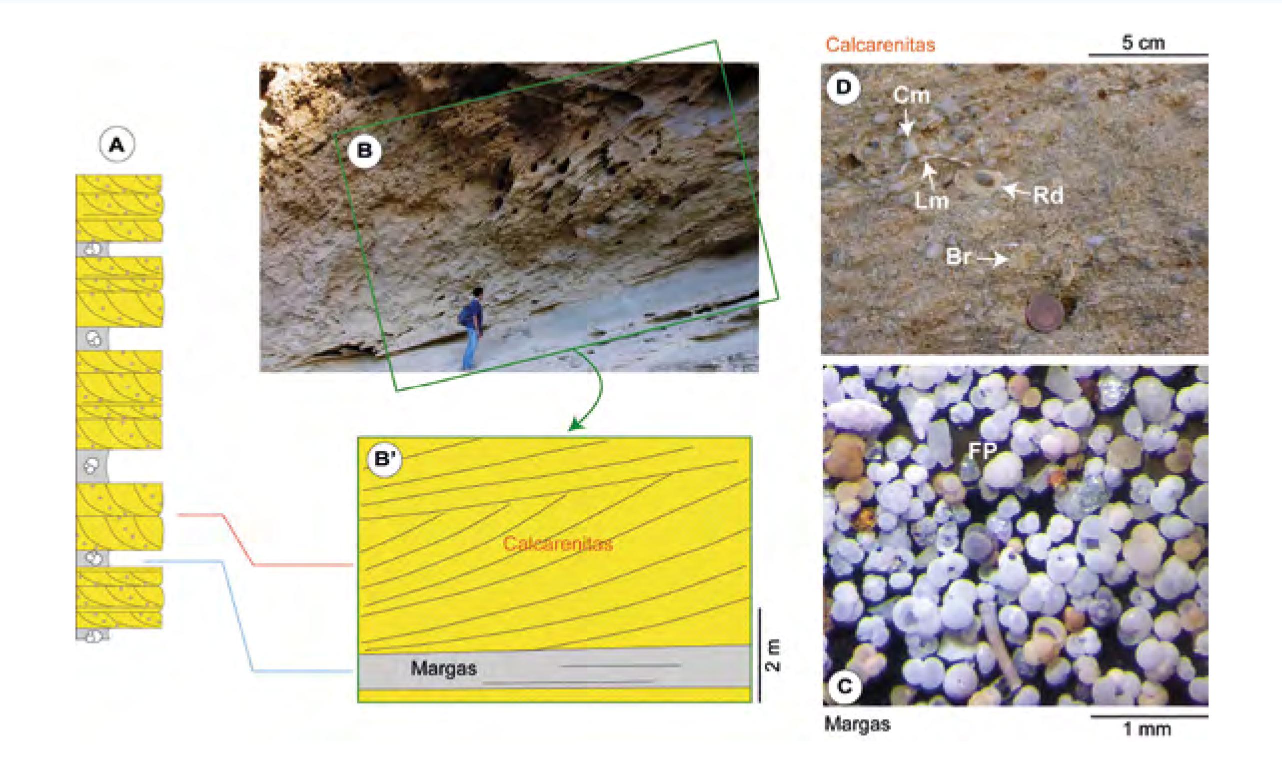


Figure 2. **A**: stacking of marl-calcarenite rhythms; only 5 of the 30 rhythms that form the complete Molicias stratigraphic sequence are represented. **B**: image of a typical rhythm and its original position (B'), with the inclination due to tectonic deformation corrected. **C**: assemblage of planktonic foraminifera (**PF**) within the marl interval. **D**: calcarenite components: lamellibranchia (**Lm**), red algae or rhodoliths (**Rd**), bryozoans (**Br**) and metamorphic rock clasts (**Mc**).

The Molicias sedimentary rhythms were formed at the margin of the Guadix-Baza Basin, more specifically on a shallow and gently sloping marine platform, adjacent to the mountainous reliefs of the Sierra Nevada (Fig. 4).

The periods of insolation minima (dry, cold climate) were characterized by a prevailing aridity. Because of the low rainfall, inputs of metamorphic clasts from the Sierra Nevada are very scarce. Thus, only clay and carbonate oozes (marls) rich in cold-water foraminifera accumulated on the shelf.

In the periods of insolation maxima (humid, warm climate), conditions on the shelf changed considerably. Higher rainfall caused increased input of sediment with metamorphic rock clasts from the Sierra Nevada.

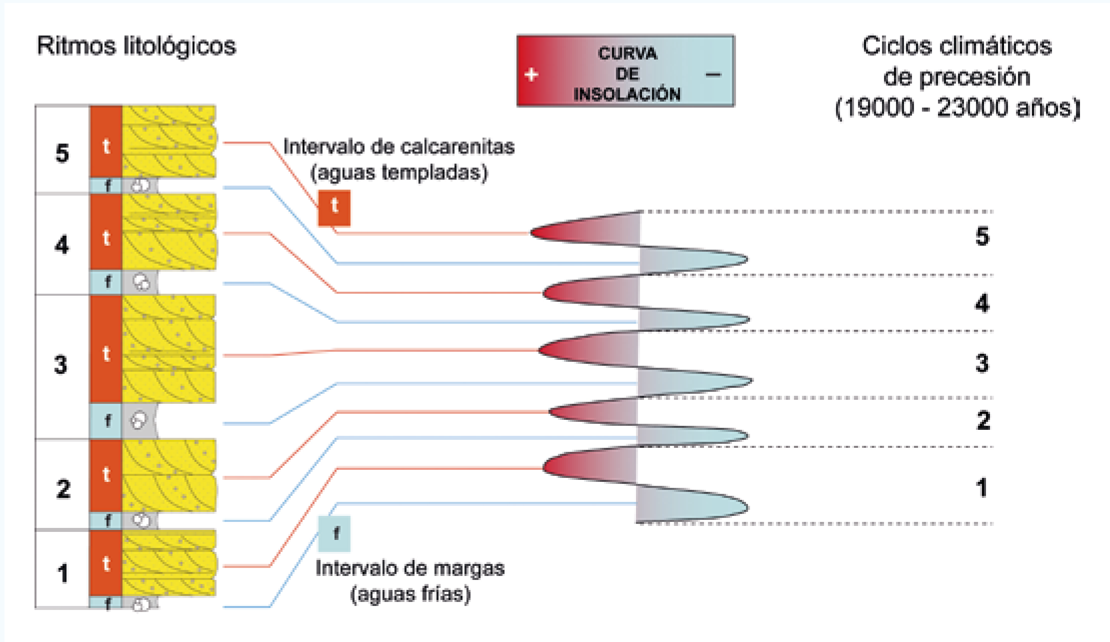


Figure 3. Correlation between lithological rhythms and climate cycles. Each marl-calcarenite rhythm is equivalent to a minima-maxima insolation cycle determined by the precession of the Earth's axis.

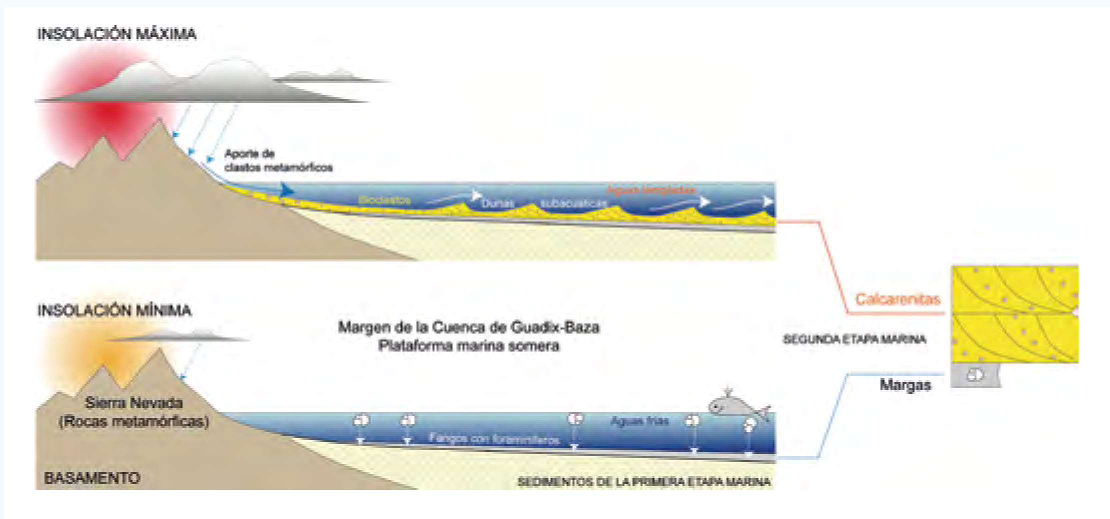
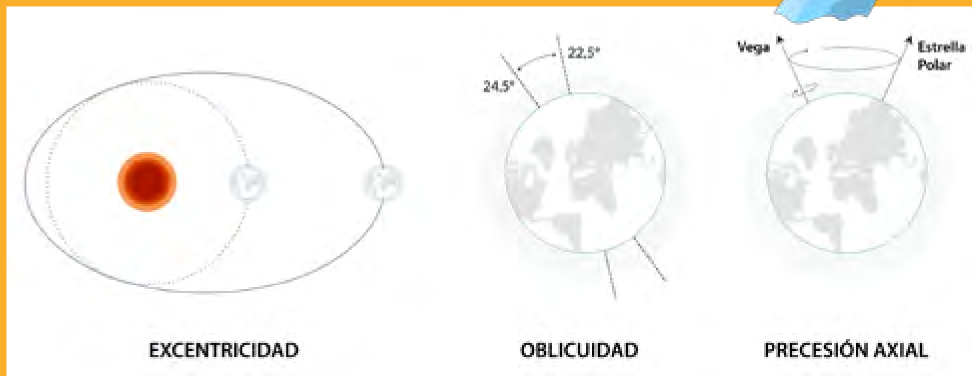


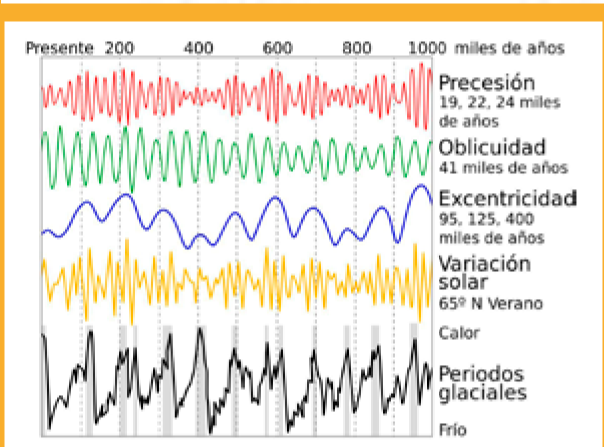
Figure 4. Changes in sedimentation on the marine shelf in relation to periods of minima and maxima insolation. The sedimentary rhythm resulting from these climate changes is indicated on the right.

This was coupled with a rise in the temperature of the seawater, which became warm and conducive to the development of communities of organisms such as lamellibranchia, red algae and bryozoans. The fossil remains of these organisms (bioclasts), together with metamorphic clasts, form the shelf sediments (calcarenites). The shallow bottom of the shelf is moved by marine currents, giving rise to subaqueous dunes and to the cross-stratification that can be observed within the calcarenites.

DID YOU KNOW...?

The author who calculated the duration of precession cycles was the Serbian physicist Milutin Milankovitch. These, together with the obliquity and eccentricity cycles, are known as Milankovitch cycles.





Variations in the Earth's orbit and movements cause cyclical changes in climate over thousands of years.

These cycles interact with each other, with some being dominant. The result is a complex pattern whose analysis can help us to interpret the past... and the future!

GEOPARQUE GRANADA

THE LAST MARINE SEDIMENTS OF THE GUADIX-BAZA BASIN: THE NEGRATÍN STRATIGRAPHIC SEQUENCE

SGI 41

At most sites in the Guadix-Baza Basin, the marine sedimentation ends with shallow deposits, such as third-stage calcarenites, coral reefs and Gilbert deltas. This is the case at Forruchu, La Lancha and Alicún de Ortega. The Negratín Reservoir, which is included in the catalogue of sites of geological interest under the name Negratín Marine-Continental Transition, SGI 41, is a magnificent place to observe the change from marine to continental sedimentation in the Geopark. At this site, on the calcarenites which stand out in the relief, lie marls rich in foraminifera with conglomerate intercalations (Fig. 1). These are the last sediments from the third marine stage. The reddish sediments that can be seen above (of a fluvial type) are part of the continental sedimentation that was to dominate the geological history of the Geopark's territory for the last 6 million years (Chapter 4).

At the Negratín Reservoir the calcarenites lie directly on multicoloured rocks of Triassic age (Fig. 2). The materials of the first and second marine stages are absent here.

These calcarenites, which are very thick, contain abundant fossils of red algae and lamellibranchia (Fig. 3), typical of a shallow marine shelf.

The marls are characterized by their large quantity of foraminifera (Fig. 4), with a predominance of shallow benthic forms. This is coupled with a high sand-grain content, indicating a shallow seabed near the coastline. The conglomerates found within the marls contain very rounded clasts, often perforated

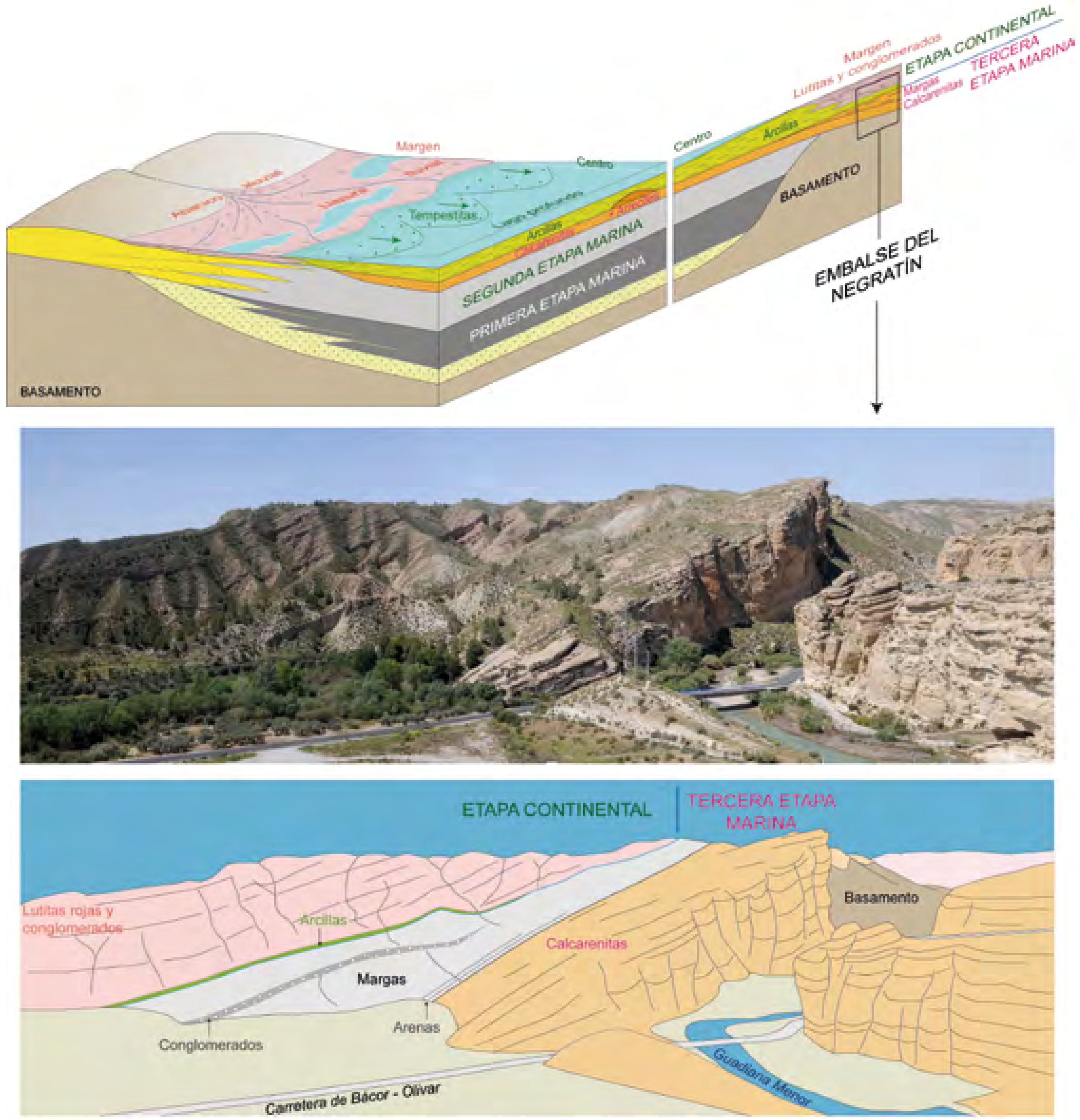


Figure 1. Stratigraphic position of the marls with conglomerates, which represent the end of the third marine stage.

by lithophages and colonized by bryozoans. These clasts come from coastal areas and were transported down the slope to the slightly deeper parts where the marls accumulated. The planktonic foraminifera have made it possible to discover the age of the marls (Fig. 4). The presence of *Globorotalia* suterae and absence of *Globorotalia mediterranea* indicate the end of the Tortonian. Other additional markers pinpoint the age at around 7.6 million years.

Figure 2. The discordant Negratín calcarenites on the basement of red clays with gypsum of Triassic age.

Figure 3. Panoramic view of the calcarenites and detailed images of the most abundant fossils: red algae and lamellibranchia. The features of these rocks can be observed in detail along the road leading down from the dam.

Figure 4. Outcrop of marls and conglomerates of the third marine stage immediately below the red lutites of the continental stage. The lower left image illustrates clasts of conglomerates perforated by lithophages (**CL**) and colonized by bryozoans (**Br**). The lower right photograph shows some of the planktonic foraminifera used to determine the age of the marls.

DID YOU KNOW...?

Fossil planktonic foraminifera are valuable indicators of the age of sediments that fill a marine sedimentary basin. The geological discipline that orders rocks chronologically by means of fossils is known as biostratigraphy. Thanks to the presence of these microfossils in the Negratín outcrop, the age of the end of marine sedimentation in the Guadix-Baza Basin has been pinpointed at around 7.6 million years.


Sucesión estratigráfica del Negratín
LIG 41
N
A Cuevas del Campo
P
Serie del Negratín
Panorámica
A Freila y Zújar
PARKING
15 min

4

RIVERS AND LAKES: THE ENDORHEIC CONTINENTAL STAGE

A herd of Iberian ibex crosses the glacis plain, with the peaks of the Sierra Nevada in the background.

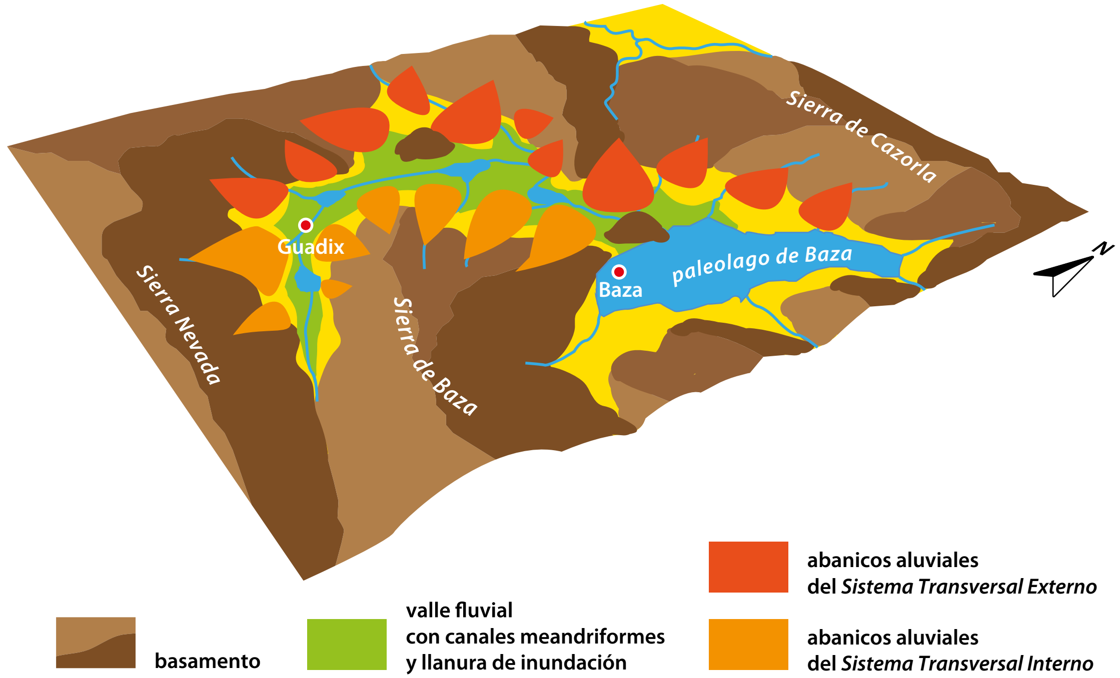


Figure 1. Schematic reconstruction of the palaeogeography of the continental infill stage of the Guadix-Baza Basin, with a large lake developed in the eastern sector and several fluvial systems in the western sector. The main fluvio-lacustrine system ran along the longitudinal axis of the basin (palaeo-Fardes river). A further two systems were transverse tributaries consisting of alluvial fans derived from the terrain of the Internal and External Zones of the Betic Cordillera.

More than 7 million years ago, the sea had finally disappeared from this territory. The Guadix-Baza Basin was still a depression surrounded by mountainous terrain, which continued to be eroded. As a result, the basin continued filling with sediments, but now these were not below sea level but were transported by rivers to interior lakes disconnected from the Atlantic and the Mediterranean. It was what is known as an endorheic continental basin; in other words, it had internal drainage and its waters did not flow into the sea.

During this period of continental sedimentation, a huge lake formed in the eastern part (Baza-Huéscar sector). The main large river, which rose at the foot of the Sierra Nevada (in the Marquisate of Zenete sector), flowed across the entire western part of the basin (Guadix sector), with its mouth at a point more or less north of Cerro Jabalcón (Fig. 1). This river is known as the palaeo-Fardes and the lake in the eastern sector as the Baza palaeolake. Together they were responsible for establishing two distinct major sectors: the western sector or Guadix sub-basin and the eastern sector or Baza sub-basin. The natural boundary between the two is the Baza fault, described in Chapter 5.

The rivers and fluvial fans of the western sector

For more than five million years, the palaeo-Fardes river (also called Axial because it flowed approximately along the axis of the ancient Guadix-Baza Basin) ran for over 50 km from the foot of the Sierra Nevada to the Baza palaeolake. During this long period of time, various climate situations arose. In times of warm, wet climatic conditions, a savanna landscape, similar to that which can be seen today in the Rift Valley in East Africa, developed in the vicinity of the great eastern lake and in the flat areas (floodplain) around the Axial river.

The sedimentary infill from the continental stage is complex and varies significantly in space and time. We must bear in mind that during the development of the continental basin, the great antiform structures of the Sierra Nevada and Sierra de Filabres were forming, and their active tectonics, together with the variations in the volume of inputs entering the basin owing to the frequent climatic changes, led to very important and very rapid changes in the distribution of sedimentary environments.

In the western (Guadix) sector, closer to the great sediment-supplying mountains (the Sierra Nevada), the palaeogeography was more complex (Fig. 1). A fluvio-lacustrine system, the above-mentioned Axial (palaeo-Fardes river) System, was confined to the central valley and flowed almost parallel to the palaeogeographic axis of the basin, developing a meandering channel pattern (a river following a winding course), which evolved into a network of anastomosed or interwoven channels leading to more distal areas (Fig. 2). At times when the climate was at its wettest, much of the axial floodplain remained waterlogged, developing extensive wetlands or ephemeral lakes dominated by marsh sedimentation (Fig. 3). The Axial river system also received inputs from two transverse alluvial fan systems derived from erosion of the reliefs on the southern margin (Internal Zone) and northern margin (External Zone) (hence the fact that they have been referred to in the literature as the Internal and External Transverse System), between which different patterns of morphology and sedimentary dynamics can be established.

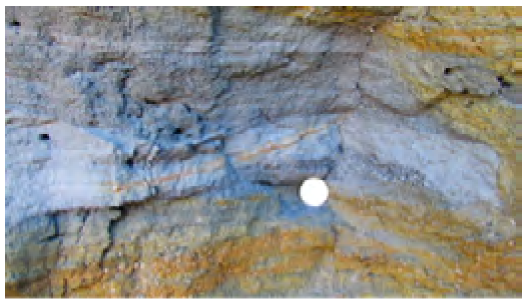


Figure 2. Sandy sediments deposited in a channel of the Axial System.

A: The geometry of the layers and the sequence of sedimentary structures make it possible to recognize that these sediments correspond to meandering channels.

B: Detail of the fluvial sediments.

Figure 3. **A**. Alternation of palustrine limestones and marly limestones developed in the ephemeral lakes of the western sector of the basin.

B. Detail of the palustrine limestones showing their characteristic nodular texture.

The Internal Transverse System was formed by a series of alluvial fans deposited by a network of low-sinuosity channels (braided rivers) which joined laterally to form a downflow system, that is, a uniform slope that dipped northwards. Its radius (10–11 km) often exceeded half the width of the basin (locally 15 km) due to the large volume of inputs from the terrain to the south (Fig. 4).

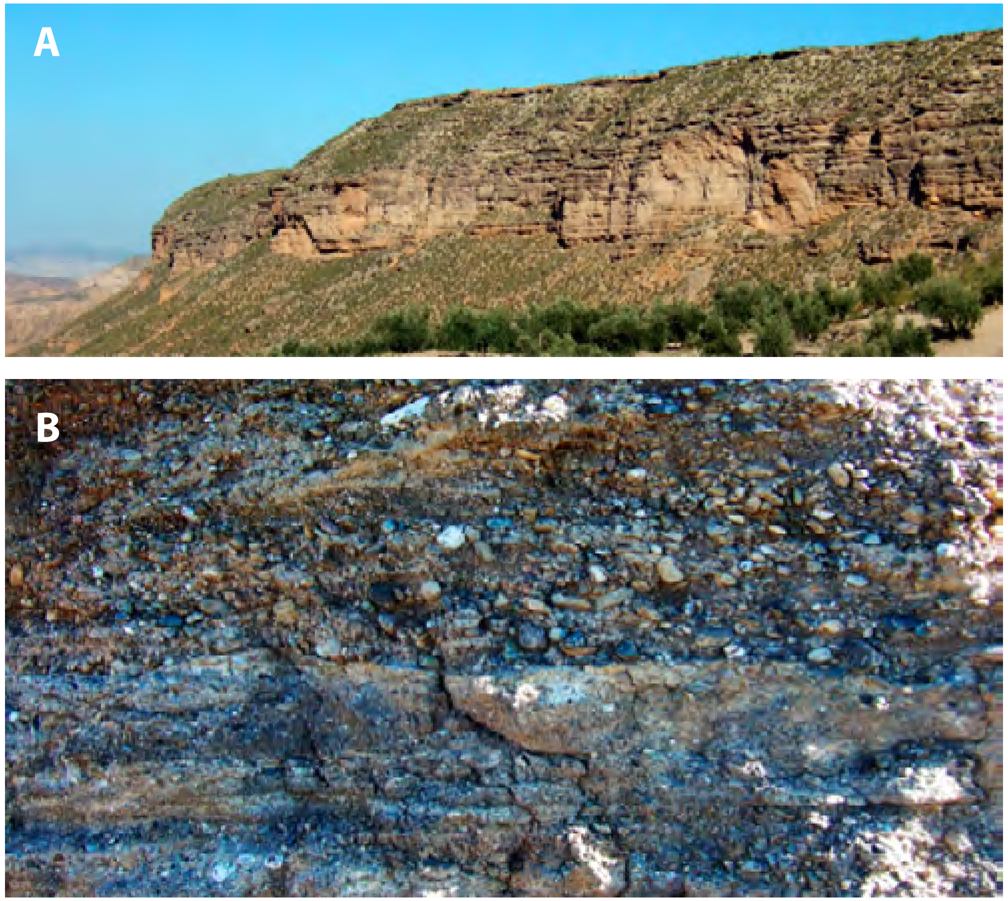


Figure 4. **A**. Field appearance of the materials of the Internal Transverse System. The more resistant layers correspond to channel sediment and the others to fine deposits that accumulated on the floodplain.

B. Detail of the conglomerates that accumulated in the channels. The lithology of the clasts and the sedimentary structures indicate that this fluvial system ran northwards from the foot of the Sierra de Baza.

The fans of the External Transverse System, mainly derived from the Sierra Arana and Mencal, were characterized by a lower volume of inputs, so they formed smaller sedimentary bodies (with a radius of less than 4 km), semicircular in plan view, often isolated from each other (Fig. 5).

Figure 5. Field view of the sediments of the External Transverse System at its junction with an ephemeral lake located in the Axial System. There are alternate levels of gravel, corresponding to the channels of the alluvial fan, and clay, deposited on the lutitic plain at the margin of the shallow lake.

The fans of the Internal Transverse System prograded or overlapped cyclically on the Axial valley to the point of blocking the axial drainage, triggering the development of marshy wetlands and ephemeral lakes on the axis of the basin (Fig. 3).

DID YOU KNOW...?

Unlike the western part, where the prevalence of fluvial sediments gives the territory a reddish colour, the predominant colour in the eastern part of the Guadix-Baza Basin is whitish. The white tones are due to the typical colour of the lacustrine sediments, with an abundance of gypsum, limestone and marl.

The palaeolake of the eastern sector

The lacustrine sediments of the eastern sector that formed in the Baza palaeolake span a temporal range of over 6 million years, from the Pliocene to the Middle Pleistocene. In some sectors their thickness exceeds 400 metres, which represents an exceptional stratigraphic record, especially for the Quaternary period. The Baza palaeolake was a shallow lake in which the sediments show numerous sedimentary cycles controlled mainly by climatic changes, giving rise to an alternation between clays, marls, limestones and gypsum. Its extent varied over time. At times of maximum expansion (wet stages), marly limestones with a variable proportion of detrital sediment depending on the volume of fluvial detritus were deposited on the bottom (Fig. 6), and coal even formed on the lake's marginal wetlands (Fig. 7). In more arid stages, the high evaporation rate led to the precipitation of salts (mainly gypsum) (Fig. 8). Seismic shocks linked to active tectonics during the period of sedimentation gave rise to deformation of the sediments, forming seismites, described in Chapter 5 (Fig. 9).

Figure 6. Marly limestones deposited in the lake by chemical precipitation in very wet periods. Cañada Gallego (Baza).

Figure 7. Coal level between the lacustrine sediments in the Baza palaeolake. Cortes de Baza Sector.

Figure 8. Alternation between marls and gypsum. In more arid stages, precipitation of gypsum occurred in the lake.

Figure 9. Deformation produced by earthquakes (*seismites*) in the sediments of the eastern lake.

In the marginal areas of the lake, alternations of marls, silts and sands can be seen, with some levels of large lenticular gypsum crystals and arrowhead twins. In the central parts of the lake (around Benamaurel) the quantity of sands and silts decreases, and the sediments are mostly marls and gypsum. The locations of the various lithologies — sands, silts, marls, sandstones and gypsum — were therefore distributed according to their positions relative to the centre or shores of the lake.

Although the main sedimentary environment of the eastern sector is lacustrine, there were also river systems originating from the mountains to the north and east that flowed directly into the Baza palaeolake. Some places where these fluvial sediments can be observed are in the vicinity of Caniles, Cúllar and the Guardal and Castril river valleys.

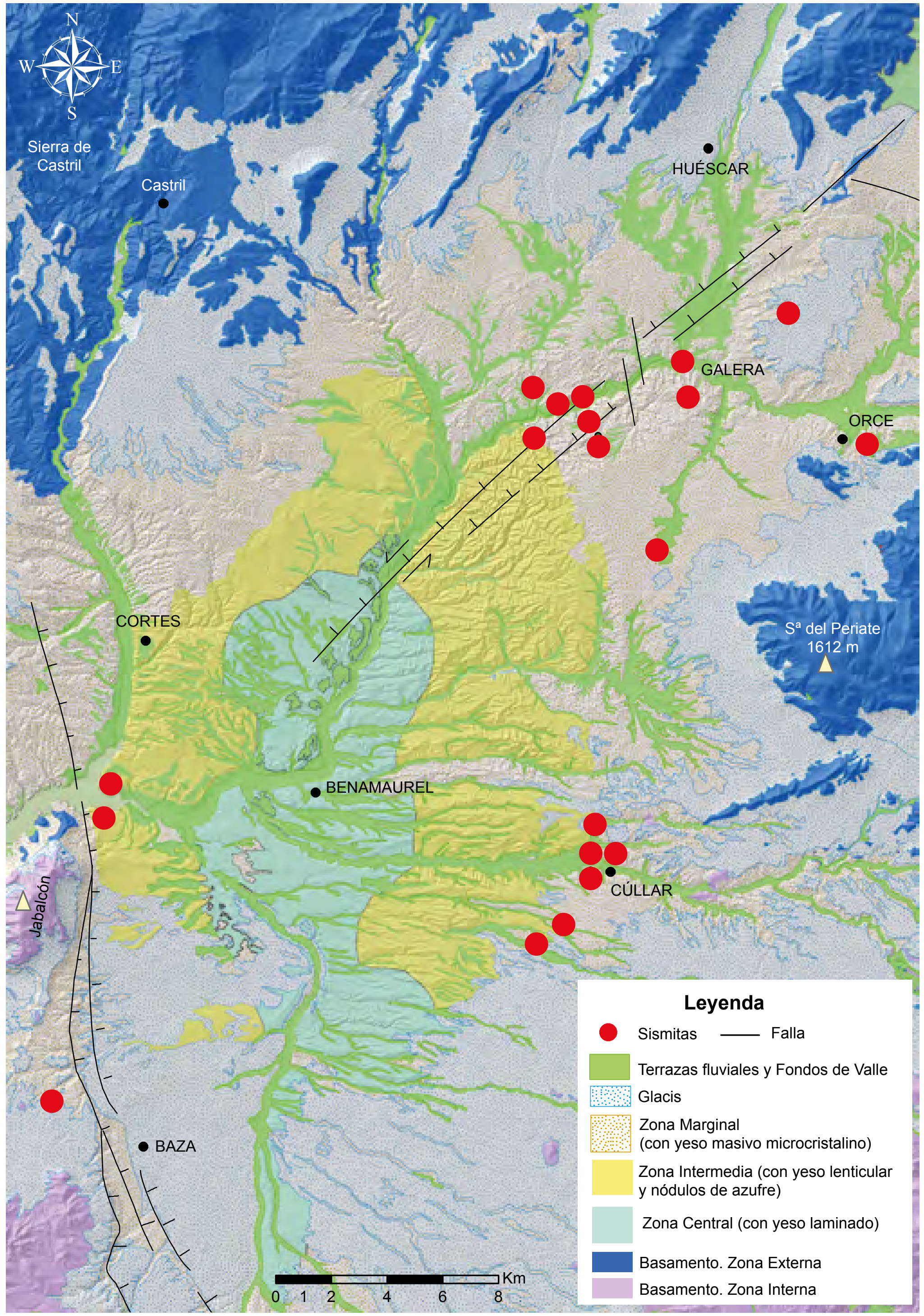


Figure 10. Geological map of the Baza Basin, showing the deposits corresponding to the Baza palaeolake.

DID YOU KNOW...?

The changes in the depth and extent of the lake can be recognized in the area of the mouth of the palaeo-Fardes, at SGI 39 (transition between the Guadix and Baza formations). What we see at this SGI is simply the alternation in the vertical dimension between red fluvial sediments and white lacustrine sediments. When the lake expanded, the lacustrine sediments were deposited on the top of the fluvial ones; when the lake level fell, the opposite occurred.

Tail of the Negratín Reservoir in the vicinity of the Zújar Thermal Baths.

During this stage of continental sedimentation of the basin, the endorheic conditions favoured the formation of an extensive plain (an area of glacis), which remained active until the basin became exorheic, that is, when the rivers had an outlet to the sea. This large area (glacis), which is still preserved between the foothills of the mountains that surround the Geopark and the centre of the basin, represents the last vestige of the latter's endorheic stage. That great plain would surround the Baza palaeolake and continue throughout the western sector, where it would be crossed by the river systems previously described.

Observing what is left of the glacis area, we can imagine an African savanna-like landscape, with the large mammals that lived in the Geopark territory, to which Chapter 6 will be devoted. Those large mammals lived on the banks of the rivers and lakes that existed during the endorheic period, and it was precisely the endorheic nature of the territory, giving rise to the accumulation of a large quantity of sediments rather than eroding them as happens now, that led to the burial and fossilization of the remains of these large vertebrates that lived in the territory of the Granada Geopark.

Figure 11. Panoramic view of the glacis in Llanos de Arana (Huélago) with the Sierra de Baza in the background.

GEOPARQUE GRANADA

THE CHANGE FROM MARINE BASIN TO CONTINENTAL BASIN: CERRO DE LA LANCHA

SGI 27

One of the most interesting aspects of the history of the Guadix-Baza Basin is the change from marine to continental sedimentation. This change can be recognized in several places where the calcarenites from the third marine stage and the clays from the continental stage are in contact, as in Forruchu and Negratín, for example, which have been described in the previous chapter, or others located in the vicinity of Dehesas de Guadix.

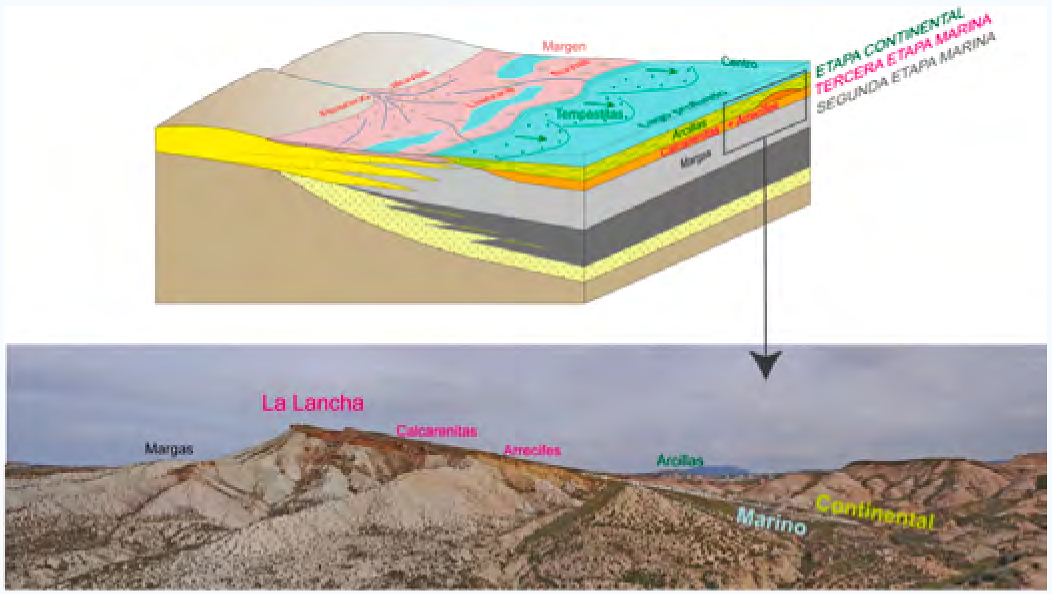


Figure 1. Position of the marine-continental change in the La Lancha outcrop.

Another of the most outstanding examples, making it a Geopark site of geological interest, is **Cerro de la Lancha** (SGI 27). This site is notable both for its scenic value and for the good conditions it offers for detailed analysis of the stratigraphic section (Figs 1 and 2).

Figure 2. Panoramic view complementary to Figure 1, in which the stratigraphic position of the marine-continental transition can be observed in more detail.

The complete stratigraphic section of La Lancha consists of four units (Fig. 3), which from bottom to top are as follows:

- **Massive** grey marls with foraminifera from the second marine stage. The benthic species of the foraminifera indicate that the sedimentation took place in a deep marine basin. The estimated depth of the deposit is 300 metres.
- **Calcarenites** with bryozoans and cross-stratification, corresponding to the third marine stage. At some points, small coral reefs are seen instead of calcarenites. In both cases they are deposits that accumulated on a shallow marine platform.
- **Conglomerates** with clasts perforated by lithophages, which mark the transition from marine to continental. The perforations of the clasts were produced by bivalves that lived within the rock and that we find today on gravel beaches.
- Green **clays** and **sandstones** with wavy cross-stratification, corresponding to the continental stage, which accumulated in a deep lake. Wavy cross-stratification is also known as "hummocky" cross-stratification and is characteristic of storm episodes that intensely agitated the waters of the lake.

In short, the change from marine to continental environments in the Guadix-Baza Basin is the final result of two previous steps of a drop in sea level (Fig. 4). The first occurred between the second and third stages, from a deep basin to a shallow marine platform. The second took place between the third stage and the level of transition from shelf to beach. After the transition, the continental stage began.

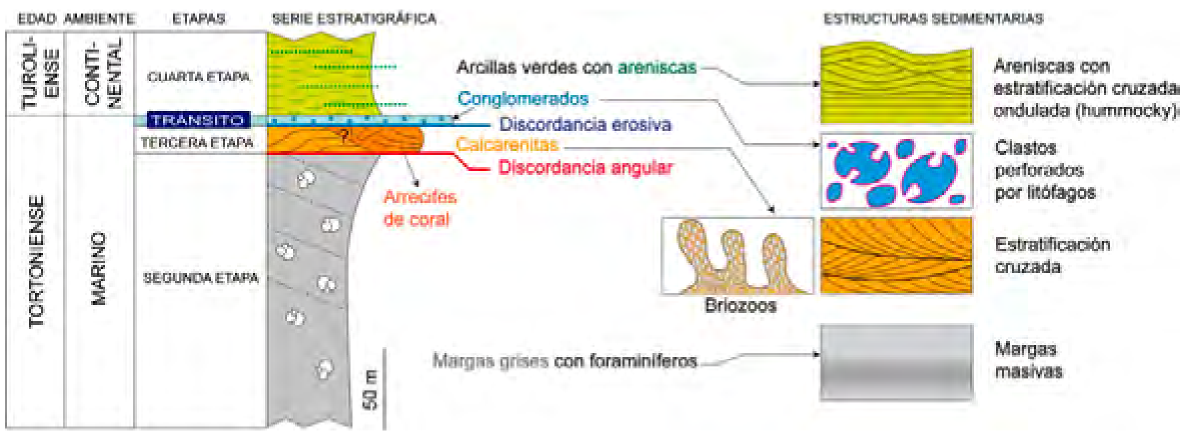


Figure 3. La Lancha stratigraphic section.

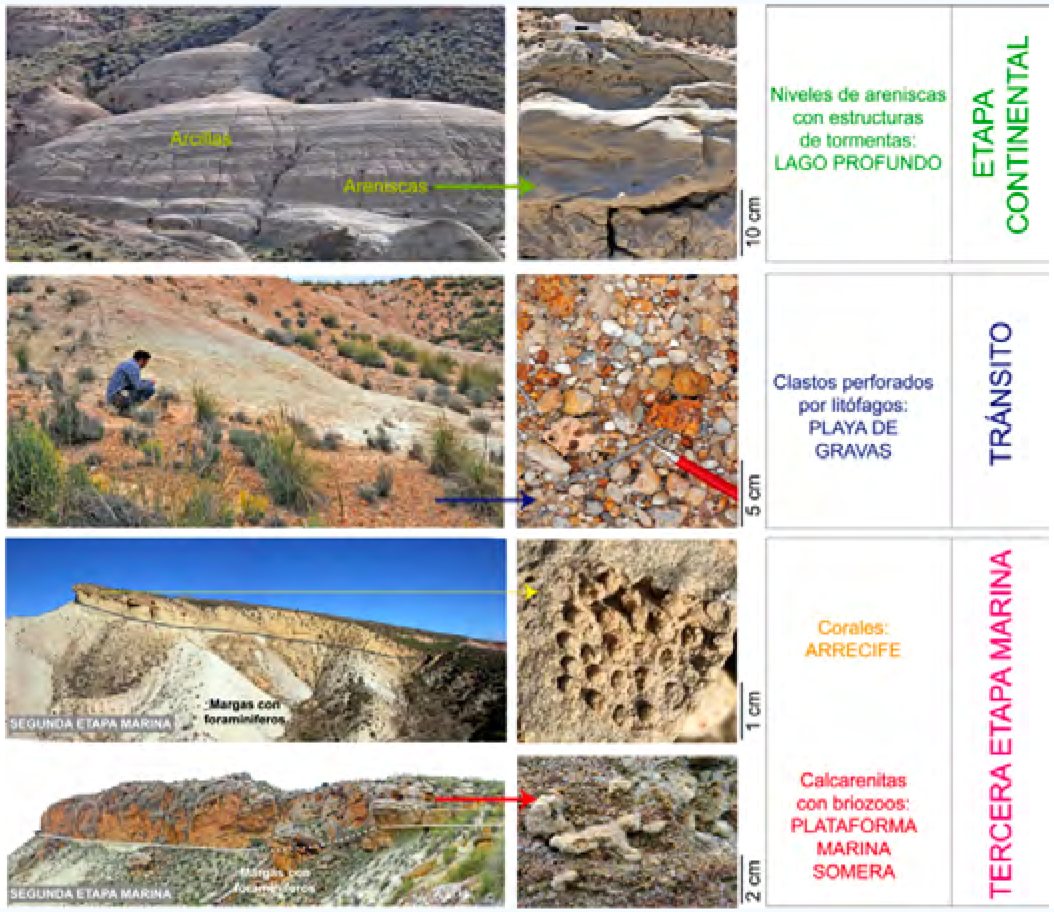


Figure 4. Changes that occurred in the Guadix-Baza Basin during its transformation from marine to continental.

DID YOU KNOW...?

The change from marine to continental in the Guadix-Baza Basin caused the closure of one of the marine corridors that connected the Atlantic Ocean to the Mediterranean Sea (see Figure 5).

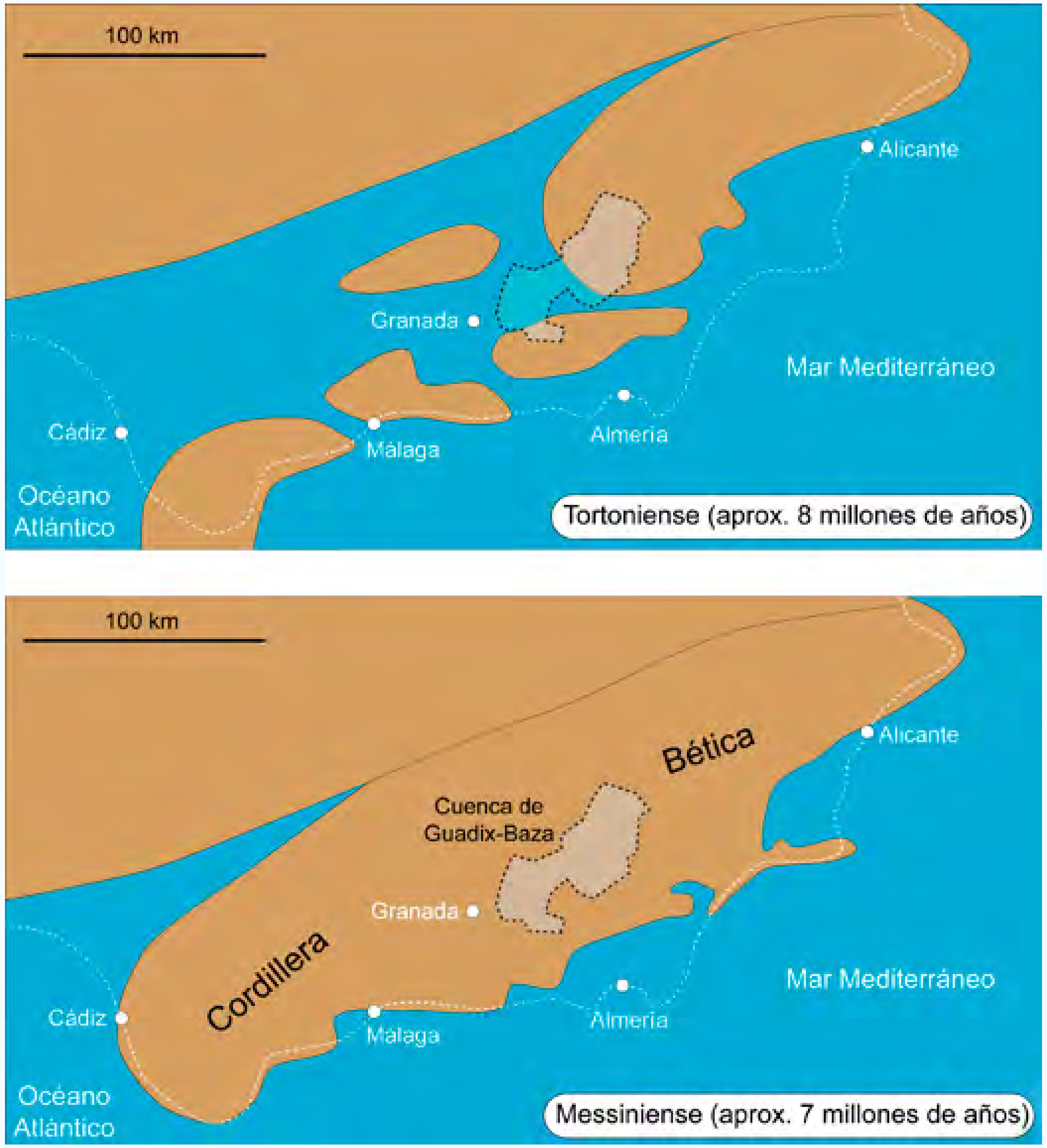


Figure 5. Evolution of the emerged and submerged relief in the Betic Cordillera during the past few million years. Modified from García-Veigas et al. (2019).

GEOPARQUE GRANADA

THE DYNAMICS OF THE RIVER SYSTEMS DURING THE CONTINENTAL SEDIMENTATION STAGE

SGI 25

During the continental infilling stage of the basin, the sediments derived from erosion of the Sierra de Baza were transported northwards via the so-called Internal Transverse System. This system was made up of a series of shallow rivers, within whose channels gravel and sand accumulated, forming elongated bodies, depending on the current (point bars) (Fig. 1). The channels intertwined around the bars, giving rise to a morphology that resembles a braid; hence the term *braided rivers*.

On both sides of the system of braided channels there were extensive almost flat areas called floodplains, which sporadically received clay- and silt-laden water from the channels at times when these overflowed. The floodplain remained dry most of the time and was colonized by vegetation (Figs 1 and 2).

After a large flood the channel could change position (a phenomenon known as *avulsion*), settling on its former floodplain. In this way, several episodes of channel and floodplain infilling can accumulate in the same vertical plane. The channels can be recognized by the fact that they have an irregular erosional surface at the base on which gravel and sand accumulate, whereas in the floodplain layers there is a predominance of fine sediment (silt and clay) with signs of having been remobilized by root action (Figs 3 and 4).

Figure 1. Current analogue of a braided river system (Oued Laou, Morocco).

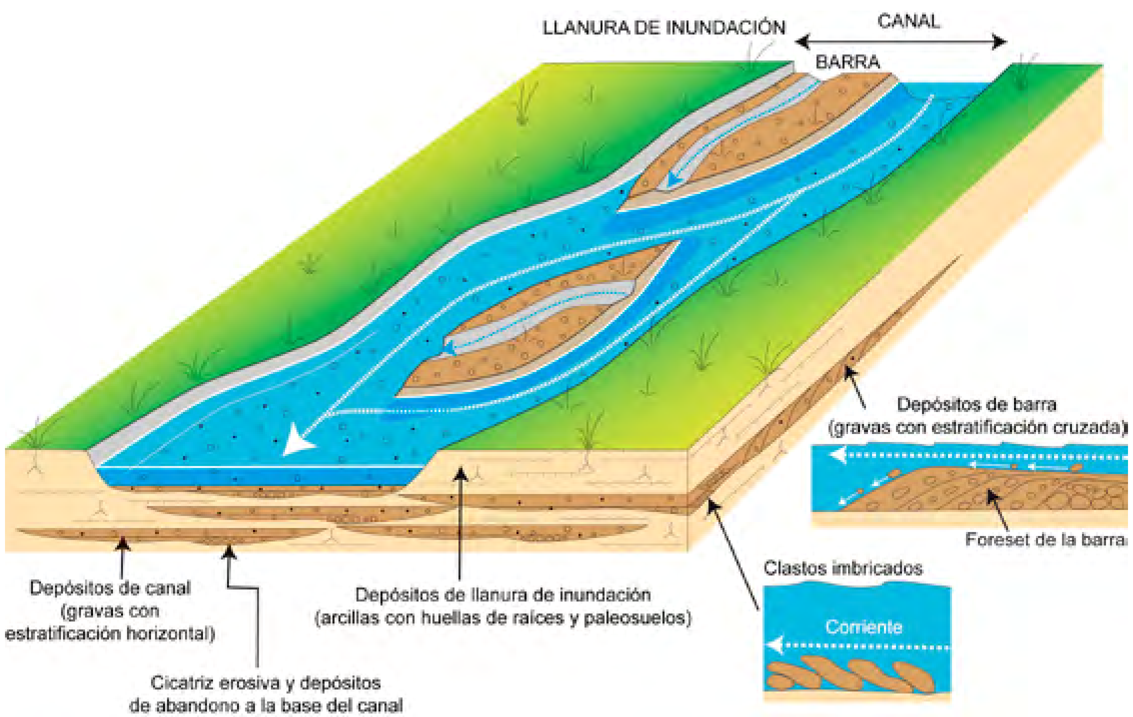


Figure 2. Main components of a braided river system.

When the force of the river current began to diminish after a flood, the larger pebbles or cobbles accumulated in the deepest parts of the channel (*abandonment deposits*). Once this irregularity in the bottom had been filled in, the smaller gravel was deposited on top in horizontal layers (Figs 2 and 3). In the process of rolling along the bottom of the channel, when a non-spherical cobble or pebble fell to the bottom, with its flat face slightly inclined upstream, it was very difficult to set in motion again. So the non-spherical pebbles are often oriented in this way, giving rise to a sedimentary structure called *imbrication* of pebbles (Figs 2 and 5).

At the time of the flood, the water made the gravel roll over the surface of the bar and fall to the bottom of the channel with its face positioned downstream. This led to the formation of layers of gravel inclined downstream (*cross-stratification*) (Figs 2 and 3), which correspond to the advance front (*foreset*) of the bar. As the bars moved downstream, they could reach areas of the channel where there were previous deposits and superimpose themselves on them.

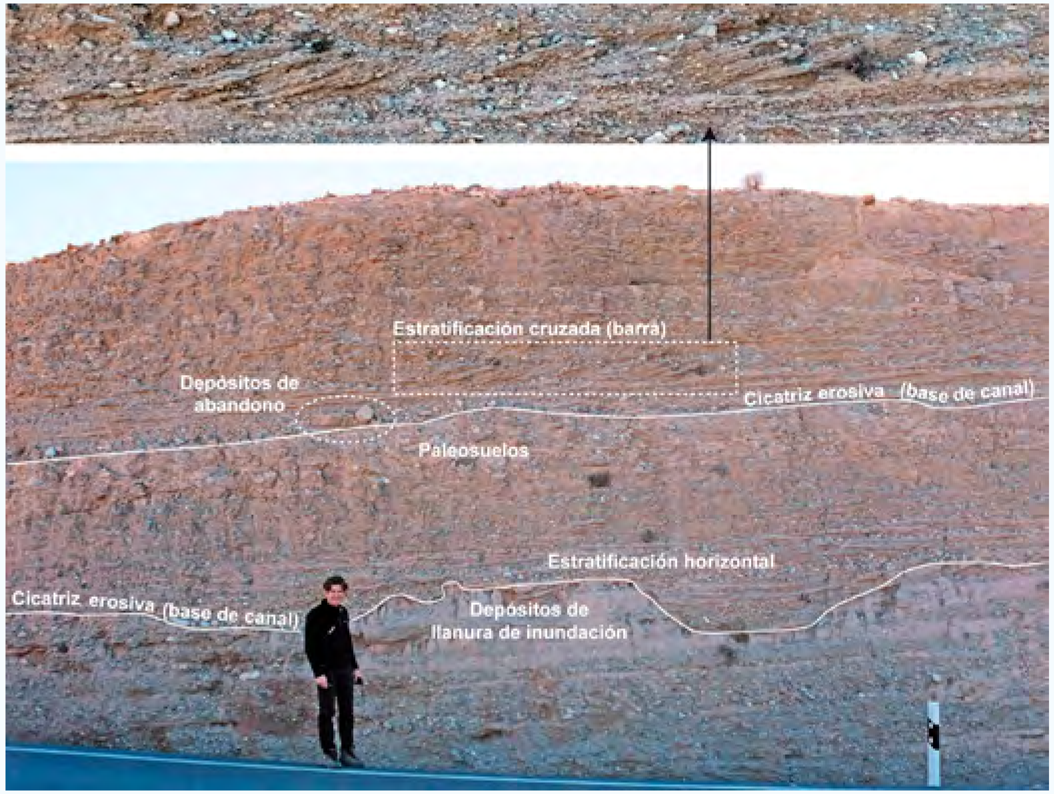


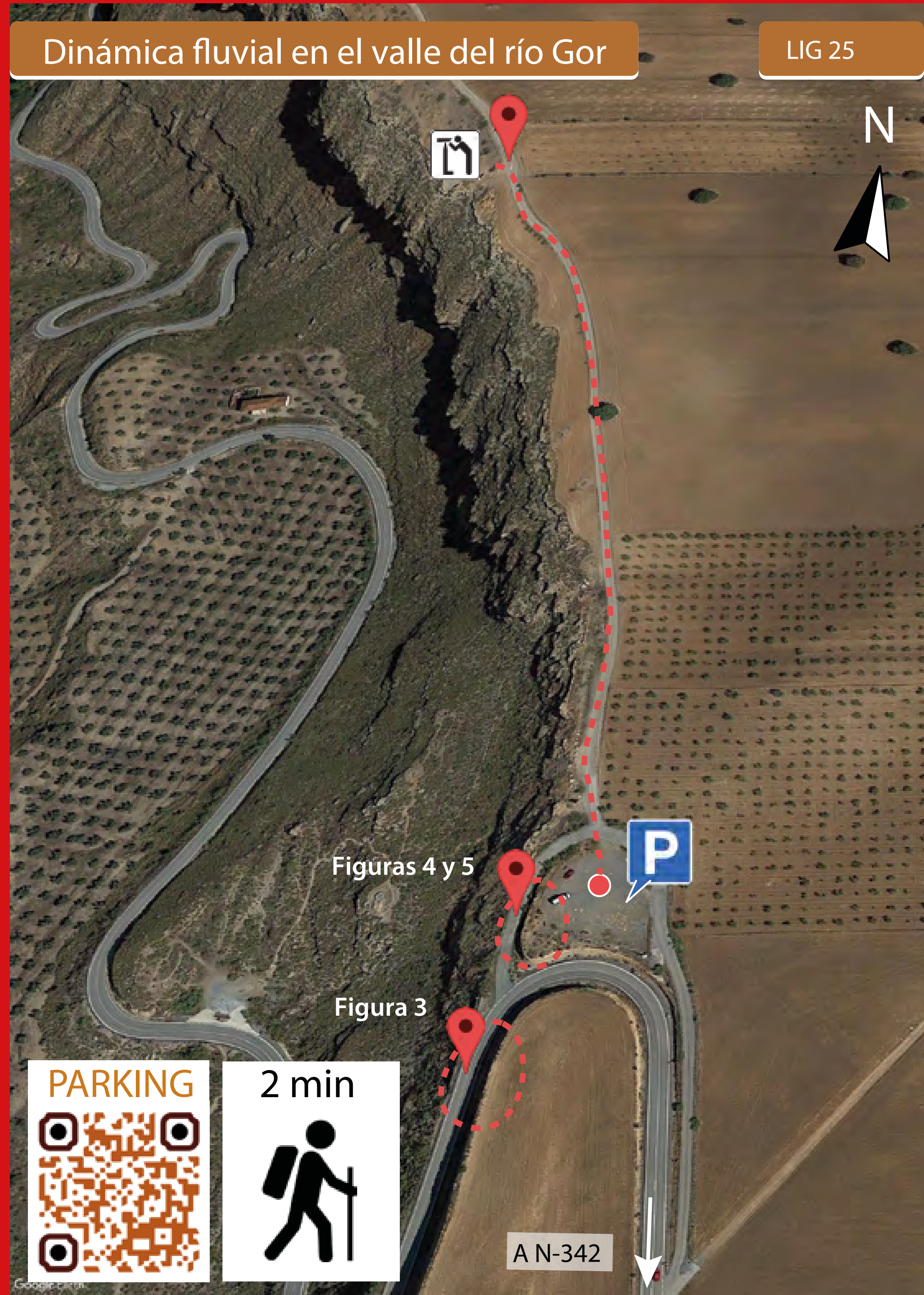
Figure 3. Road cutting showing the deposits of braided rivers of the Internal Transverse System derived from the Sierra de Baza. Several channel and floodplain infilling episodes can be observed.

Figure 4. Carbonate concretions (arrows) around the roots of plants that remobilized the silt and clay of the floodplain.

Figure 5. The preferred orientation of non-spherical pebbles (imbrication) indicates a direction of flow towards the left (north).

DID YOU KNOW...?

The structure in which gravel and sand are deposited in a river channel (orientation of pebbles, inclination of layers, etc.) can be used to reconstruct precisely the direction, flow and energy of the current that transported them. This is very useful when it comes to reconstructing the trajectory and force of the water after a catastrophic flood.



PALAEOGEOGRAPHY OF THE CONTINENTAL BASIN: THE MEANING OF THE COLOURS OF THE DESERT

SGI 04

In the broad panoramic view of the badlands that the Don Diego Viewpoint offers us (see Chapter 8), the great variety of colours is striking. The origin of each colour is related to where the sediment came from, that is, the position occupied in the landscape by the sediments from the various fluvial and lacustrine systems that filled the basin during its continental stage. It is therefore an expression in the landscape of the ancient geography, also known as palaeogeography.

This palaeogeography comprised a great river, the Axial System, also referred to in this guide as the palaeo-Fardes, which ran from south to north across the central part of the basin for 50 km, from the foot of the Sierra Nevada to where it flowed into a large lake located in the eastern area (the Baza palaeolake, Fig. 1A). The Axial System had two tributary river systems, made of up various rivers shorter than the axial one. These brought water and sediment from the mountains of the External Zone, located to the north (Montes Orientales, Mencal, Sierra del Pozo, Sierra de Castril, Sierra de Huéscar, Sierra de Orce and Sierra de María), and the Internal Zone, to the south (Sierra de Baza, Sierra de las Estancias), known as the External and Internal Transverse Systems. At times the Axial System received so much sediment from the transverse rivers that its drainage to the north was partially obstructed. This damming temporarily turned part of the central valley into a shallow lake.

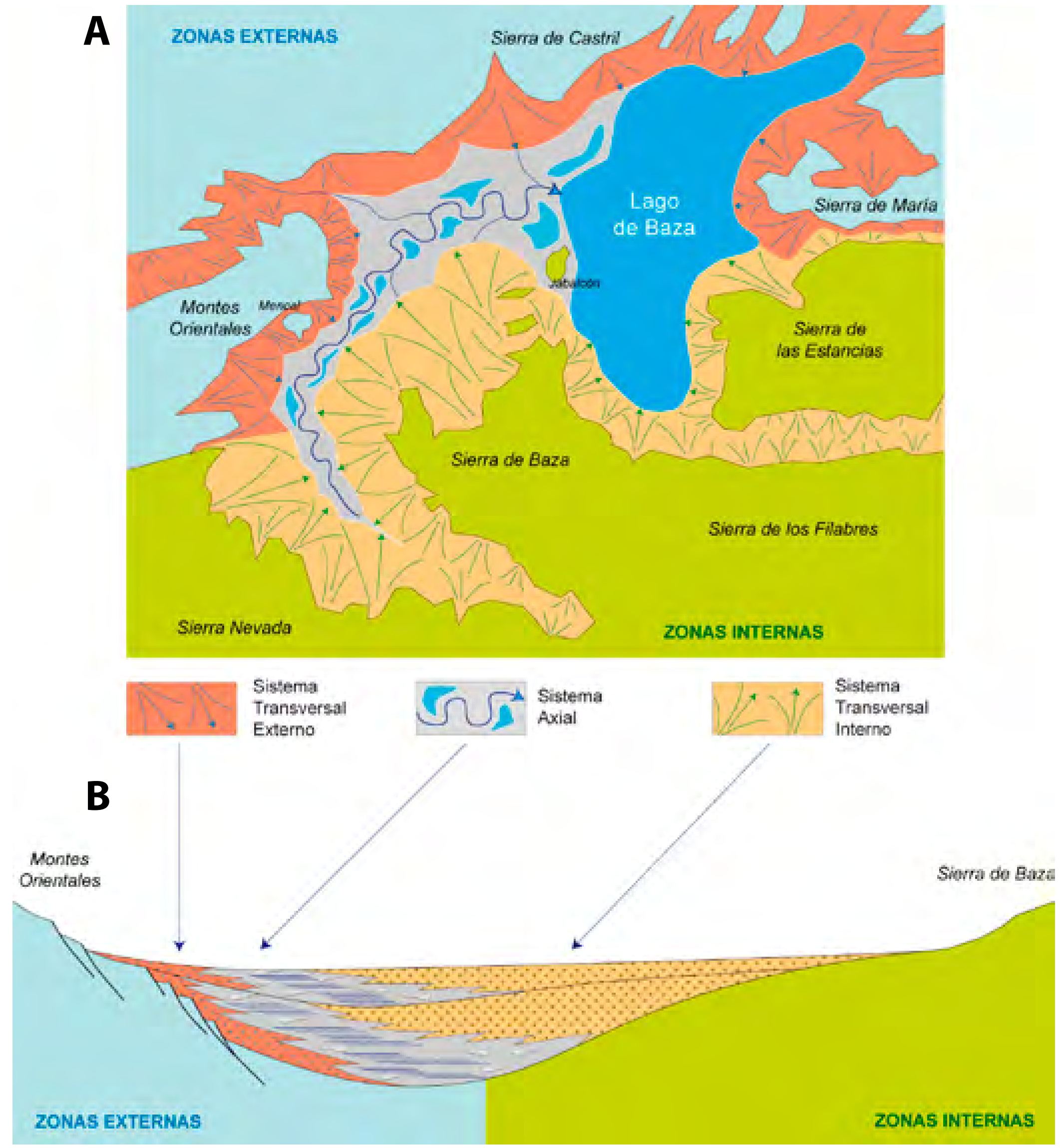


Figure 1. **A**. Schematic map showing the approximate distribution of sediments from the various river systems that occupied the basin during the continental sedimentation stage.

B. Schematic cross-section from northwest (left) to southeast showing the gradual northward shift of the Axial System.

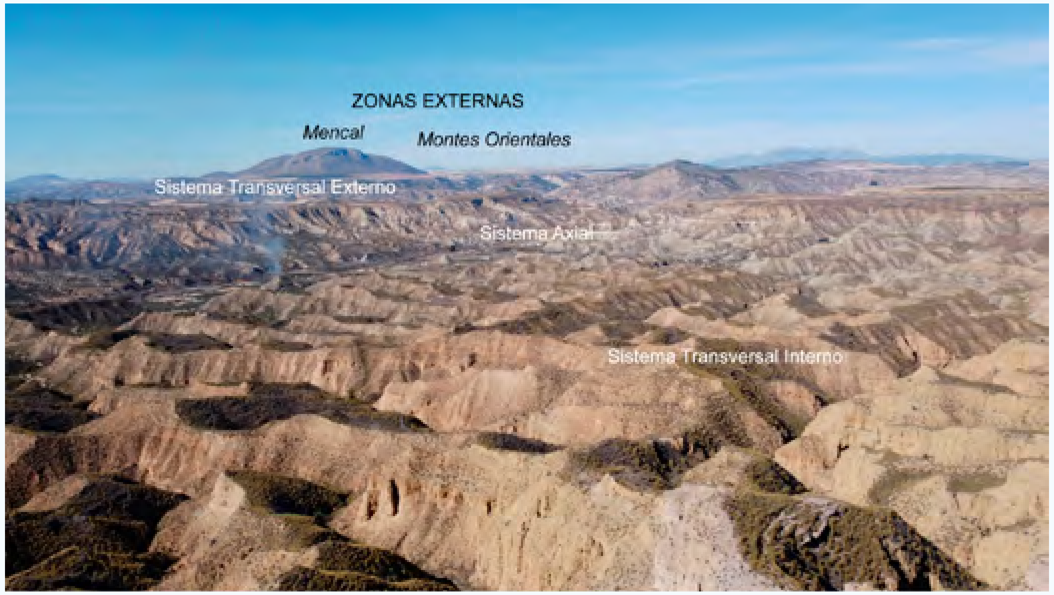


Figure 2. Panoramic view looking west. On the western side of the River Gor valley (below Cerro Mencal in the photograph) we can see that the change of colour from brown to white is further to the north (the right of the image) in the upper part of the wall.

Figure 3. Panoramic view looking north, in which the brown and purplish colours of the Internal Transverse System can be seen in the foreground, with the grey sediments of the Axial System further away and the pink hues of the External Transverse System in the background.

The Axial System was fed mainly with sand and gravel derived from erosion of the Sierra Nevada, with a predominance of grey colours. When the drainage was obstructed and the area turned into a lake, white marls and limestones were deposited. So the part of the landscape dominated by grey and white colours basically corresponds to sediments of the Axial System when it was a large river (grey) or a shallow lake (white) (Figs 2 and 3).

The rivers of the External Transverse System transported sediments originating from erosion of the limestone uplands located north of the basin. These limestones were partially broken down by chemical change through a process called karstification, which gives rise to a deep red clay residue (terra rossa). Thus, to the north of the grey and white colours of the Axial System, pinkish colours can be seen in the landscape, corresponding to the clays deposited by the rivers of the External Transverse System (Fig. 2).

The rivers that came from the southeast brought material derived from erosion of the schists, phyllites and marbles of the Sierra de Baza, which give the sediment brown and purplish hues. So in the landscape closest to our eye (the southern part of the panorama), the materials in these colours correspond to the sediments of the Internal Transverse System.

The position in space of the three drainage systems described varied over the period of more than 6 million years that the continental infill stage lasted. During this time, the mountains to the south (Sierra de Baza), in the very process of uplift, were gradually becoming higher, while those to the north, at the end of the continental stage, were highly eroded and could provide very little sediment. Thus, the disproportion in the amount of sediment contributed by the two transverse systems increased in favour of that from the south, so that the Internal Transverse System gradually "pushed" the Axial System northwards. This is why, if we turn our gaze towards Cerro Mencal (in the panoramic view looking west, Fig. 2) we can see how the change of colour from brown (Internal Transverse System) to white-grey (Axial System) in the materials that fill the basin is located further north, in higher sediments (which are also more recent).

GEOPARQUE GRANADA

THE GYPSUM DEPOSITS OF THE BAZA PALAEOLAKE

SGI 55, 56, 59, 60, 66, 68

During the more than 5 million years that the ancient Baza lake existed, the high evaporation rate in the most arid stages favoured the precipitation of salts, outstanding among which was gypsum. Another strikingly unusual feature is the presence of sulphur associated with gypsum, which is very abundant in the area around Benamaurel (SGI 55: Benamaurel Sulphur Mines). A tour of the eastern part of the Geopark reveals numerous sparkling mineral gypsum crystals (popularly known as espejuelos, literally “little mirrors”) among the whitish sediments. In the Geopark’s catalogue of sites of geological interest there are several that are notable for the presence of gypsum deposits: Benamaurel (SGI 56), Castilléjar and Galera Badlands (SGI 58), Galera Gypsum Deposits (SGI 60), Castellón Alto Gypsum Mine (SGI 66) and Rambla de los Pilares (SGI 68).

What is gypsum?

Gypsum is the name applied both to the mineral composed of hydrated calcium sulphate ($CaSO_4{\cdot}2H_2O$) and to the rock in which this mineral predominates. So it is common to speak both of gypsum crystals and of gypsum rock. The presence of two molecules of water for each molecule of sulphate means that this mineral is very soft; in fact, it can easily be scratched with a fingernail. If gypsum loses water it turns into another mineral known as anhydrite ($CaSO_4$), which is harder and cannot be scratched with a fingernail.

Where does gypsum form?

Gypsum formation takes place in both sea and lake waters. In the sea, the water has sufficient sulphate content to produce gypsum when it is saturated with these salts. In lakes, as in the Geopark, the sulphates come from other older rocks rich in gypsum that border the Baza palaeolake. The main rock that contributes these sulphates to the lake is Triassic gypsum, which outcrops at numerous points in the basement of the Guadix-Baza Basin.

In the Baza palaeolake gypsum precipitated throughout practically its entire area, from the marginal or shallower to the central or deeper zones. In each of these zones different types of gypsum appear, as shown in Figure 1.

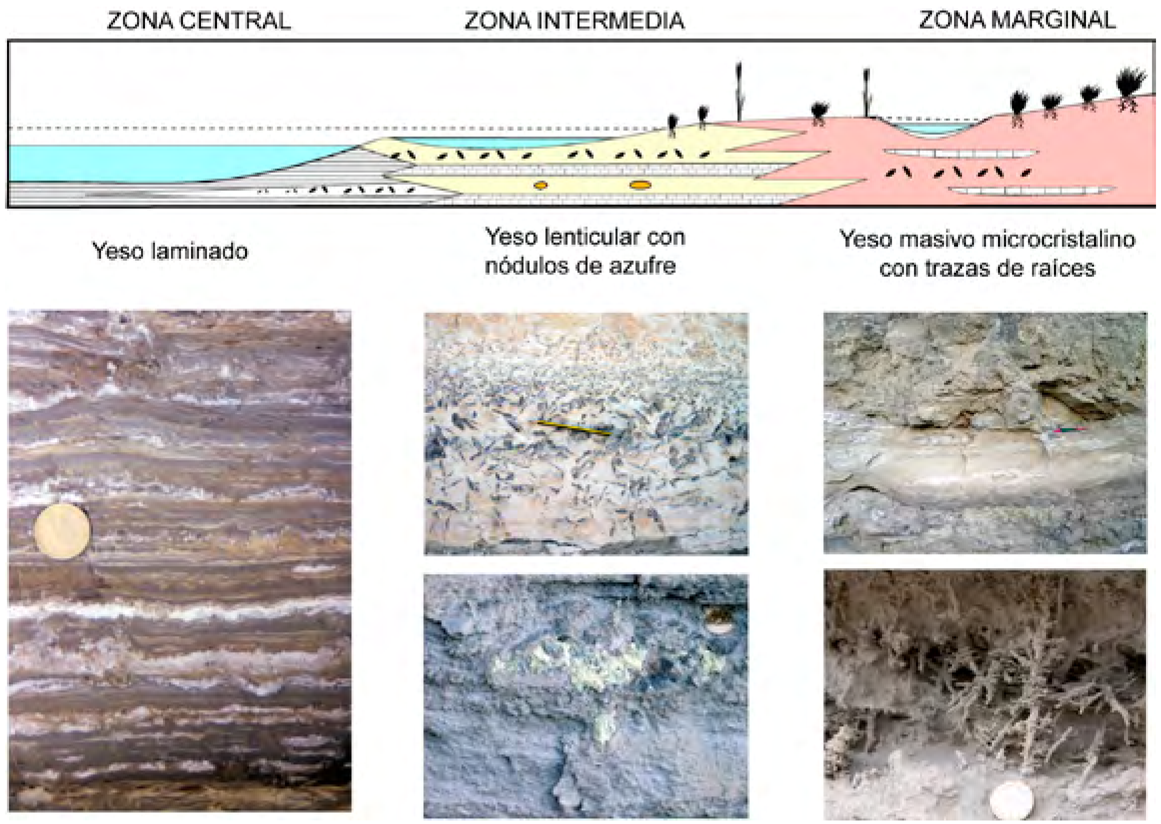


Figure 1. Sedimentary model for the Baza palaeolake indicating the different types of gypsum present in each zone of the lake.

Types of gypsum

Gypsum appears in the Geopark in various forms:

MICROCRYSTALLINE MASSIVE GYPSUM

consisting of small crystals (usually less than a millimetre) which you need a magnifying glass or a microscope to see. These tiny crystals precipitate rapidly, with no time for them to grow. Traces of roots are often observed, from which it can be deduced that they formed in marginal zones of the lake with abundant vegetation. This type of gypsum can be recognized in numerous mines in the area around Galera (Fig. 2).

Figure 2. El Alcázar mines. Mine excavation at Galera for exploitation of massive gypsum.

LENTICULAR (LENS-SHAPED) GYPSUM

occurring as isolated crystals or groups of crystals (gypsum rosettes or desert roses, Fig. 3). They can be several centimetres in size. They crystallize within the sediment at the bottom of the lake, originally composed of carbonate oozes, marls or clays. The water that permeates these oozes is loaded with sulphates, and when it is saturated it allows the gypsum lenses to precipitate and grow.

Figure 3. Group of lenticular gypsum crystals.

LAMINATED GYPSUM

(Fig. 4), arranged in very thin strata or lamellae (several millimetres thick). These lamellae have a gently undulating or deeply wrinkled morphology (very irregular folds). The succession of stacked lamellae represent individual episodes of water saturation and gypsum precipitation.

Figure 4. Outcrop of laminated gypsum in the vicinity of Baza.

FIBROUS GYPSUM

filling fractures or veins (Fig. 5). It is called fibrous because of the elongated shape in which the gypsum crystals grow. Its formation is related to the circulation of mineralized water very rich in sulphates through the fractures. These sulphates come from dissolution of the gypsum previously formed in the Baza palaeolake. As in the cases described above, the precipitation of fibrous gypsum requires saturation of the water, in this case inside the fractures.

Figure 5. Veins filled with fibrous gypsum

Sulphur in the palaeolake

A distinctive feature of the Baza palaeolake is the formation of **native sulphur** (Fig. 6) at certain stages in its geological evolution. This chemical element has been exploited economically, and numerous small mines were worked for this purpose in the area around Benamaurel in historical times. The sulphur occurs as nodules or lenticular bodies, with sizes exceeding 10 cm, within strata of gypsum or marls. Its origin is related to the activity of bacteria that lived at the bottom of the lake. It has been extracted in underground galleries, such as the Benamaurel Sulphur Mines (SGI 55) (Fig. 7).

Figure 6. Nodules and levels of native sulphur in the Benamaurel mines.

Figure 7. Benamaurel sulphur mine.

DID YOU KNOW...?

Gypsum is a mineral of huge economic interest. Its main application is as a building material (plaster and other commercial derivatives). Remember that gypsum is present in most of our homes, whether in the walls of the rooms, ceiling panels or built-in shelves. If you visit the Alhambra, you will see the beauty of the *mocárabes* (muqarnas) modelled in gypsum plaster inside the Nasrid palaces.

The Espejuelo Trail. Gypsum and tradition

EIn the area around Benamaurel, Castilléjar and Galera you can find a great variety of gypsum. The kind that often goes unnoticed is the laminated gypsum deposits such as those of Benamaurel, and also the microcrystalline massive gypsum, which can form strata up to several metres thick. These thicker layers have been exploited in the town of Galera, in the mines of Castellón Alto (Fig. 8) and El Alcázar, as well as in small open-cast quarries. In the case of Castilléjar, gypsum has been exploited primarily in the form of *espejuelos* (large lenticular gypsum crystals) such as those found in the Cueva de los Amos (Fig. 9).

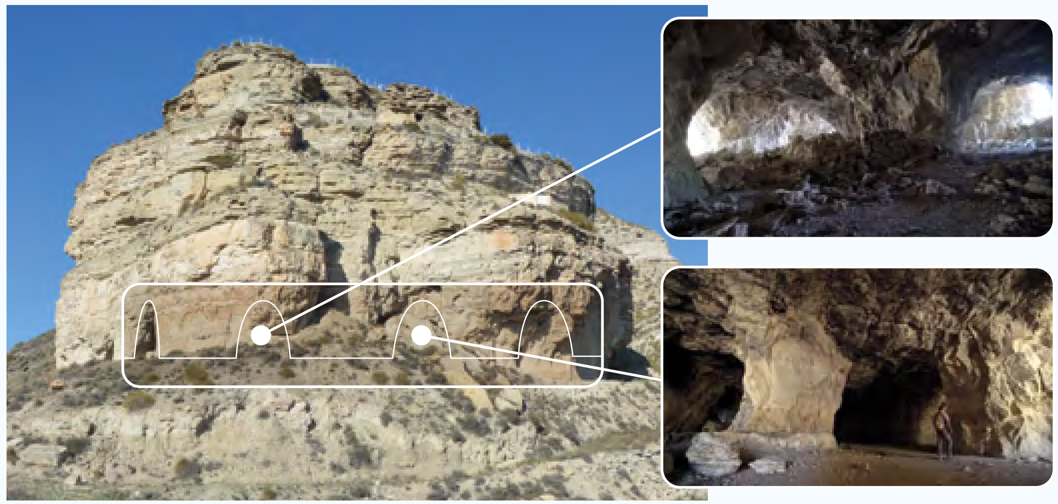


Figure 8. Gypsum mine at the base of Castellón Alto (Galera). Interior of the galleries excavated to exploit the gypsum.

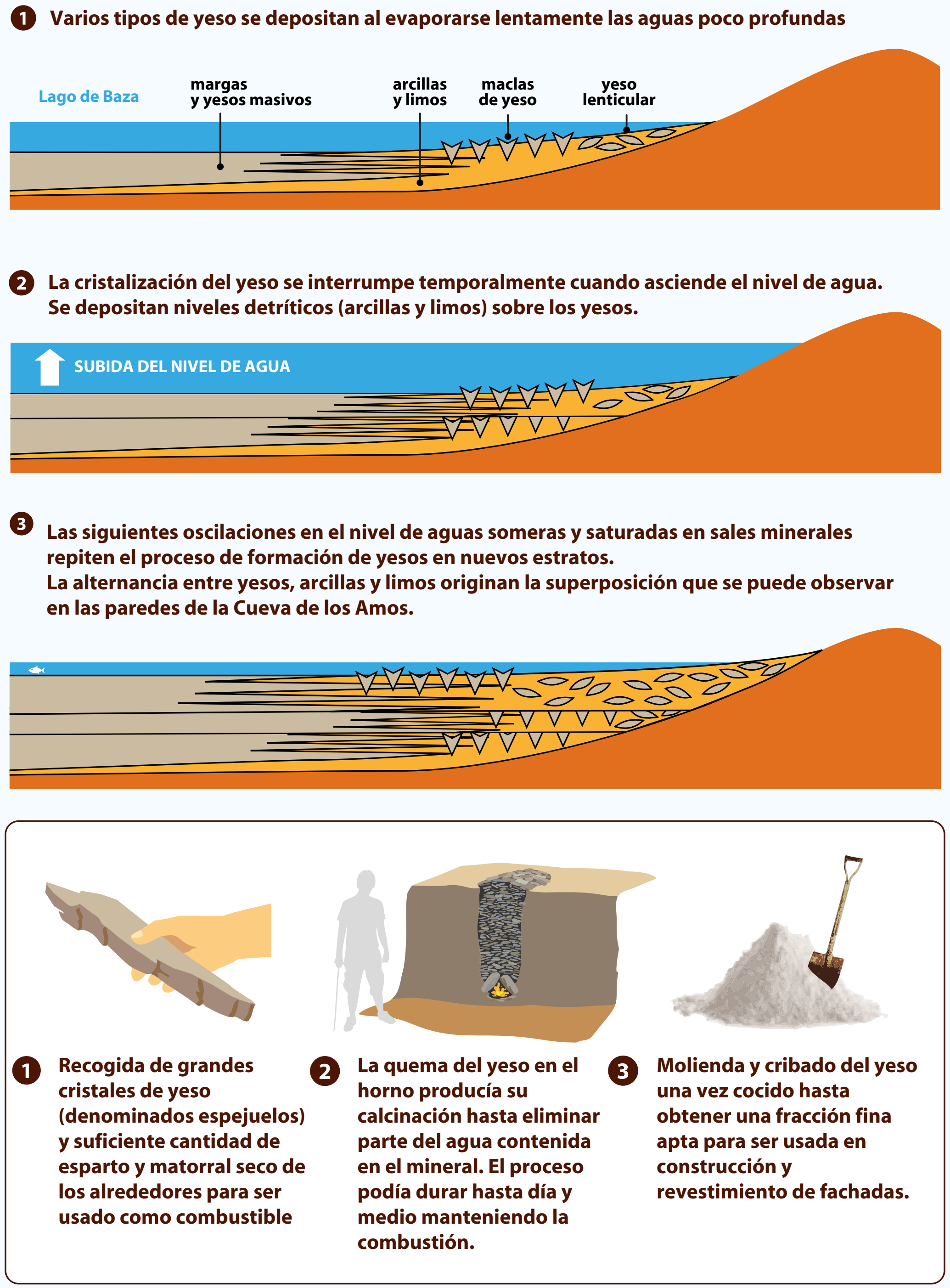


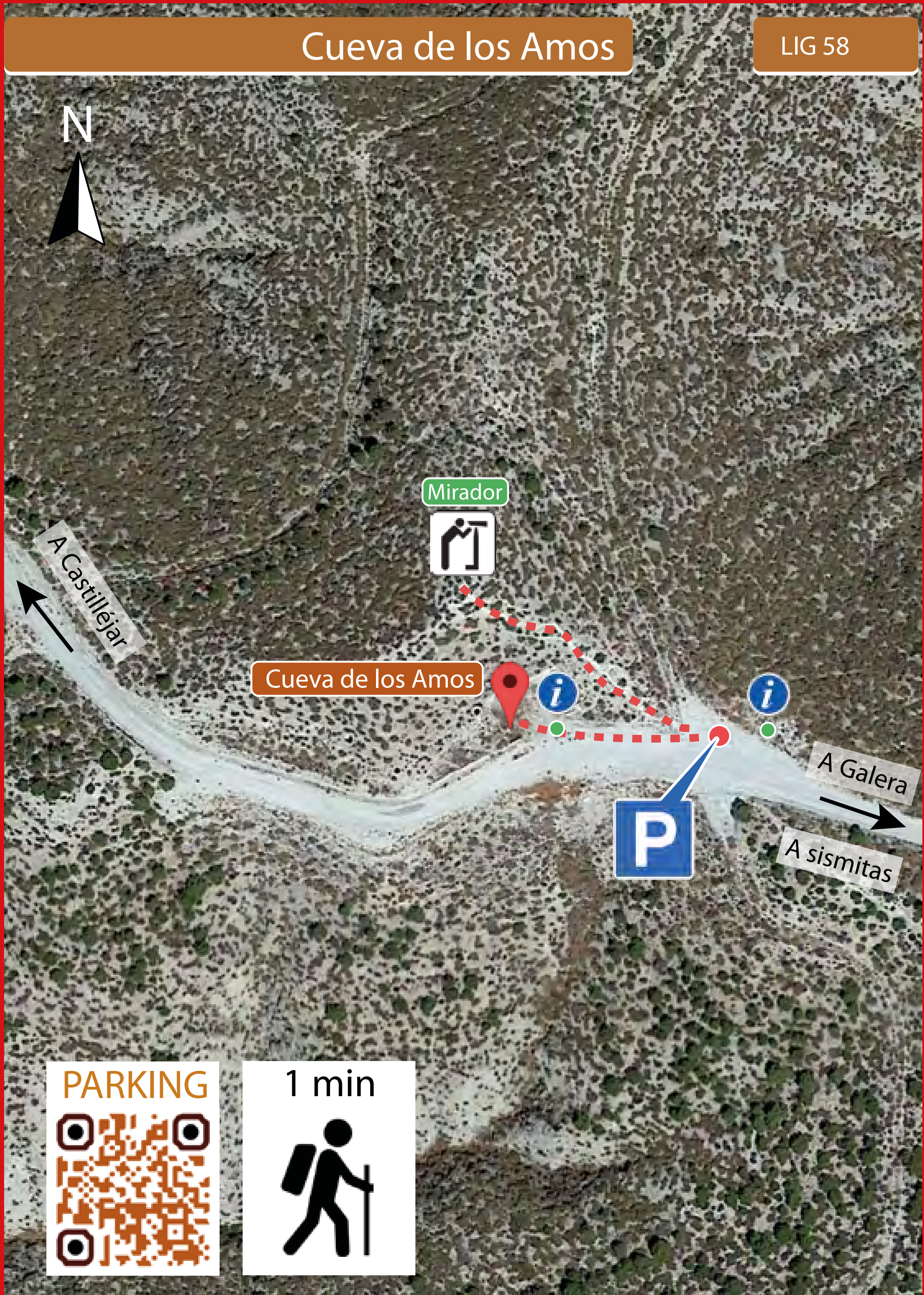
Figure 9. In the Cueva de los Amos we can understand the sedimentary process that gave rise to the gypsum deposits in the eastern sector of the Geopark.
Above: Process of gypsum formation by evaporation in the Baza palaeolake.
Below: Traditional method of obtaining gypsum from *espejuelo* crystals.

Figure 10. Interior of the Cueva de los Amos.
The gypsum layers can be seen alternating with lutites and marls.

Veins of gypsum: the Rambla de los Pilares

As mentioned above, one of the ways in which gypsum appears in the eastern part of the territory is by filling fractures, the scientific term for which is veins. These veins can be seen in many places in the Geopark, but those of the Rambla de los Pilares (Fig. 11) are outstandingly spectacular and beautiful (see Chapter 5).

Figure 11. Detail of veins filled with fibrous gypsum.


Cueva de los Amos
LIG 58
N
Mirador
A Castilléjar
Cueva de los Amos
A Galera
A sismitas
P
PARKING
1 min


La Rambla de los Pilares
LIG 68
N
Venas de yeso
Falla de Galera
Rambla de los Pilares
Sismitas
AVISO IMPORTANTE
Para acceder al punto de parking hay que circular por un camino de tierra y vadear un pequeño río. Aunque es fácilmente accesible con cualquier tipo de vehículo, es recomendable no acceder durante o tras días lluviosos.
PARKING
45 min
A Castilléjar


Ruta Castilléjar - Galera
Galera
N
INICIO
4. Castellón Alto
3. Mirador del valle del río Galera
PARADA 1
PARADA 3
2. Sismitas
PARADA 4
PARADA 2
Castilléjar
1. Mirador Cueva de los Amos

5

RECENT TECTONICS IN THE GRANADA GEOPARK

INFLUENCE ON THE CURRENT RELIEF

Panoramic view of the Baza Fault, the natural boundary between the western and eastern sectors of the Granada Geopark.

The most characteristic feature of the relief of the Granada Geopark is its mean altitude of around 1,000 m above sea level, which, among other factors, determines its climate and landscape. Within the Geopark, we can distinguish higher areas, such as the great plain known geologically as the glacis, with mean altitudes close to 1,000 m, and lower areas, where the badlands landscape has developed. Both areas together are called the Guadix and Baza Depressions. The Geopark is surrounded by mountains over 2,000 m high, outstanding among which are the Sierra Nevada (3,478 m), Sierra de los Filabres (2,168 m), Sierra de Baza (2,260 m), Sierra de María (2,045 m), Sierra de La Sagra (2,381 m), Sierra Seca (2,136 m), Sierra de Castril (2,106 m), Sierra del Pozo (2,026 m), Sierra Mágina (2,187 m) and Sierra Arana (2,027 m). Indeed, from a geological point of view the Granada Geopark is located in the Guadix-Baza sedimentary basin, which is the largest intramontane basin (meaning “among mountains”) in the Betic Cordillera, and in one of the sectors of highest mean altitude in the entire Iberian Peninsula (Fig. 1).

The origin of the particularities of the Geopark’s relief lies in the interaction of two great tectonic plates, the Nubian (African) plate and the Eurasian plate, with the notable participation of another smaller one, the Alboran plate, situated between the two.

Just over 20 million years ago, in the Early Miocene, the Alboran plate began to collide with Iberia, located at the southern end of the Eurasian plate (Fig. 2). At that time there was an extensive marine shelf of Mesozoic and Cenozoic sedimentary rocks in southern Iberia. From then on and until the Late Miocene (up to approximately 10 million years ago), the collision between the Alboran plate and Iberia intensely deformed these marine rocks, forming folds and faults (mainly thrust faults). As a result of this, the bottom of that sea located southeast of Iberia gradually began to rise, and therefore some reliefs

emerged and slowly grew to form the María, Cazorla and Arana mountain ranges, among others. From a geological point of view, these rocks, originally located on the marine shelves of southeastern Iberia, constitute the External Zone domain of the Betic Cordillera. Evidence of these folds and thrust faults can be found in the Peña de Castril and the Gorafe unconformity, described in detail in Chapter 2, and in the La Sagra overthrust fault, described in this chapter.

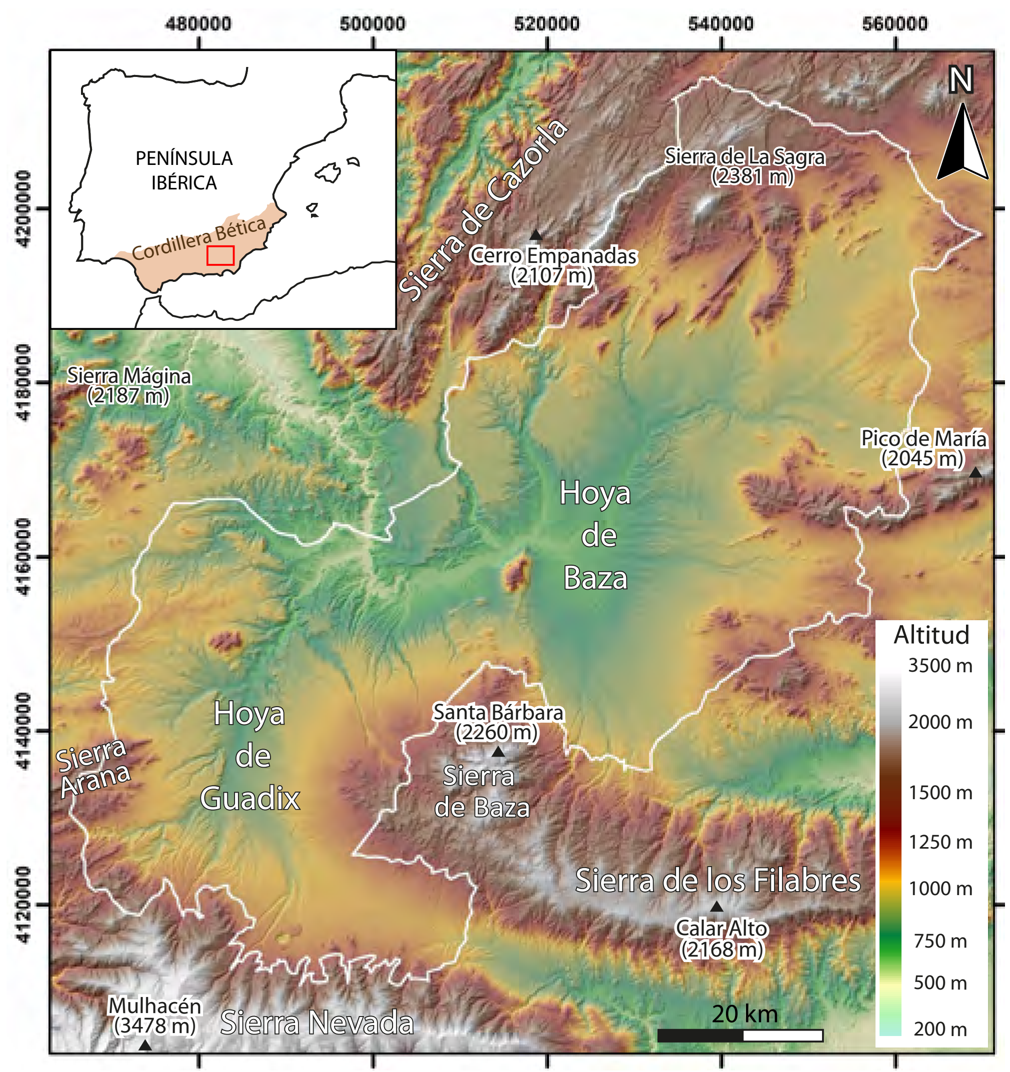


Figure 1. Main features of the relief of the Granada Geopark, with the location of the Baza and Guadix depressions and the main mountain ranges that surround them.

The collision between plates also caused the deformation of the rocks of the Alboran plate. In this case, larger folds were generated, and their uplift formed reliefs such as the Sierra Nevada, the Sierra de los Filabres and the Sierra de Baza. These rocks, originally belonging to the Alboran plate, constitute the Internal Zone of the Betic Cordillera (Fig. 3).

However, the geological events that have most influenced the current configuration of the Geopark are those that occurred after the collision between Iberia and Alboran, that is, over the course of the last 10 million years.

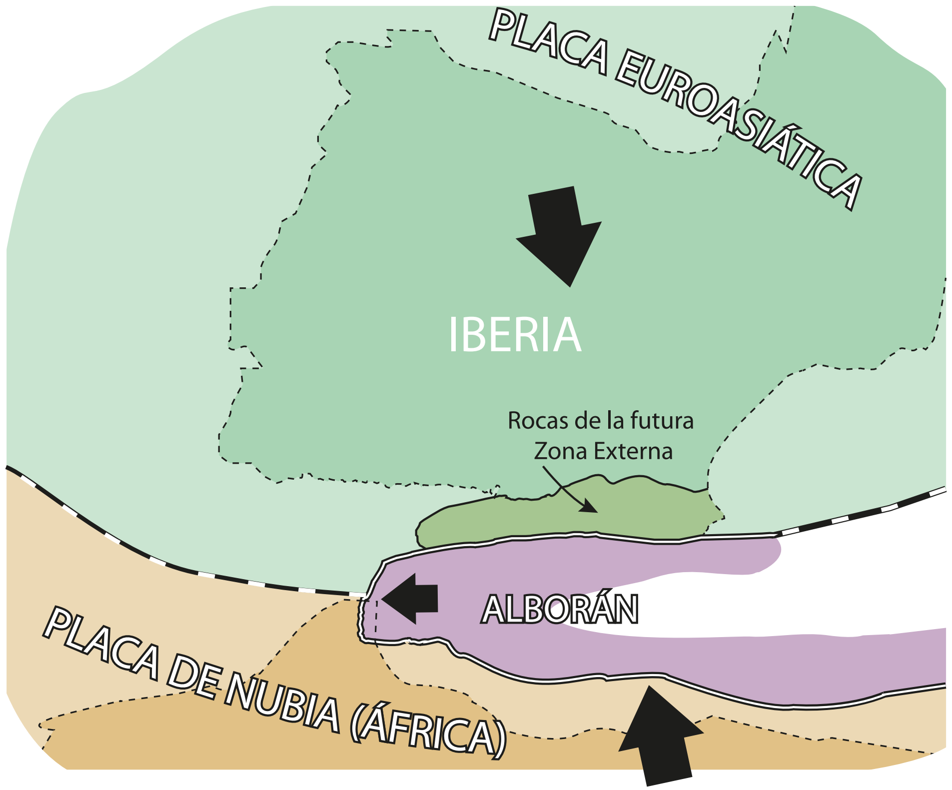


Figure 2. Map with the three plates responsible for the formation of the Betic Cordillera and the relief of the Geopark: the Eurasian plate to the north, the Nubian (African) plate to the south and the small Alboran plate between the two.

During this latest stage, the relief of the central sector of the Betic Cordillera, where the Geopark is located, has been shaped by two tectonic processes which have deformed the Earth's crust. These processes, which have been acting simultaneously during the last million years and are still doing so today, are:

- **Shortening** produced by the convergence of the Nubian (African) and Eurasian plates, giving rise to regional uplift of the relief.
- **Extension** of the crust, which has influenced the formation of the Guadix-Baza Basin.

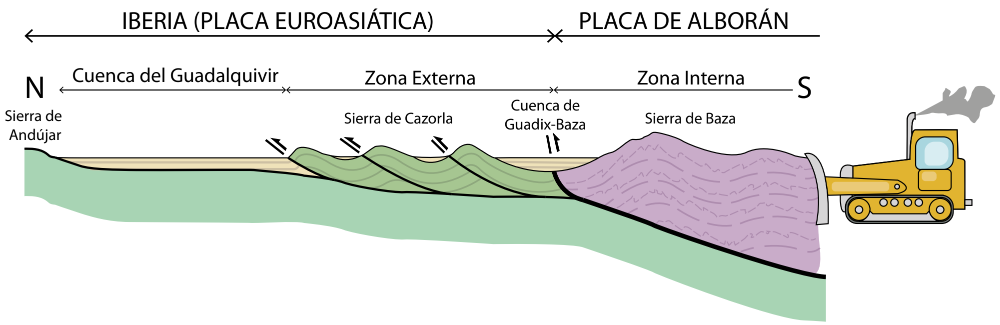


Figure 3. Schematic geological section showing the deformation (shortening) of the rocks of the External and Internal Zones and the formation of the Betic Cordillera. The Guadix-Baza Basin (Granada Geopark) is located on the old plate boundary between Eurasia and Alboran.

DID YOU KNOW...?

Under the more recent sediments that fill the basin there is a PLATE BOUNDARY which was active until a few million years ago. This old plate boundary separates two very different basements or substrates. To the north the sedimentary rocks of the External Zone predominate, and to the south the mainly metamorphic rocks of the Internal Zone. This former tectonic activity has notably enriched the geodiversity of the Geopark.

Shortening due to the convergence of Nubia (Africa) and Eurasia: regional uplift

About 10 million years ago, the territory of the Geopark was occupied by the sea. At that time, in what are now the territories of Andalusia, Murcia and Alicante, there were small islands with narrow marine passages or corridors between them. The Guadix-Baza Basin was located in one of the main corridors connecting the Atlantic Ocean to the Mediterranean Sea (Fig. 4).

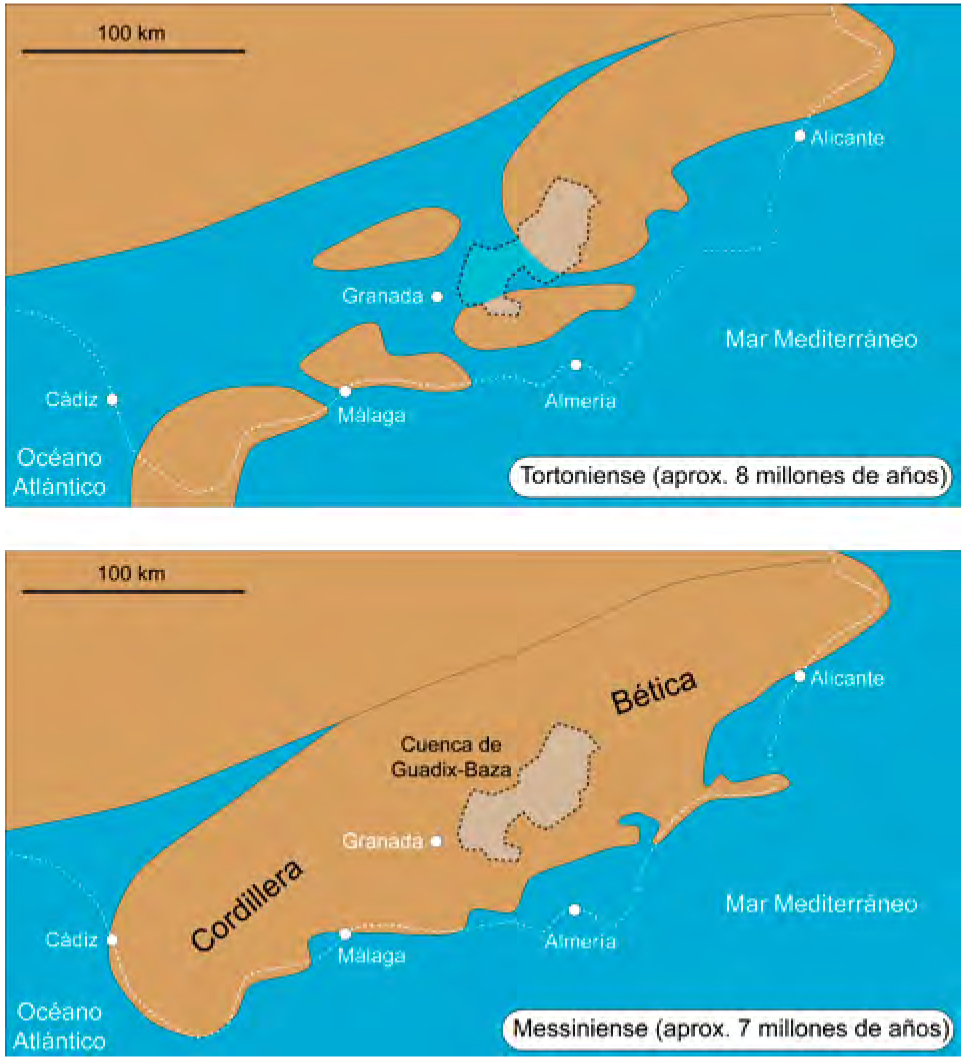


Figure 4. Evolution of the emerged and submerged relief in the Betic Cordillera during the last few million years. Modified from García-Veigas et al. (2019).

Since then, the convergence between the Nubian (African) and Eurasian plates has produced a regional shortening in the Betic Cordillera. This shortening has led to a continuous thickening of the Earth's crust, which has gradually raised the terrain. Figure 5 represents the current height of rocks that were under the sea some 10 million years ago. In other words, this image gives us an idea of how much each region has been raised above sea level in the last few million years. We can see here that the territory of the Geopark has undergone one of the greatest regional uplifts in the whole Betic Cordillera.

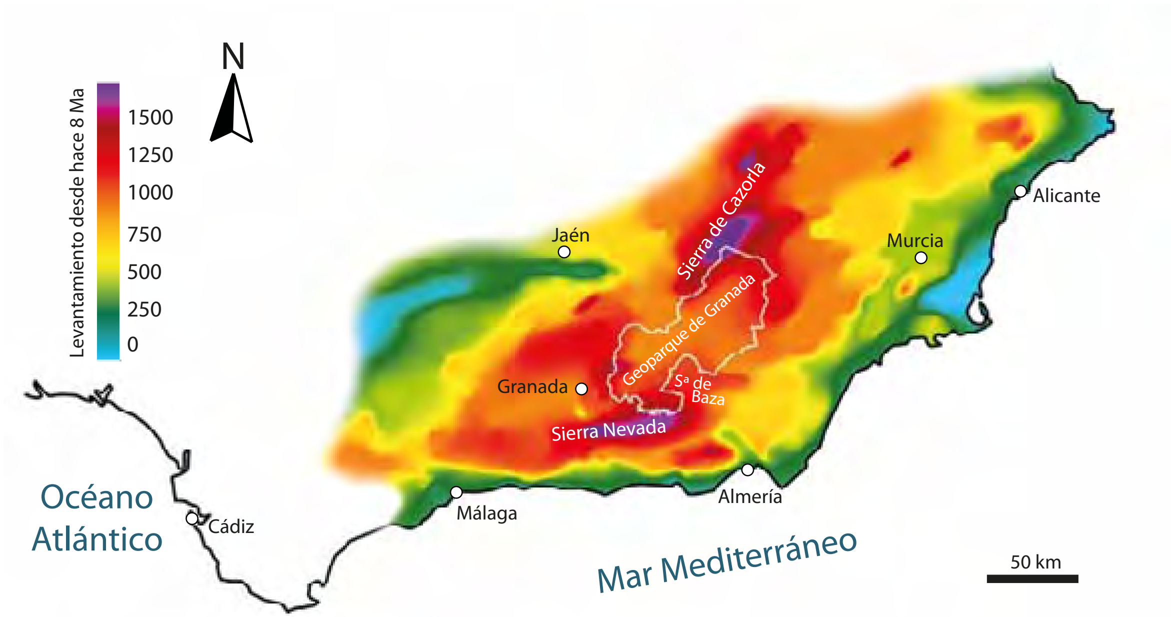


Figure 5. Uplift of the Betic Cordillera since the Late Miocene.

This process has gradually increased the mean height of the mountains and the basins, such as that of Guadix-Baza, promoting the progressive emergence above sea level of new areas.

The maps in Figures 4 and 5 show that the emerged areas have gradually increased in extent from about 10 million years ago to the present. This uplift is still taking place today, so in the near future new sectors will continue emerging to the south and southeast of the Betic Cordillera.

If we focus on the territory of the Geopark, in the Guadix-Baza sedimentary basin the continuous uplift of the terrain since about 10 million years ago has had two major consequences. The first was disconnection from the sea approximately 7 million years ago, when the altitude of the basin rose above sea level. At that moment the basin became emerged and surrounded by mountains, turning into an isolated, closed basin (endorheic basin).

The second consequence is that this continuous and still active uplifting of the relief accelerated the process of headward erosion (in an upstream direction) of a tributary of the River Guadalquivir which later became the River Guadiana Menor. This intense erosion reached the Guadix-Baza Basin just over half a million years ago. At that moment, the river captured the drainage network of the basin, diverting its waters towards the Guadalquivir valley, and therefore towards the Atlantic Ocean. From then on, the basin ceased to be isolated (marking the start of the exorheic basin stage), and the erosion caused by the rivers of the Geopark's territory began. The downcutting of the rivers formed, as a result, the spectacular erosional landscape of the badlands (Chapter 7).

In short, the fact that the basin has such a high mean altitude, and that the great plain was formed first and the badlands landscape developed later, is determined by the convergence of the Nubian (African) and Eurasian plates.

DID YOU KNOW...?

In the territory of the Geopark there is evidence of the shortening caused by the convergence of these two great plates. This shortening has left its mark on the sedimentary rocks of Late Miocene, Pliocene and Quaternary age (the last 10 million years), in the form of folds and faults. The best examples of recent folds are in the Galera sector (Fig. 6) and in the area between the Negratín Reservoir and the town of Hinojares on the southern slopes of the Sierra del Pozo. Moreover, in the latter sector, the shortening has caused the extrusion of Triassic materials (mainly clays and gypsum), which rose through fractures until they reached the surface (diapiric structures such as those described in Chapter 2), creating a landscape dominated by reddish tones (Fig. 3 in Chapter 2).

Figure 6. Active folds in Galera affecting Pleistocene sediments. Embankment on the A-330 road, km 21.

Extension in the central sector of the Betic Cordillera: influence on fluvial and lacustrine sedimentation

Simultaneously with the shortening caused by the convergence between Nubia (Africa) and Eurasia, a stretching (extension) of the crust in a perpendicular direction has also been taking place in the last few million years (Fig. 7).

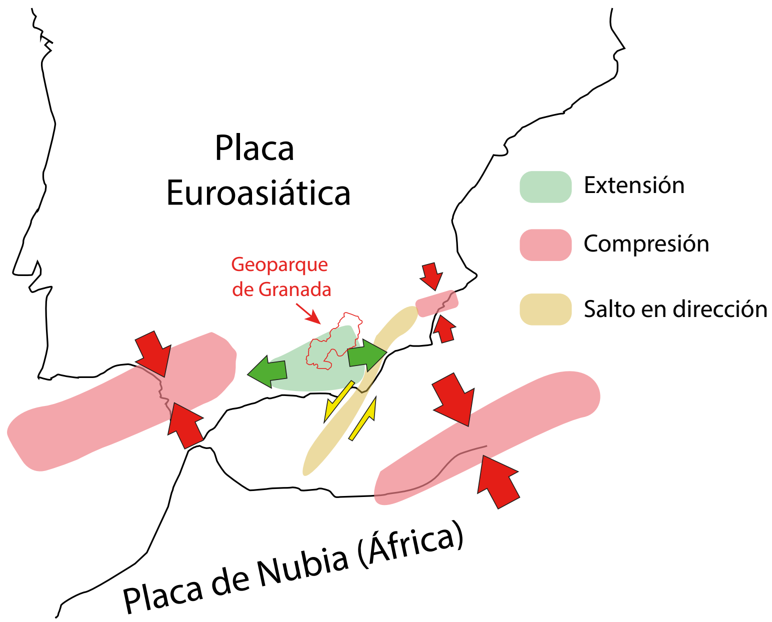


Figure 7. Currently, the Geopark is close to a plate boundary where Eurasia and Nubia (Africa) are converging at a rate of about 5 millimetres per year, but the dominant tectonic activity within the Geopark is the extension generated by the Baza fault and other smaller faults located in the vicinity of Guadix.

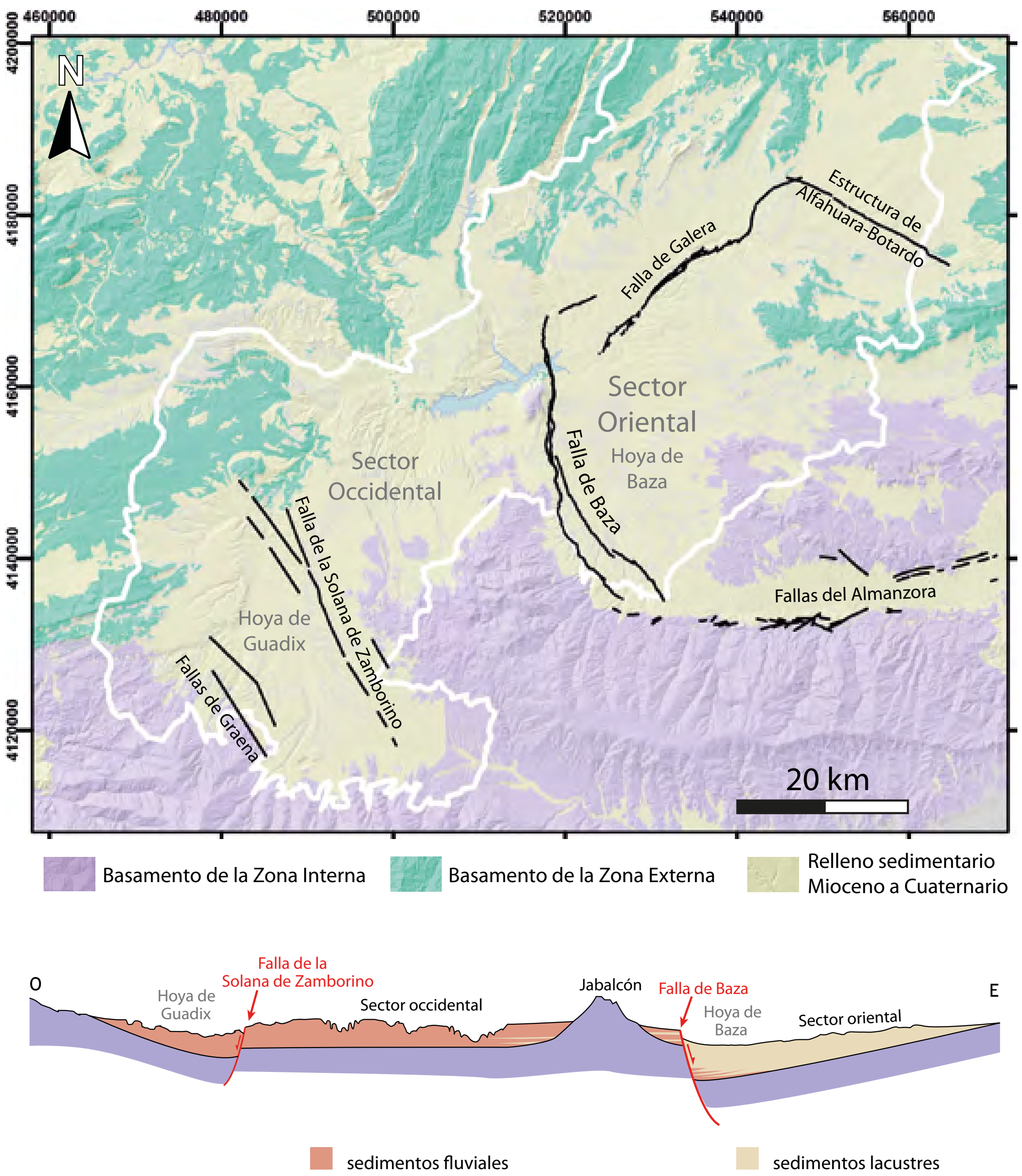


Figure 8. Geological map of the Geopark showing the main active faults.

The lower part shows a geological section across the Geopark from southwest to northeast.

In the territory of the Granada Geopark, crustal extension has resulted in the formation of several normal faults, such as those of Graena and Zamborino, and most especially the Baza fault (described in detail in this chapter). All these great fractures raise and sink large blocks of land, producing stepped reliefs which, among other features, are responsible for the differences of altitude of the glacis in different areas of the Geopark, and for large differences in the thickness of sediments (Fig. 8).

Particularly noteworthy among these faults is the Baza fault (Fig. 9), whose activity during the Pliocene and Pleistocene (the endorheic stage of the basin) produced the natural boundary between the two major sectors of the Geopark. Thus, in the western or Guadix sector (the upthrown block of the fault) landscapes dominated by rivers developed, whereas the eastern sector (the downthrown block of the fault) was dominated by the Baza palaeolake.

Figure 9. Panoramic view of the Baza fault, in the Cañada de Gallego. In this sector a geotourism trail has been set up, with this fracture as the main feature.

Associated with the activity of the Baza fault, the Galera fault has also developed. In this case, the fault produces a main horizontal displacement of the blocks north and south of it (Figs. 10 and 11). As well as its horizontal movement, the Galera fault has a small vertical displacement, which raises the block located to the south of the fault and is responsible for the spectacular badlands landscape between Castilléjar and Galera (Chapter 7).

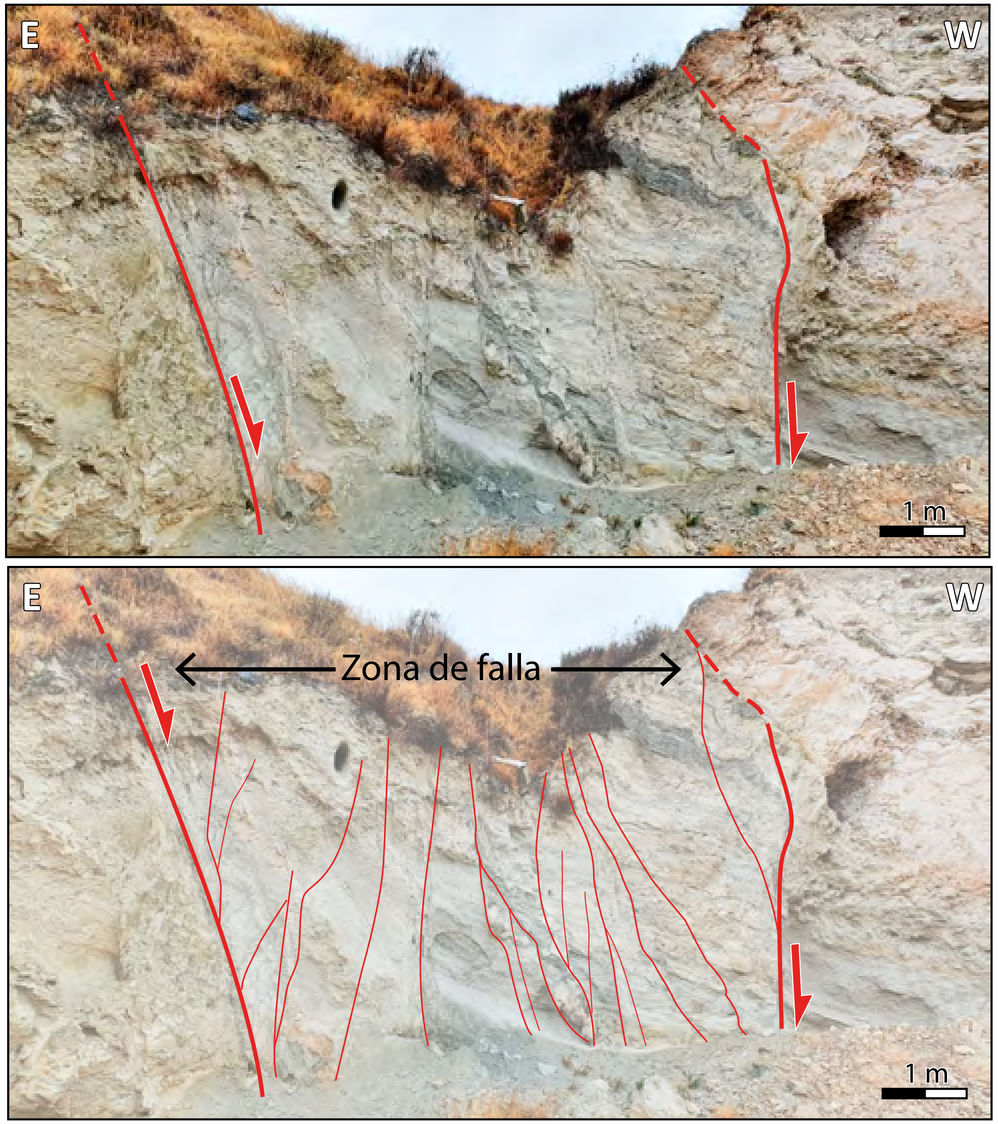


Figure 10. Photograph of the Galera fault in an outcrop in the vicinity of the town.

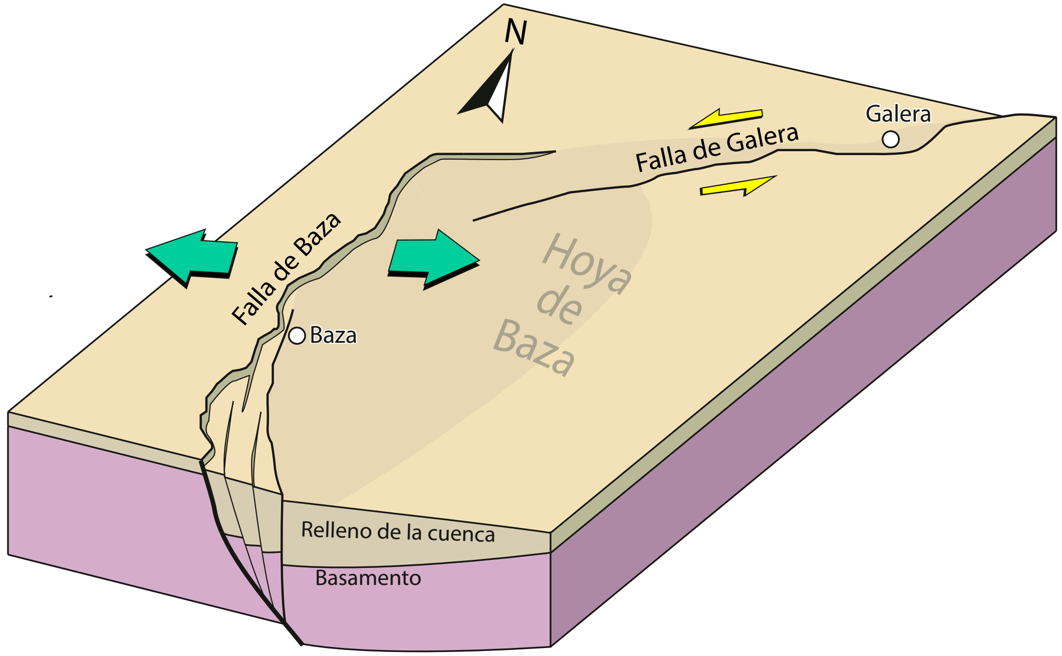


Figure 11. Diagram showing the Baza and Galera faults.

DID YOU KNOW...?

The relief of the Geopark's BASEMENT is very irregular. In some parts, the sedimentary infill of the last 8 million years is over two thousand metres thick, while in others it is much less. In certain places the basement even outcrops on the surface, forming isolated hills of ancient rocks (inselbergs) surrounded by more recent sediments, as is the case with Mencal and Jabalcón. All these differences are controlled by active tectonics (Fig. 8).

In the eastern sector, in the downthrown block of the Baza fault (Baza Depression), there is evidence that more than two thousand metres of sediment thickness accumulated from the Late Miocene to the Middle Pleistocene.

DID YOU KNOW...?

When you cross the Geopark on the A92N motorway you can make out the steps in the landscape produced by active normal faults. The most marked is in Baza (when you climb the hill between the Benamaurel and Zújar exits, you are passing from the downthrown block to the uplifted block of the Baza fault). Other steps can be found before reaching Guadix, when the motorway crosses the sector between Hernán Valle and the junction between the A92N and A92 sections.

In the following pages, several of the Geopark's **sites of geological interest** have been chosen to show that the great driving force that has created this remarkable terrain is the convergence of the tectonic plates of Nubia (Africa) and Eurasia during the past 20 million years:

- The tectonic pushing force of Africa and the **La Sagra overthrust fault**.
- The **Baza fault** provides evidence of the crustal extension that is currently occurring in the central sector of the Betic Cordillera.
- The **Galera and Cúllar seismites** are an internationally exceptional example of the recent activity of these faults. They are one more sign of a geologically living territory.
- Finally, in the **Rambla de los Pilares** we can visit the area of the Galera fault, which is responsible, among other factors, for the badlands landscape within which the *rambla* (dry ravine) lies. The gypsum-filled fractures are particularly remarkable.

THE LA SAGRA OVERTHRUST FAULT

SGI 34

The **Sierra de La Sagra** contains the highest mountain in the Granada Geopark (2,381 m) (Fig. 1) and together with Mencal and Jabalcón it constitutes one of the Geopark's visual reference points. La Sagra is a highly spectacular massif in scenic terms, which is of geological interest in various respects. The origin of this mountain's spectacular topography lies in the type of rock of which it is composed (mainly very resistant carbonate rocks) and in tectonics, that is, in the process of deformation that gave rise to this mountain. Other aspects of interest are its geomorphology and its stratigraphy.

Figure 1. Aerial view of La Sagra looking south.

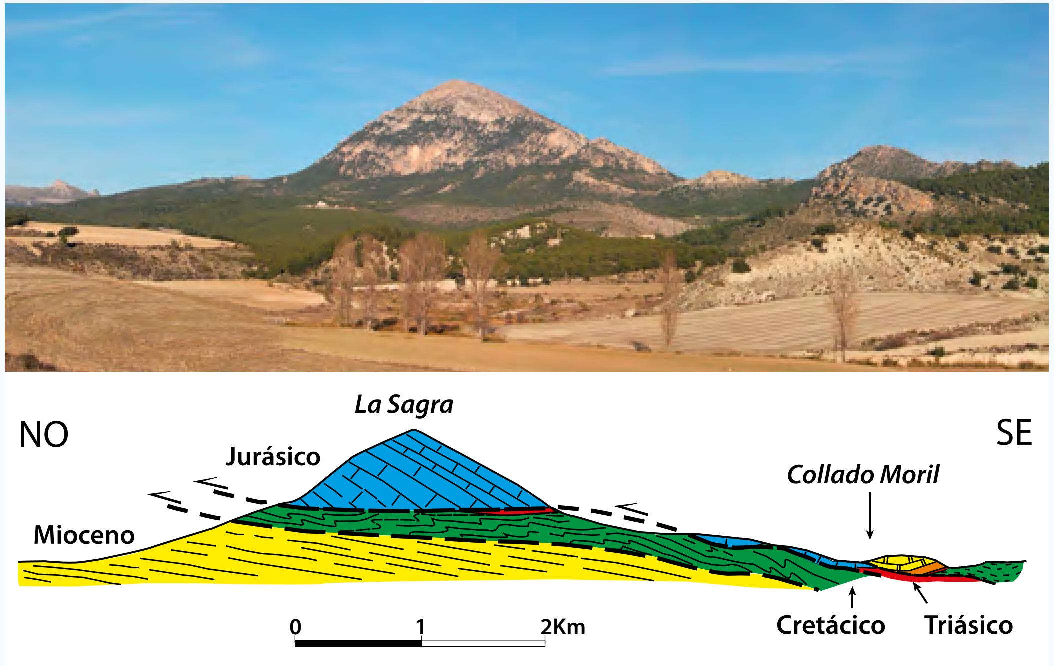


Figure 2. **A**: Panoramic view of the Sierra de La Sagra looking east.
B: Schematic geological section of the overthrust fault described in the text.
Modified from Foucault, A. (1971).

The La Sagra overthrust fault

From a tectonic point of view, the Sierra de La Sagra was formed by the superposition of Sub-betic rocks on Pre-betic rocks by means of an overthrust, that is, an inverse fault with very substantial displacement (hundreds of metres or even kilometres) (Fig. 2). The thrust plane causes the Sub-betic rocks, which are older (Lower Jurassic), to overlie much younger rocks (Miocene), belonging to the Pre-betic domain. The overthrust is clearly visible due to the fact that the materials of the lower half of the mountain, the younger ones, are soft, light-coloured rocks, while those of the upper half, the older ones, are much more resistant, dark-coloured limestones and dolostones. Under the Jurassic carbonate rocks, Triassic clays and gypsum can be seen. These materials facilitated the “detachment” of the carbonate mass and its progression over the younger materials that were left beneath it. The age of the overthrust could be Early Tortonian, since Serravallian white marls and limestones are involved.

This overthrust is the result of the convergence between the Alboran plate and Iberia and thus the formation of the Internal and External Zones of the cordillera. The push of the Alboran plate caused the Sub-betic rocks to “detach” from their original position and forced them to lie on top of the former Pre-betic shallow marine shelf.

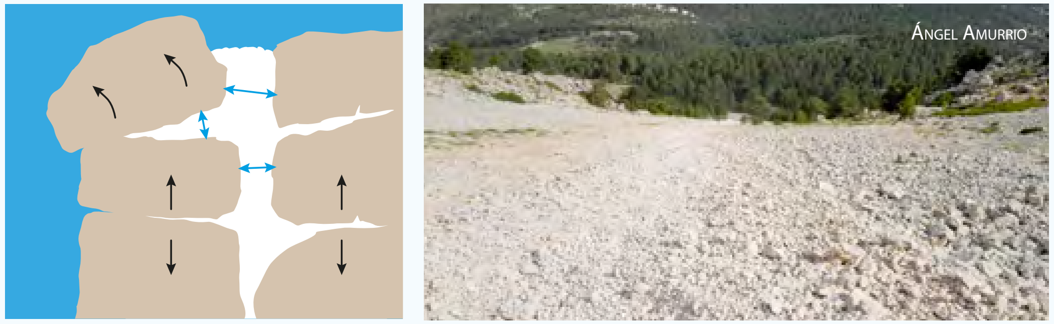


Figure 3. As water freezes between the cracks and fractures in the rock, it increases in volume, breaking up the rock and producing *pedreras* or *canchales* (scree).

Geomorphological aspects

The massif of La Sagra, with its characteristic “inverted boat” shape, rises more than a thousand metres above the surrounding valleys, which in turn are the origin of some of the most important rivers in the Geopark, which end up, downstream, becoming the Guadiana Menor.

The high altitude of La Sagra enables a characteristic high mountain landform, known as a periglacial landform, to develop on its slopes, generating accumulations of rock fragments on its steep sides, known as canchales (scree) (Fig. 3). These rock fragments are produced by the water that enters the fractures and cracks in limestone rock, which eventually freezes, breaking up the rock. Rock fragments accumulate on the slopes, especially on its north face, located in permanent shade, where low temperatures are maintained for a long time over the course of the whole year.

On the north face there is an area known, because of its morphology, as the “funnel” of La Sagra. Some researchers have suggested that its formation was due to accumulation of snow in colder and wetter periods in the past, conditions that allowed the formation of a large snowfield which shaped this part of the mountain.

For observation of La Sagra there are many places that offer us spectacular views of the mountain and its various geological aspects. Some of them are along the road between Huéscar and Santiago de la Espada (A-4301). One of the best places is La Losa Pass (see next page).

THE BAZA FAULT

SGI 70

The **Baza fault** is a large fracture 40 km long and 15 km deep which crosses the territory of the Granada Geopark from south to north. This fracture, which runs through the municipalities of Caniles, Baza, Benamaurel and Cortes de Baza (Fig. 1), is the natural boundary between the western and eastern sectors of the Geopark.

WHAT IS THE BAZA FAULT LIKE?

There are various types of faults (see Fig. 2).

Faults break and displace the Earth's crust on either side of the fracture. The Baza fault is a normal fault which raises the western sector and sinks the eastern sector of the Geopark. The schematic illustration of its development below (Fig. 3) shows how the displacement caused by the Baza fault has led to older rocks (from 4 million years ago [Ma]) being in contact with more recent ones (1 Ma).

Since approximately 8 Ma, the fault has produced a vertical displacement of more than 2,000 metres. This means that rocks equivalent to those that form Jabalcón (located in the western block of the fault) are buried at a depth of 2,400 metres in the eastern sector, under the Baza Depression (Fig. 4). The displacement caused by the fault is very slow. To calculate the velocity (slip-rate) at which faults move, high precision GPS devices are used.

These are similar to the ones we have in our mobile phones, but they make it possible to calculate the position of a point with an error of less than a millimetre. Scientists have estimated that the fault is moving at a speed of approximately half a millimetre per year.

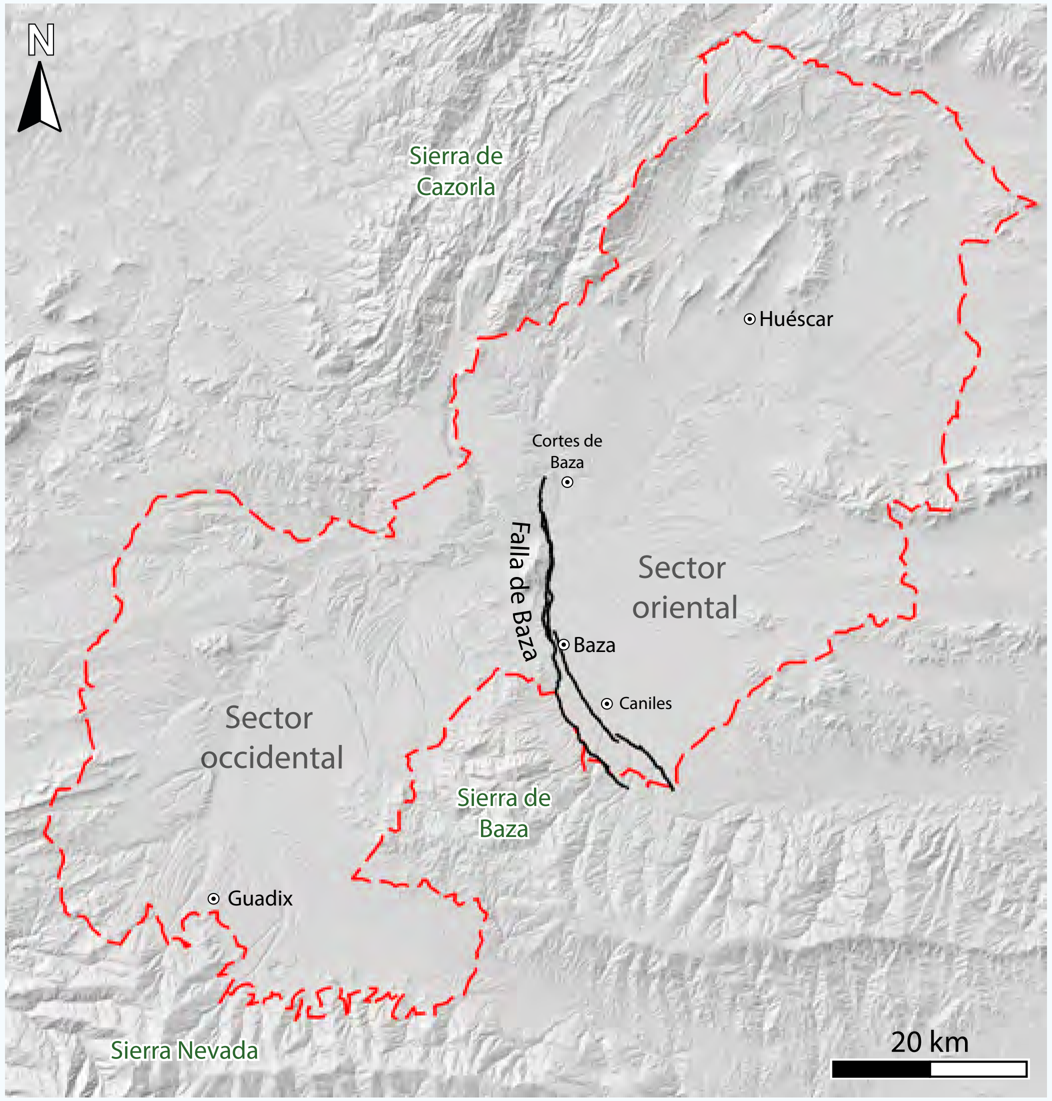


Figure 1. The Baza fault (black line) in the Granada Geopark (red line).

The fault extends from south of Caniles to Cortes de Baza, passing through the town of Baza.

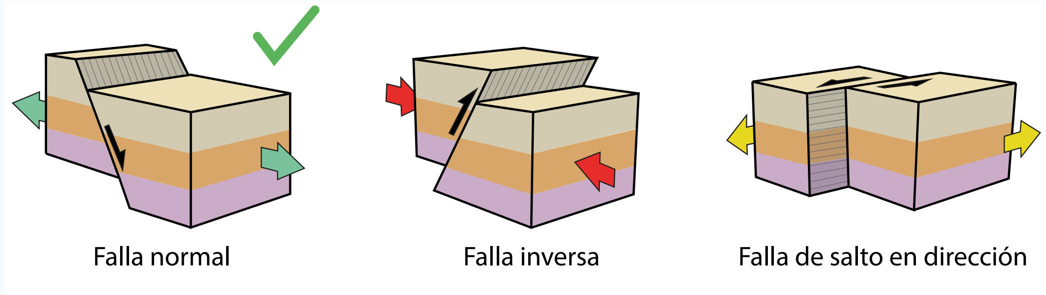


Figure 2. Existing types of faults according to the type of displacement between the blocks. The Baza fault is a normal fault (left block).

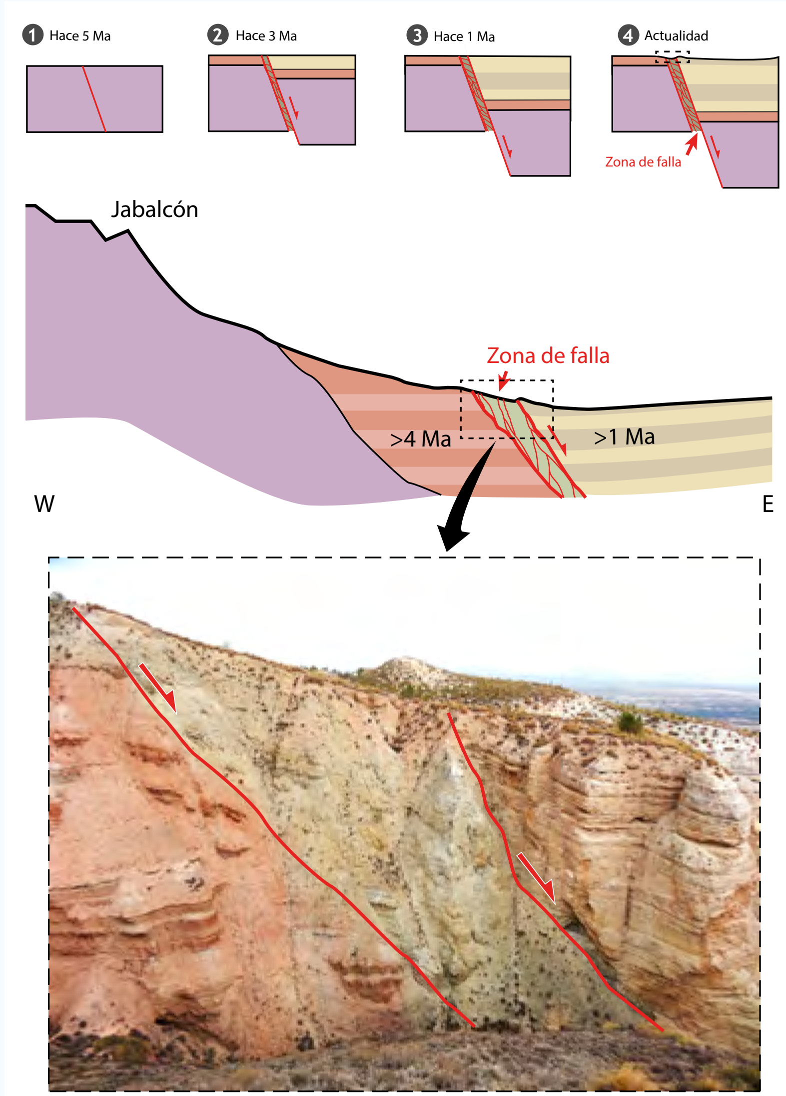


Figure 3. The displacement of the fault over time has brought rocks of different ages into contact.

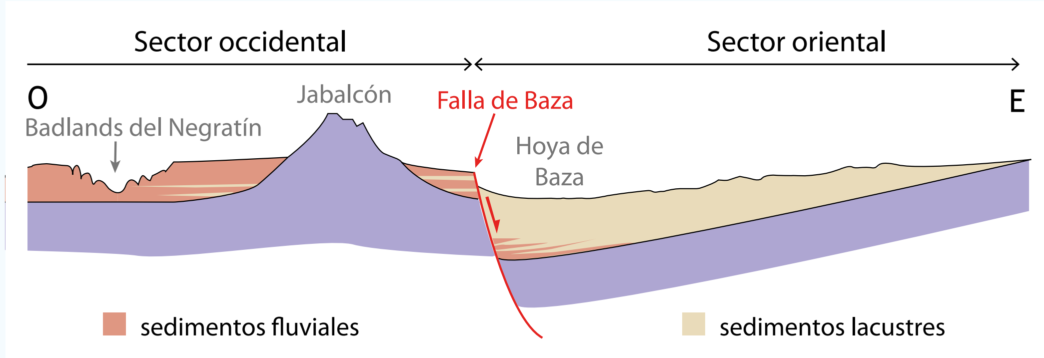


Figure 4. The Baza fault is the natural boundary between the western and eastern sectors of the Granada Geopark.

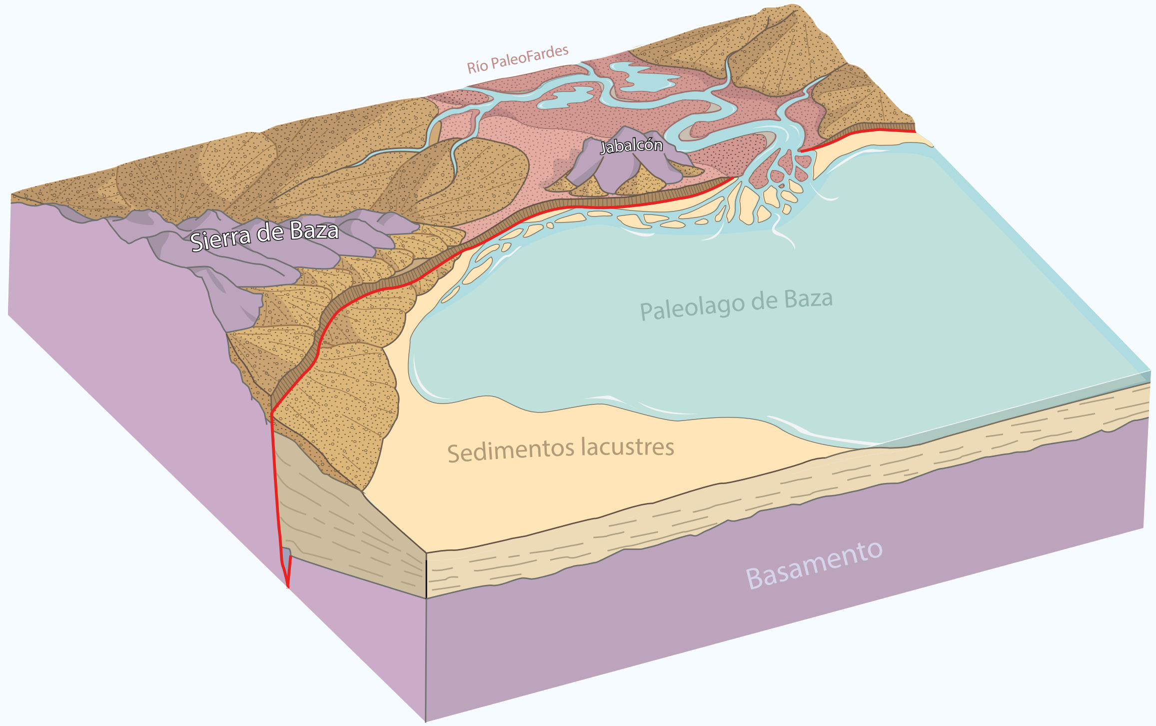


Figure 5. Representation of the Baza fault during the Pliocene and Pleistocene. The displacement of the fault allowed a large lake to develop in the eastern sector of the Geopark, which sank relative to the western sector.

The Baza fault has played a key role in the geological history of the Guadix-Baza Basin. During the Pliocene and the Pleistocene (between 5 and 0.5 million years ago), the area located to the west of the fault gradually rose. Therefore, the runoff water flowed through a river system towards the east (the sector sunk by the fault), where it accumulated, forming a large lake: the Baza palaeolake (Fig. 5). The fluvial sediments generally have reddish tones, while the lacustrine sediments show whitish colours. This explains the contrast observed in the Geopark's landscape between the western Guadix sector (reddish fluvial sediments) and the eastern Baza sector (white lacustrine sediments) (Fig. 3).

Normal faults like the Baza fault tend to have a strong landscape expression, as their displacement gives rise to large topographical steps. However, the step produced by the Baza fault seems, at first sight, to be smaller than one would expect. This is due to the fact that during the endorheic stage of the Guadix-Baza Basin (Chapter 4), sediments were being deposited on the fault as it moved. The rate at which they were deposited was as fast as or faster than the movement of the fault, and therefore the step that was created was immediately covered (Fig. 6, steps 1 and 2). However, during the exorheic stage, the sedimentation stopped, so from then on the step we can now see, with a height of about 100 metres, began to grow (Fig. 6, steps 3 and 4).

Faults are the result of deformation of the Earth's crust. In the central sector of the Betic Cordillera an east-

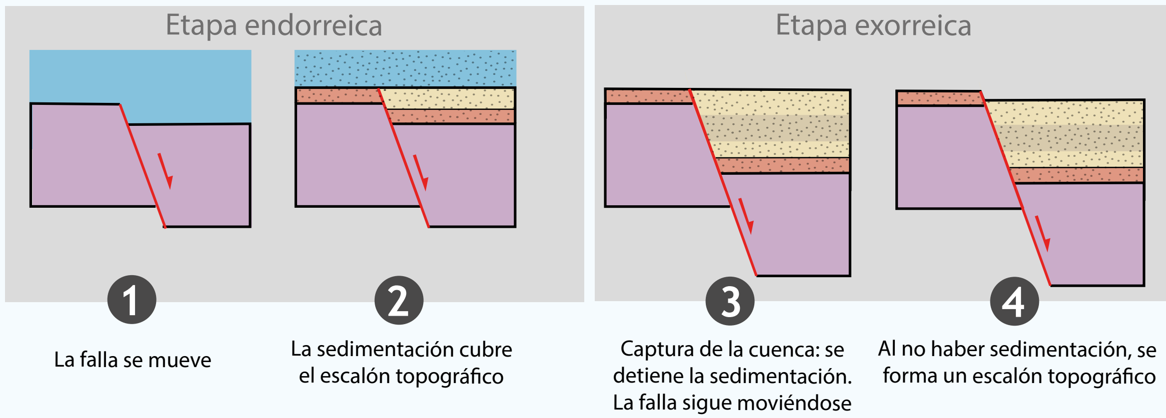


Figure 6. The Baza fault scarp did not begin to form until the exorheic stage began (Chapter 7), since during the endorheic stage it was covered by sediments.

west crustal stretching has been taking place for about 8 million years (Fig. 7) and has given rise to the formation of numerous normal faults. The Baza fault is the most important of these structures, as it is the one that accumulates most of this stretching.

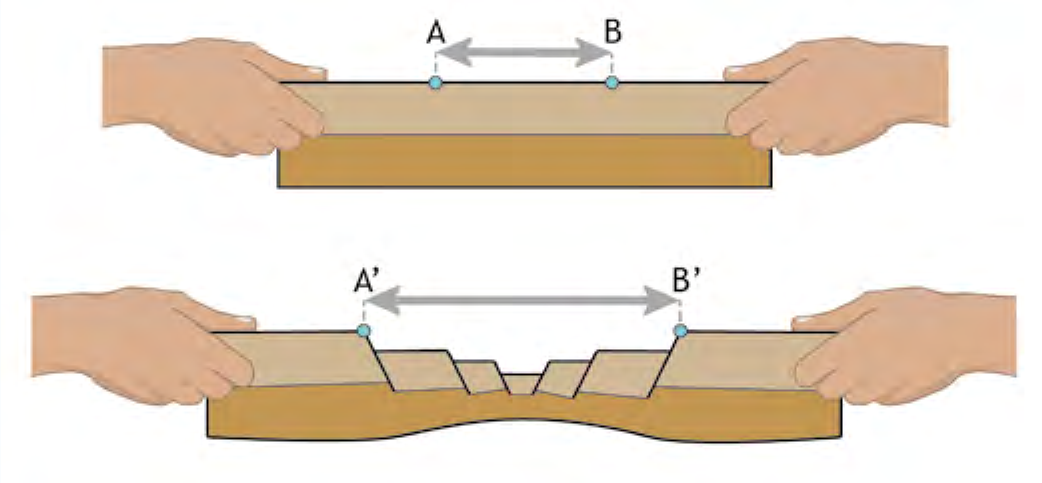


Figure 7. Simplified schematic illustration of the stretching of the Earth's crust and the formation of normal faults. The extension that the central sector of the Betic Cordillera is currently undergoing is being accommodated mainly by the Baza fault and the Granada fault system.

DID YOU KNOW...?

The Baza fault has several peculiarities that make it unique. Most of the world's normal faults separate resistant rocks on one side from softer rocks on the other. In the case of the Baza fault, it separates soft materials on both sides, giving rise to a band of deformed rock (Figure 8) with some distinctive features that have aroused the interest of the international scientific community.

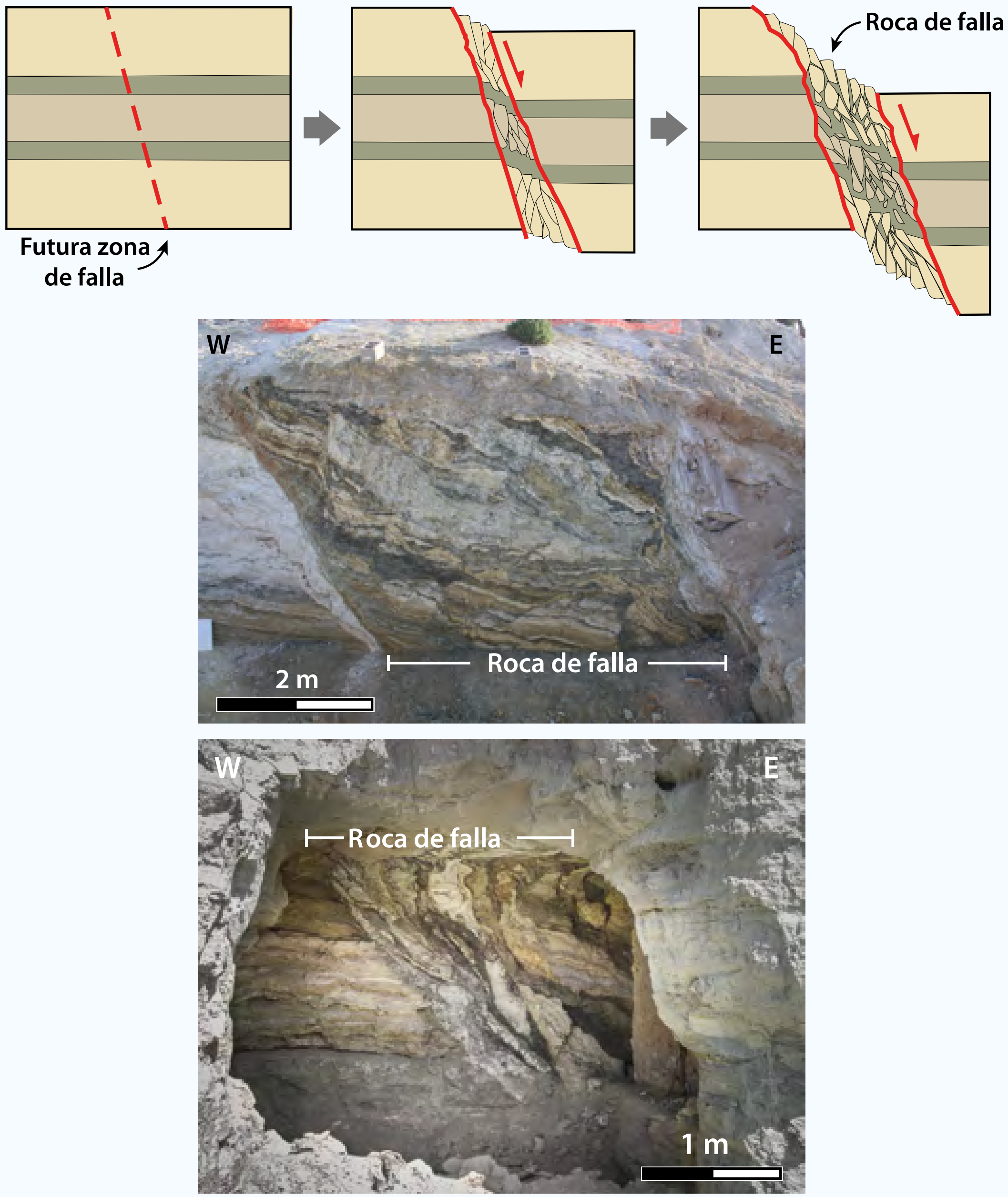


Figure 8. Simplified schematic illustration showing the formation of a fault rock.

Upper photo: North of Baza (Arroyo del Carrizal) excavations have been carried out where bands of fault rock of great scientific interest can be seen.

Lower photo: Southwest of Cortes de Baza (near the Cortijo de la Cuesta) the fault rock can be observed inside some former cave houses.

GEOPARQUE GRANADA

FOSSILIZED EARTHQUAKES

THE GALERA AND CÚLLAR SEISMITES

SGI 29, 68, 69

Earthquakes, from a certain magnitude threshold, can leave a trace in sediments. If the necessary conditions exist, the vibrations produced by seismic waves turn the sediment into a kind of "quicksand" for a few moments. The water present in the pores of the sediment is expelled, separating the grains and converting the material into a viscous fluid. This process is known as **liquefaction** (Fig. 1).

When this occurs, the sediment is deformed very rapidly. The term **seismite** has become widely used in the scientific literature to denote the sedimentary deformation structures produced by earthquakes (Figs 2 to 6).

In order for seismites to form, the following conditions are necessary in the sediment:

- It must not have started to turn into a rock. It has to be a totally or largely uncompacted sediment with no cementation.
- It must be saturated with water (shallow water table).
- It must be capable of being deformed. Deformation is facilitated when the sediment has a denser upper layer (coarse sediment) and a less dense lower layer (finer sediment).

These requirements are met in many places on the planet, but especially in sediments deposited in lakes, such as the one that existed in the eastern part of the Geopark during the Pliocene and much of the Quaternary.

In addition, earthquakes of moderate to high magnitude must occur. Low-magnitude earthquakes (less than 4.5) do not have enough energy to deform the sediment.

Figure 1. In order for seismites to be produced, the sediment must be in an unstable condition. One such situation is when a layer of denser (thicker) sediment lies on top of a layer of less dense (finer) sediment. When liquefaction occurs, the dense sediment sinks and the less dense rises, causing folding of the sheets and the formation of seismites.

Figure 2. Level of seismites (Cúllar).
The stratification remains horizontal both above and below the deformed level, where liquefaction of the sediment occurred

Figure 3. Layer of seismites (Galera).
The Galera seismites are unique in the world for several reasons: their large size, their lateral continuity, with the liquefied level sometimes extending for hundreds of metres, and the possibility of seeing them in three dimensions.

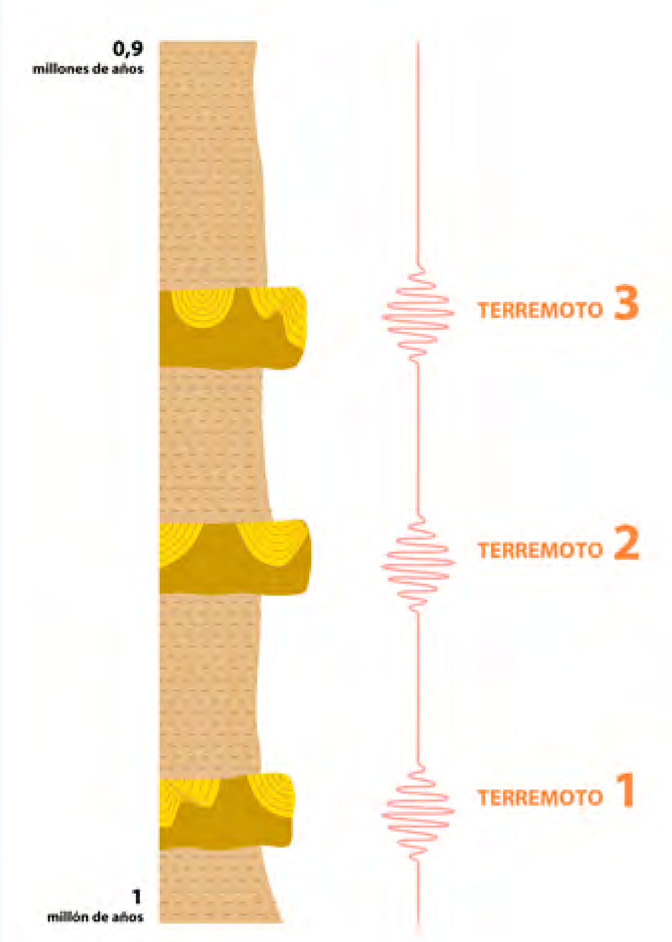


Figure 4. In the Granada Geopark, scientists have identified several superimposed layers of seismites that enable us to learn of the existence of palaeo-earthquakes in the Baza palaeolake during the Quaternary period.

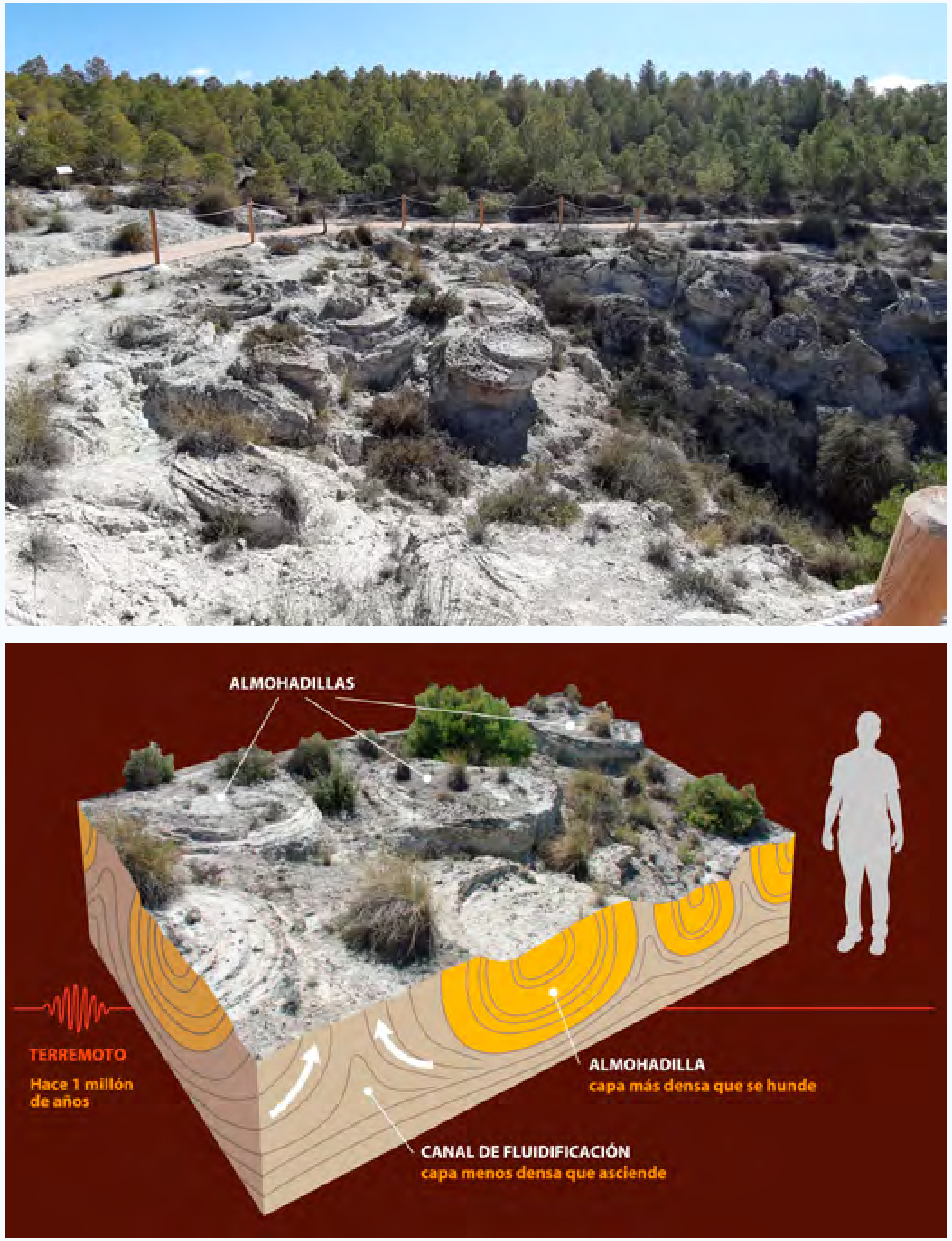


Figure 5. Panoramic view of the **Galera Seismite Trail**. Several large outcrops of seismites can be observed along the route. Between the large pillows we can see the channels through which the liquefied sediment rose.

Figure 6. The appearance of seismites depends mainly on the type of sediment. The alternation of sediments of different grain sizes and colours offers some highly spectacular outcrops of seismites in the town of Cúllar.

WE SUGGEST…

There are short videos in which it is possible to watch how an earthquake liquefies sediment and deforms it. Moreover, there are more and more recordings of the liquefaction phenomenon during recent earthquakes (and a spectacular increase can be expected in the next few years due to the abundance of mobile telephones, with millions of reporters spread all over the territory). We recommend you use platforms like YouTube with keywords such as *liquefaction* or *seismic liquefaction*; you can also add the name of the earthquake or some geographical reference (e.g., *Japan, New Zealand, Emilia Romagna, Italy*…).

THE RAMBLA DE LOS PILARES GEODIVERSITY IN THE BAZA PALAEOLAKE

SGI 68

Between the towns of Castilléjar and Galera lies the Rambla de los Pilares (Fig. 1). Along its course, concentrated in a very small area, are several of the most important sites of geological interest in the eastern sector of the Granada Geopark: the Galera fault zone, three-dimensional seismite outcrops, gypsum-filled fractures and spectacular badlands landscapes (Chapter 7).

DID YOU KNOW...?

In the Rambla de los Pilares there is an outcrop where you can see **seismites in three dimensions.** In a few square metres there are several examples on the bed of the ravine with a "plan" view from which their characteristic morphology can be identified. These bowl or pool-shaped morphologies remain filled with water for some time after rainfall events, and this has given the *rambla* its name.

Figure 1. Seismites in the Rambla de los Pilares.

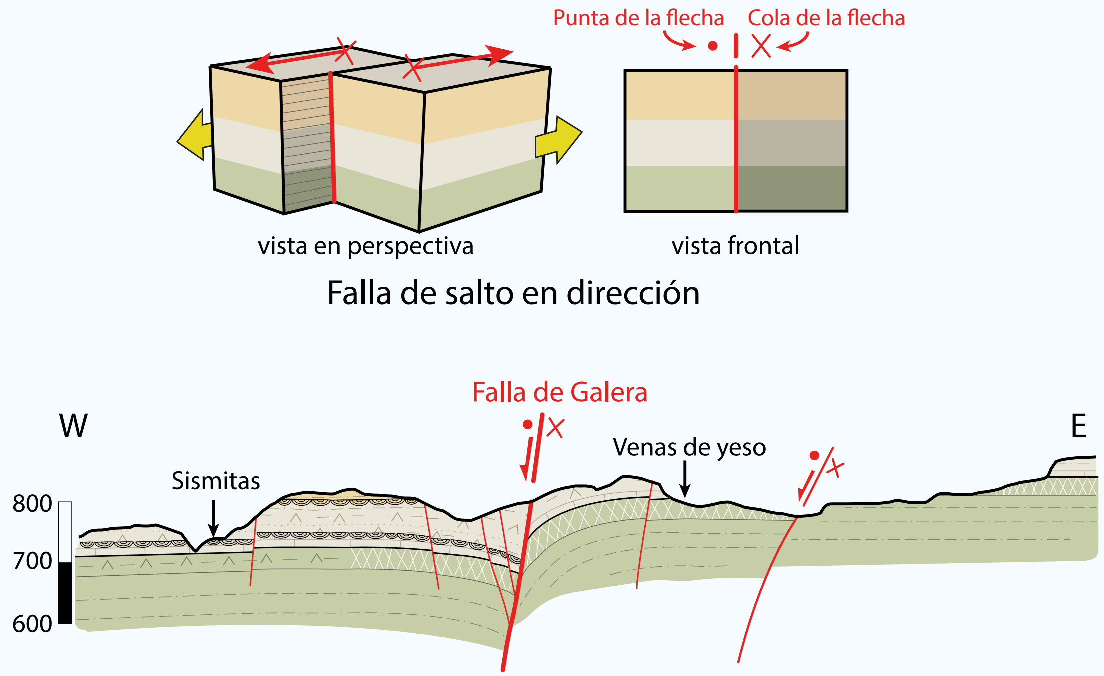


Figure 2. The Galera fault is a fracture with mostly lateral displacement. In the Rambla de los Pilares one of its branches can be recognized; it stands out for the sudden change of materials, the abundant presence of gypsum-filled fractures and the inclination of the layers.

The Galera fault and its influence on the Geopark's relief

The Galera fault is a fracture some 30 km long. It is a strike-slip fault, that is, one that causes a lateral displacement. Figure 2 shows this horizontal displacement of the Galera fault and how its activity is closely related to that of the Baza fault. In the Rambla de los Pilares several indications of this fault can be observed.

The Galera fault cuts through and displaces mostly Lower Pleistocene rocks (between 2.5 and 0.7 Ma), but there is also evidence of deformation in the most recent river terraces of the Holocene (from the last 10,000 years), which shows that it is an active fault.

GPS studies enable us to calculate that the fault moves laterally about half a millimetre per year. As well as its horizontal displacement, the fault also has a small degree of vertical displacement, which uplifts the block located to the south. Although this is much smaller than the horizontal displacement (barely 0.02–0.05 mm/year), it is responsible for the course of the River Galera and the River Guardal, which flow parallel to this uplifted block and to the fault zone (Fig. 3). But most importantly, the vertical movement of the southern block, though very small, is what causes the development of the spectacular badlands landscape of Castilléjar and Galera. This tectonic uplift facilitates a more intense erosion of the block south of the fault, and thus the formation of deeper ravines, giving rise to a dense network of canyons and gullies in easily erodible sedimentary rocks (Fig. 3). The semiarid climate conditions also favour this intense process of erosion which has dominated this sector of the Geopark for at least the last half million years.

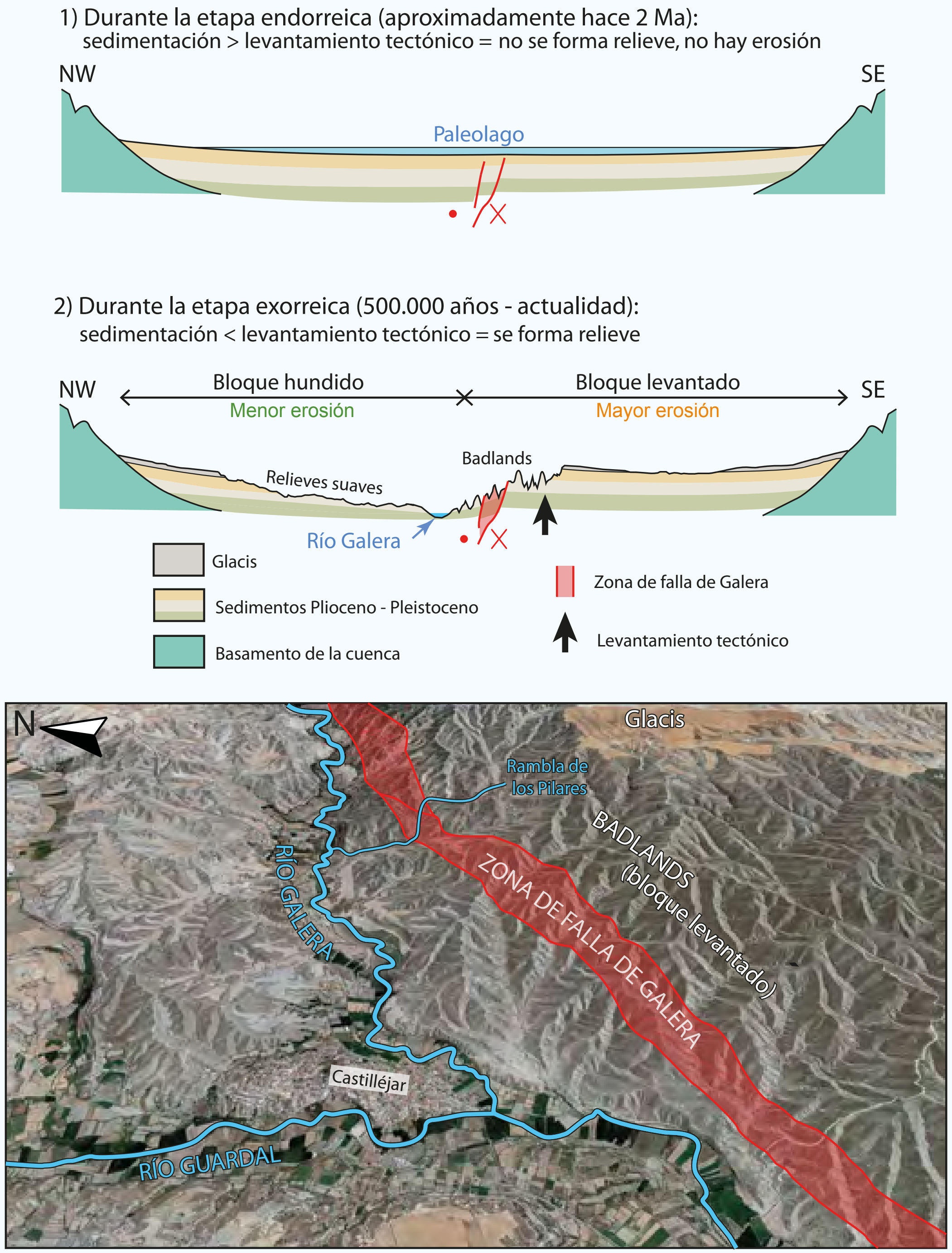


Figure 3. The Galera fault also has a small vertical displacement which is responsible for the badlands relief of Castilléjar and Galera.

Palaeo-earthquakes or fossilized earthquakes

In areas of the planet with slow faults (moving at velocities below one millimetre per year) such as the Guadix-Baza Basin, major earthquakes are repeated at intervals of thousands of years. The recent seismic history of the Geopark's faults, such as the **Baza or Galera faults**, dates back to the last 500 years, since historical documentation began, and with somewhat greater precision to the last 100 years, since we acquired a network of seismographs in Spain. Our record of large earthquakes is therefore incomplete and imprecise.

To improve knowledge of how the active faults in the territory work, the maximum magnitude of the earthquakes that can occur and how often these major seismic events are repeated, scientists try to identify **palaeo-earthquakes** or **fossilized earthquakes** in the geological record.

On the Baza and Galera faults, scientists have conducted studies with the aim of completing their seismic history by identifying these ancient earthquakes. To do so, they look for places where the fault is covered by very recent deposits, a few thousand years old. At these points, they dig trenches and analyse whether the fault has been able to rupture, to cut, these young sediments (Fig. 4). If it has, they know it was due to an earthquake. From radiometric analyses, the sediments can be precisely dated, so the age of these palaeo-earthquakes can be discovered.

In the Baza fault, 9 palaeo-earthquakes have been identified in the last 45,000 years, enabling us to calculate a recurrence or repetition interval of approximately 5,000 years for these major events. It needs to be made clear that this figure represents a minimum frequency, because it is likely that there have been other palaeo-earthquakes that are not recorded in these trenches, Recently, scientists have excavated several trenches in the Galera fault (Fig. 4), in the vicinity of Castilléjar and the Rambla de los Pilares, where the existence of several palaeo-earthquakes has been confirmed.

Figure 4. Interior of a palaeoseismic trench dug in the Galera fault to identify palaeo-earthquakes.

Gypsum-filled fractures

One of the most abundant sediments deposited in the Baza palaeolake was gypsum (Chapter 4). In the Galera fault area, numerous layers of gypsum alternate with sandstones and marls of Pliocene and Quaternary age.

During the endorheic stage, the Galera fault was covered by the Baza palaeolake, so that groundwater seeped through the numerous fractures in the fault zone. This water was mineralized and very rich in sulphates. Under these conditions, gypsum crystallized in the fractures, forming secondary gypsum, which is very abundant in the Baza and Galera fault zones.

In the Rambla de los Pilares, in the Galera fault area, there is a highly spectacular outcrop of gypsum-filled fractures which has aroused the interest of scientists. The technical name for these fractures filled with mineral gypsum is veins. The gypsum grows within the fracture, forming fibrous crystals (Fig. 5).

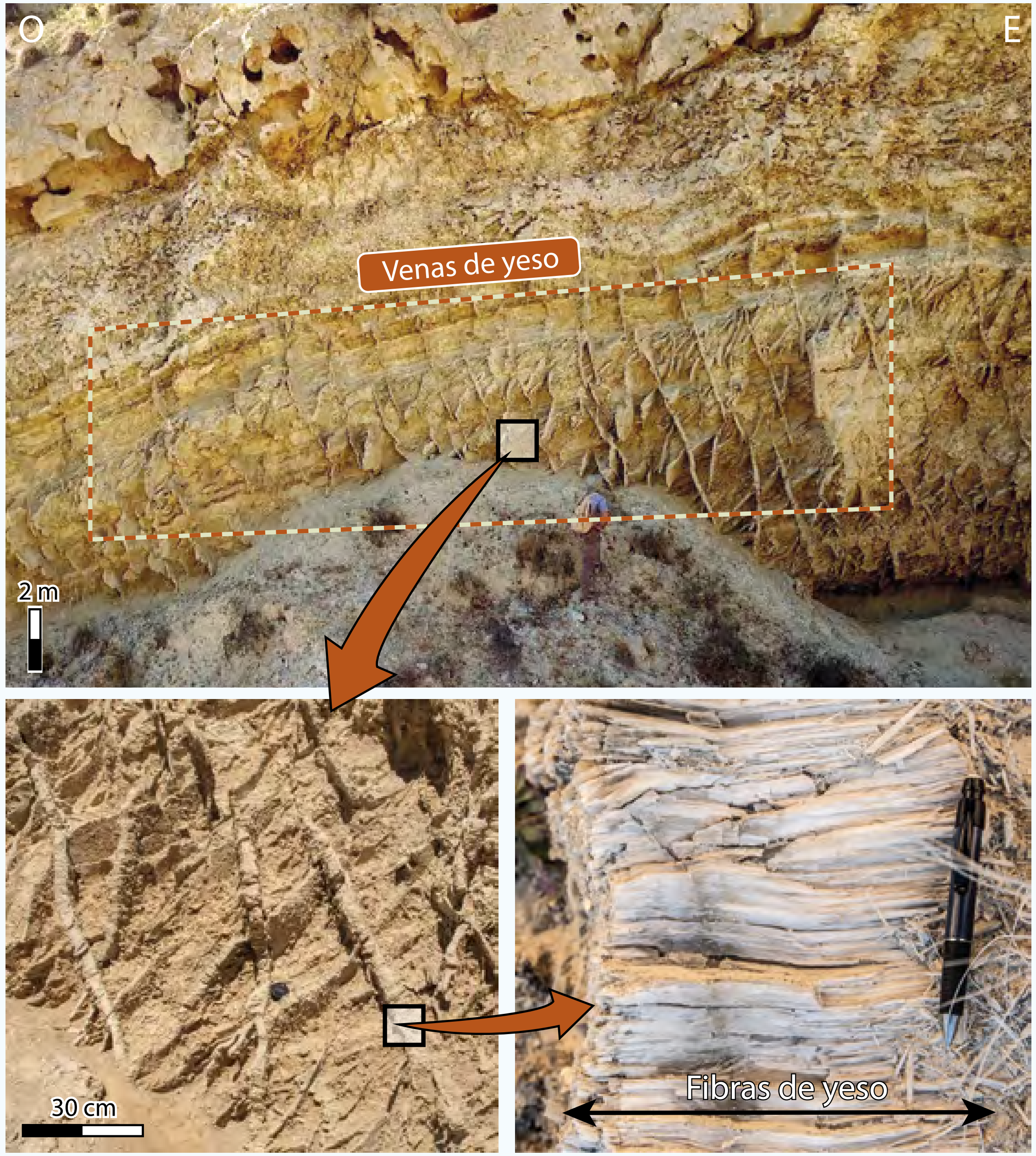


Figure 5. In the Rambla de los Pilares there are spectacular outcrops of fractures filled with fibrous gypsum, which form a mineral gridded pattern of great beauty.


La Rambla de los Pilares
LIG 68
N
Venas de yeso
Falla de Galera
Rambla de los Pilares
Sismitas
AVISO IMPORTANTE
Para acceder al punto de parking hay que circular por un camino de tierra y vadear un pequeño río. Aunque es fácilmente accesible con cualquier tipo de vehículo, es recomendable no acceder durante o tras días lluviosos.
PARKING
45 min
A Castilléjar

6

THE LARGE FOSSIL MAMMALS OF THE GRANADA GEOPARK

Interior of the River Fardes Valley Palaeontological Station.
Fonelas P-1 Palaeontological Site.

A great treasure: the palaeontological heritage of the Geopark

The Granada Geopark, which encompasses the entire Guadix-Baza geological basin, has an exceptional and almost continuous fossil record of the evolution of terrestrial mammals aged between 5 million years (Pliocene) and half a million years (Middle Pleistocene).

Palaeontology is the geological science that studies them, by analysing fossilized bones and teeth. This type of record is very scarce on the planet, and in highly significant cases it forms part of palaeontological and geological heritage. In view of their scarcity and vulnerability to looting (collecting fossils of any kind is prohibited throughout the Geopark's territory), the locations of palaeontological sites are confidential, except those that are physically protected and developed so that they can be used and enjoyed, for educational and cultural purposes, by society.

Nearly 200 vertebrate palaeontological sites have been located in the Granada Geopark during just over a century of research, in which dozens of palaeontologists have taken part. Some of these sites, because of the quality and uniqueness of the information and fossil content they provide, have been catalogued as part of the geological heritage and are included in the Granada Geopark's list of Sites of Geological Interest (SGIs). Seven of them have even attained international importance and have acquired the status of Geosites (**National Heritage and Biodiversity Law, 42/2007**).

Among all the researchers who have studied the palaeontology of large mammals in this territory, one who stands out for his vision, tireless dedication and personal quality is Dr Josep Gibert y Clols (Vals, 1941–Tarrasa, 2007). Gibert, together with some of the professionals who came together in his work team in the 1980s and 1990s, put some of the most remarkable fossil records in the Granada Geopark on the map of science and international geological heritage.

Milestones in the history of life in the Granada Geopark through its palaeontological sites

The Granada Geopark has very significant deposits from the Pliocene epoch, but the Early Pleistocene (between 2.58 and 0.78 Ma) is the period best represented by extensive fossil-bearing units that tell unique stories about the evolution of the Earth and of life.

The following sections, from oldest to most recent (Fig. 1), present the most significant palaeontological sites or records of mammals in the Granada Geopark, of not only scientific but also heritage interest, starting with the transition from the ancient seas (marine basin) to the endorheic continental basin, by way of a delta, at the end of the Miocene.

◆ NEGRATÍN-DELF PALAEONTOLOGICAL COMPLEX

SGI 13; Cuevas del Campo, location confidential

This is a set of sedimentary units that represent an ancient delta at its junction with the sea and are of Mio-Pliocene age. There are abundant layers of sandstone from the intertidal zone with numerous fossils of brachiopods, barnacles and bivalves (scallops and oysters, among others), interspersed with mixed continental/supratidal units containing vertebrate fossils. Both terrestrial (bovids, pigs and the rhinoceros *Dicerorhinus megarhinus* or *Dihoplus megarhinus*) and marine vertebrates, with dolphin vertebrae and jaw fragments, can be recognized. The bone fossils are highly eroded — and rounded — by wave action in the supratidal and intertidal zones. The group as a whole represents a climate period with tropical conditions (there are large balanids). It is in the process of initial research.

◆ BAZA-1

SGI 43; Baza, location confidential pending development

At this site, which formed on the edge of an ancient marsh dating from the Early Pliocene (Ruscinian; approximately 4.5 Ma), various fossils have been found, including some that indicate the coexistence of two proboscideans of the mastodon group: *Anancus arvernensis* and *Mammut borsoni* (or *Zygolophodon borsoni*). Some of the specimens are exhibited in the Baza Municipal Archaeological Museum.

◆ DARRO KARST DEPOSIT

SGI 12; Darro, location confidential

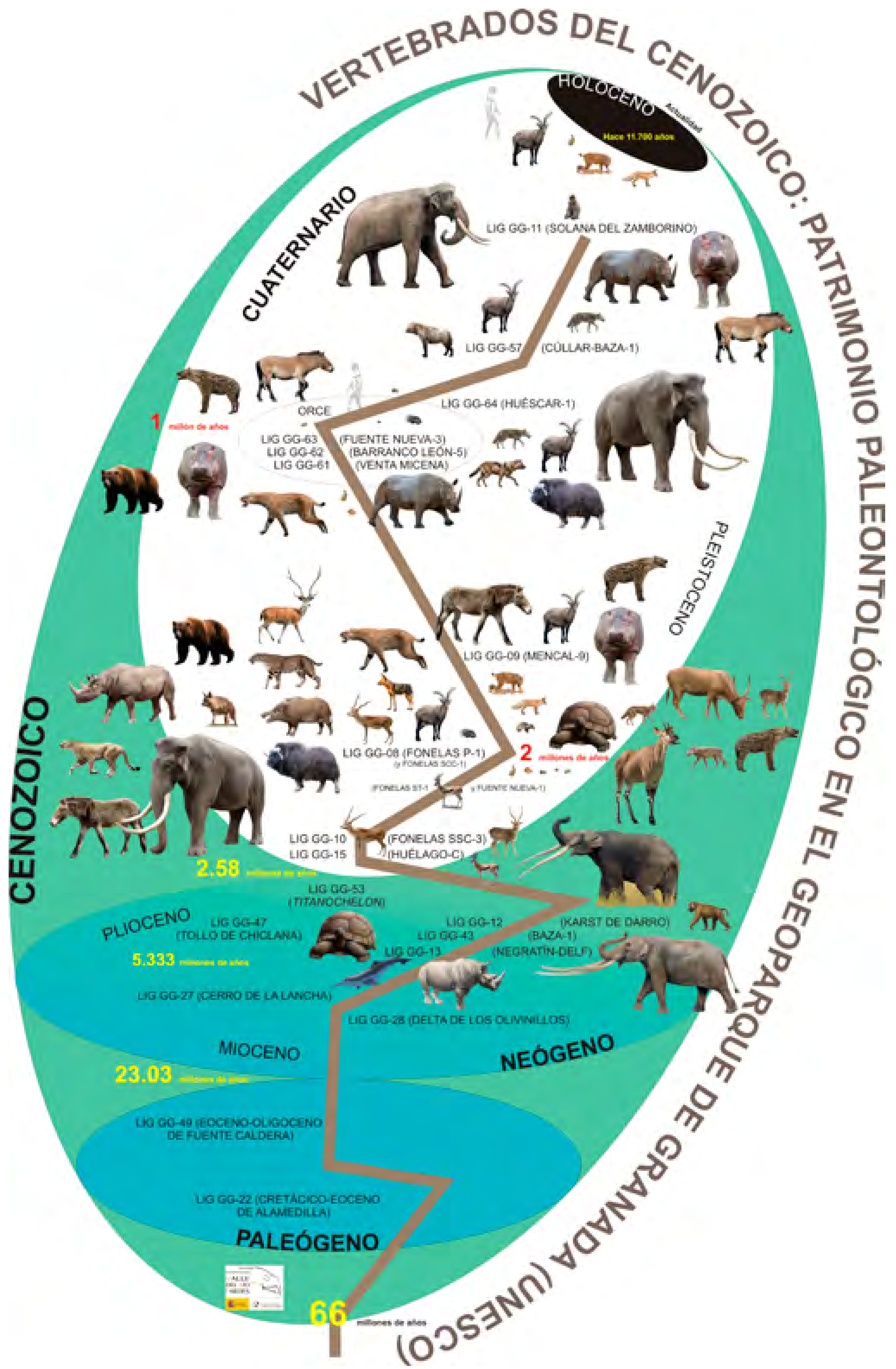
This palaeontological site, dating from the Late Pliocene (3.5–3.2 Ma), developed in a karst infill. It contains abundant micromammal remains (mainly bones and teeth of rodents), which are found enclosed within a deep red clay, corresponding to the insoluble remnants from the dissolution of limestone rocks. The microvertebrates were captured and consumed by birds of prey and "inserted" into the cracks in the karst by the accumulation of the birds' pellets on the outer surface areas of the karst. Exceptionally, there are fossil bones of small tortoises, monitor lizards (indicating subtropical climate conditions) and Old World monkeys (*Paradolichopithecus*, animals comparable to modern mandrils and African baboons), originally inserted into the cavity by gravitational processes. Some specimens are exhibited at the IGME River Fardes Valley Palaeontological Station in Fonelas. .

◆ TOLLO DE CHICLANA PALAEONTOLOGICAL COMPLEX

SGI 47; Gorafe, location confidential

This site comprises a complete series of Pliocene continental units with a (chronologically) extensive and (taxonomically) diverse record of continental micromammals (rodents and insectivores, including a new species of early desman or semiaquatic mole). This complex is also important because the series of sites located reveals a major change in rodent fauna that occurred at around 3.5 Ma and must be the origin of the current fauna of this group in Europe. This change involves the replacement of faunas dominated by mice (family Muridae) and hamsters (family Cricetidae, subfamily Cricetinae) by those now current, in which voles and muskrats predominate (family Cricetidae, subfamily Arvicolinae). The primary interest of the complex is essentially scientific. .

Figure 1 (next page). Diagram showing a synthesis of the palaeontological heritage (SGIs) of vertebrates in the Granada Geopark. The remaining Cenozoic (palaeontological) Sites of Geological Interest inventoried to date are also represented.



◆ HUÉLAGO-C

SGI 15, Huélago, location confidential

This is an Early Pleistocene palaeontological site, with an estimated age of approximately 2.5 million years. It has fossil remains of vertebrates (even-toed and odd-toed ungulates, carnivores and proboscideans), which appear in medium-to-coarse-grain detrital sediments, and reductive palustrine units with an interesting record of freshwater gastropods. It contains fossils of the first known zebra population in the basin (*Equus livenzovensis*), monodactyl equids that came from North America, via Asia, permanently superseding the original tridactyl equids (*Hipparion*).

◆ FONELAS SCC-3

SGI 10; Fonelas, location confidential

This palaeontological site is at an initial stage of investigation. The fossiliferous unit consists of microconglomerates and sands of metamorphic origin, sedimented on the bars of an ancient river channel. Its age, established by palaeomagnetic dating, has been calculated as 2.4–2.5 Ma (the beginning of the Quaternary). The site contains only remains of megafauna: teeth of the last mastodons that inhabited Europe (*Anancus arvernensis mencalensis*, the most recent and smallest representatives of this species), located together with teeth of the first mammoths (*Mammuthus meridionalis*) to reach Iberia (from North America and across Asia to Europe). Both types of proboscideans, mastodons and mammoths, coexisted at this site, indicating the end of the lineage of the former and the beginning of the evolutionary success of the latter throughout the European Early Pleistocene.

Some specimens are exhibited at the IGME River Fardes Valley Palaeontological Station in Fonelas.

◆ FUENTE NUEVA-1

Orce, confidential location

A small continental outcrop of detrital sedimentary rocks associated with small flint beds, dating from between 2.5 and 2.1 Ma (Quaternary, Early Pleistocene), with a palaeontological record that is not very diverse but includes fossil remains of zebra (one species), spiral-horned antelopes, and above all abundant cranial remains of a species of gazelle (*Gazella borbonica*) that became extinct in Europe 2.1 million years ago. More complete scientific knowledge is required at this site.

In its faunal assemblage, abundance of *Gazella borbonica* crania and chronology (2.1 Ma at the latest or older), this site is similar to the one in Fonelas called **Fonelas ST-1**.

◆ FONELAS P-1

SGI 08, Geosite VP014 -Natural Heritage and Biodiversity Law (Law 42/2007); Fonelas, IGME River Fardes Valley Palaeontological Station, National Heritage.

The Fonelas P-1 palaeontological site, dated to 2 Ma by palaeomagnetism and fossil content, preserves a den and feeding place used by giant short-faced hyenas (*Pachycrocuta brevirostris*) which developed on the dry floodplain of the great palaeo-Fardes river (which transported sands, silts and clays of metamorphic origin in its channels). The assemblage at Fonelas P-1 consists of 24 large mammal species (equids — zebras — are represented by a single large species) and a large reptile, among other organisms. This site contains a record of a mixture of native European faunas together with African and Asian immigrants. It also has the following unique features: various large mammal species and subspecies new to science, the largest known collection of spiral-horned antelopes (*Gazellospira torticornis hispanica*), the first European population of wolves (*Canis etruscus*), the first Iberian lynx population in the Peninsula, the first ibex population in the world (*Capra baetica*), the only populations of brown hyena and red river hog outside Africa, the most recent Iberian population of *Palaeotragus* giraffids and the last known European population of giant tortoises of the genus *Titanochelon*. The presence of this tortoise at this date, so recent and unexpected for this lineage (thought to have been extinct since 3.3 Ma), tells us that the Guadix-Baza Basin still had a subtropical climate two million years ago, when intense glaciation had been developing in the northern hemisphere since 2.5 Ma.

The site is the type locality for various new species and varieties of extinct mammals and extends for several kilometres to the NE, where its technical designation changes to **Fonelas SCC-1**.

In short, this site represents a Quaternary (Early Pleistocene baseline) ecosystem never before identified in Europe, a precursor ecosystem of the large mammal community structure that developed in this continent between 2 and 0.9 Ma. The IGME River Fardes Valley Palaeontological Station is equipped for research, dissemination and teaching and admits guided visits.

◆ MENCAL-9

SGI 09; Villanueva de la Torres, location confidential

This is a palaeontological site dated to 1.7–1.5 Ma by palaeomagnetism (it is 4 metres above the top of the Olduvai Subchron) formed in a desiccated marsh system. The Mencal-9 site was located in a systematic palaeontological prospecting season conducted in 2006 by the Fonelas project team (IGME) and systematically sampled by that team in 2009. It is a site at which skeletal remains were concentrated in a gradual ("attritional") process, whereby mammal bones were buried slowly after decades of exposure to the elements and under the effects of sunshine (very high weathering by solar radiation). There is a fossil record of *Pannonictis nestii*, *Canis etruscus*, *Pachycrocuta brevirostris*, *Capra* sp., *Antilopinae* indet. cf. *Gazellospira* sp., Bovidae gen. indet., *Leptobos etruscus*, Cervidae gen. indet., *Hippopotamus* sp., *Equus cf. altidens*, *Stephanorhinus etruscus* and *Mammuthus meridionalis*. This site has the oldest known hippopotamus population in the Iberian Peninsula. It may contain indirect evidence of human presence (open hypothesis).

The three Orce sites related to early human presence in the Iberian Peninsula (Venta Micena, Barranco León-5 and Fuente Nueva-3)

Some researchers have assigned dates of 1.5 Ma to Venta Micena, 1.4 Ma to Barranco León-5 and 1.3 Ma to Fuente Nueva-3. However, the age of these sites is the subject of scientific debate.

From a geological perspective, the three sites, taken as a whole, represent different but contemporaneous contexts and biotypes. These sites are an exceptional source of information for palaeoenvironmental reconstruction, the interrelationships between the various organisms and the landscape they inhabited at an age, regardless of the above-mentioned debate, close to 1.2 million years in each case. Some of their features are described below:

◆ VENTA MICENA

SGI 61, Geosite VP015; BIC (Asset of Cultural Interest): Archaeological zone

The Venta Micena site is a vast accumulation of bones produced by a clan of Pachycrocuta brevirostris hyenas in their den and eating area, located in the open air on the desiccated shores of a lake environment devoid of vegetation (calcareous substrate: originally dry micritic mud). It contains a diverse assemblage of extinct mammals, notably including evolved wolves (Canis mosbachensis), hippopotami, wild dogs, some bovids of Asian origin and a single derived species of zebra (Equus altidens granatensis). No lithic remains related to human activity have been located at this site. On the basis of the scientific collection here, an internationally important model of the feeding activity and palaeoethology of giant short-faced hyenas has been established.

The site is the type locality of various new species and varieties of extinct mammals.

The range of species identified makes this the reference site for the earliest presence of humans in the Iberian Peninsula, according to current data, revealing the ecosystem in which those hominins inhabited the Peninsula around 1.2 million years ago. Some of their remains are in the Centro de Interpretación Primeros Pobladores de Europa Josep Gibert (Josep Gibert First Settlers in Europe Interpretation Centre). .

◆ BARRANCO LEÓN-5

SGI 62, Geosite VP16; BIC (Asset of Cultural Interest): Archaeological zone

This site is located in an ancient fluvial flood deposit (originating from the Jurassic carbonate rocks of the nearby mountains). It is on an erosional palaeosurface that developed in a previously dry former marsh and its palaeontological and archaeological components are resedimented, except the hippopotamus fossils. The fossil bones have high sphericity indices, and also a characteristic polished surface, due to having been transported by water currents before being sedimented on the surface of the initially dry marsh (sedimentary break). There is an abundance of Oldowan-type flint lithic industries, manufactured by hominins. This site is important for having yielded two human fossils (two milk teeth, one of them fragmented) of a child aged approximately 10 years. There are fossils of two equid species: an evolved zebra (*Equus altidens*) and a primitive horse (*Equus suessenbornensis*). Some of their remains are in the Josep Gibert First Settlers in Europe Interpretation Centre.

◆ FUENTE NUEVA-3

SGI 63, Geosite VP17; BIC (Asset of Cultural Interest): Archaeological zone

This site formed on the edge of a marsh, originally with moderate plant cover. Its calcareous (micritic) lower horizon can be correlated with the white layers of Venta Micena (sedimentary break). The upper horizons are characterized by severe deformations, possibly due to megafaunal bioturbation and/or post-depositional processes related to earthquakes. This site contains abundant fossilized hippopotamus and mammoth (*Mammuthus meridionalis*) bones. As regards taphonomy, on one of the upper levels of Fuente Nueva-3 a largely complete skeleton of this type of proboscidean has been recovered, with the bones scattered, surrounded by giant hyena (*P. brevirostris*) coprolites (fossilized faeces) and lithic remains of anthropic origin (Oldowan lithic industries). From this it could be inferred that there was a competition between hyenids and hominins for exploitation of the megaherbivore on the edge of a waterlogged area. The faunal assemblage once again includes the coexistence of two equids: an evolved zebra (*Equus altidens*) and a primitive horse (*Equus suessenbornensis*). Some of their remains are in the Josep Gibert First Settlers in Europe Interpretation Centre.

◆ HUÉSCAR-1

SGI 64, Geosite VP018, part of the SGI named Barranco de las Cañadas, Barranco de las Quebradas and Cortijo de la Calahorra Palaeontological Complex; Huéscar, location confidential

The fossil remains at this palaeontological site are associated with a system of alluvial fans which flowed into a lacustrine area, and they are contained in alluvio-lacustrine carbonate microconglomerates, sands and silts. It is a transported complex in which the bones show numerous marks of abrasion and dragging. The remains, which accumulated gradually, appear in three sedimentological contexts: as bed load filling palaeochannels, in accumulated pockets at outflow points of the channels into the lake, and scattered sporadically in carbonate sediments. The mammal fauna of this site enables us to place it at the top of the Lower Pleistocene of the basin, with an age of around 0.95–0.83 Ma. The list of fauna (with two equid species: *Equus altidens* and *Equus suessenbornensis*) is similar to those identified at Barranco León-5 and Fuente Nueva-3. Its fossil record includes a proboscidean, identified decades ago as *Elephas antiquus* but recently reassigned to the species *Mammuthus meridionalis*. This site therefore contains one of the last populations of this mammoth before its disappearance. The presence of lithic industries has been reported; these are being studied.

◆ CÚLLAR-BAZA-1

SGI 57, Geosite VP019; Cúllar, BIC (Asset of Cultural Interest): Archaeological zone, location confidential

This palaeontological site was originally marshland, with a set of large mammal fossils slightly more recent than that of Huéscar-1 (possibly near the end of the Early Pleistocene, about 0.8–0.7 Ma). The proboscidean identified in this case is *Mammuthus trogontherii*, a more recent species than *M. meridionalis*. Again, the two equids mentioned previously coexisted here. The sporadic presence of lithic industries has also been reported, and these are being studied.

◆ SOLANA DEL ZAMBORINO

SGI 11, Geosite VP020; Fonelas, BIC (Asset of Cultural Interest): Archaeological zone, location confidential

Solana del Zamborino is a site generated in a lake/marsh environment, located chronologically in the Middle Pleistocene, since all the vertebrate fauna identified in it is characteristic of the European Middle Pleistocene: that is, between 0.781 and 0.126 Ma. The proboscidean identified is *Elephas antiquus*, the equid is *Equus caballus torralbe*, and in addition, fossils of macaques have been discovered. Lithic industries have been found at the site, but in this case of an Acheulean nature (more modern and/or sophisticated than the previous Oldowan ones), including a flint hand-axe.

In recent decades there has been a scientific debate about its age, and consequently about the age of the Acheulean in Europe: some authors establish an age of around 0.76 Ma for the site, while others assign it a date close to 0.48–0.30 Ma. Both figures, within the Middle Pleistocene, are in principle consistent with the fauna identified, until the large mammal taxonomy described at the site in the 1970s is revised. It is currently being studied.

The most important palaeontological milestones in relation to evolution of the mammals recorded in the Granada Geopark

- Transition from marine to continental ecosystem (Mio-Pliocene): concentration on beaches, on a delta, of cadaveric remains of bovids, primitive rhinoceroses and dolphins at Cuevas del Campo (SGI 13). These fossils of river or oceanic dolphins (we do not yet know which) are the only known cetaceans in the Guadix-Baza Basin.
- Coexistence of two species of mastodons (*Anancus arvernensis* and *Mamut borsoni*), 4.5–4.0 Ma in Baza (SGI 43).
- First Old World monkeys inhabiting the Geopark, 3.5–3.2 Ma in Darro (SGI 12).
- New species of small mammals during the Pliocene in Gorafe and Freila (SGI 47).
- Arrival of the first zebras (*Equus livenzovensis*) from Asia, 2.5 Ma in Huélago (SGI 15).
- Arrival of the first mammoths (*Mammuthus meridionalis*) from Asia, which coexisted with the last native European mastodons (*Anancus arvernensis mencalensis*), 2.5–2.4 Ma in Fonelas (SGI 10). Extinction of mastodons.
- Novel European ecosystem (“biodiversity hotspot”), 2.0 Ma: Fonelas P-1 (SGI 08). First wolves, giant hyenas, ibex and last giraffes and giant tortoises in Europe.
- First hippopotamus population in the Peninsula, 1.7–1.5 Ma in Villanueva de las Torres (SGI 9).
- Ancestral human populations and information on the palaeoenvironmental context in which they lived, approx. 1.1 ± 0.2 Ma (Venta Micena SGI 61, Barranco León-5 SGI 62 and Fuente Nueva-3 SGI 63) in Orce.

- Arrival of the first horses in the strict sense of the term (*Equus suessenbornensis*), also from Asia, approximately 0.9 Ma in Huéscar (SGI 64)(?). This species is also recorded in Barranco Léon-5 and Fuente Nueva-3. Depending on their definitive chronologies, the location and/or chronology of the event may vary.
- Last mammoths in the Geopark, during the beginning of the Middle Pleistocene in Cúllar (SGI 57).
- Macaques (*Macaca sylvanus*) inhabiting the region, coexisting with the first elephants in the strict sense during the Middle Pleistocene (0.78–0.126 Ma) in Fonelas (SGI 11).

The following pages contain more detailed descriptions of the most important palaeontological sites in the Geopark, which can be visited at any of the centres belonging to the network of heritage information centres of the Granada Geopark: Baza-1, Fonelas P-1 and the three Orce sites (Venta Micena, Barranco León-5 and Fuente Nueva-3).

THE BAZA-1 PLIOCENE PALAEONTOLOGICAL SITE

SGI 43

The Baza-1 site is a palaeontological location of the first order from the Early Pliocene, specifically the Ruscinian, and is approximately 4.5 million years old.

It is located on the well-known Cuesta del Francés, 300 metres from the built-up area of Baza. Geologically, it lies on the western uplifted block of the Baza fault (Figure 1).

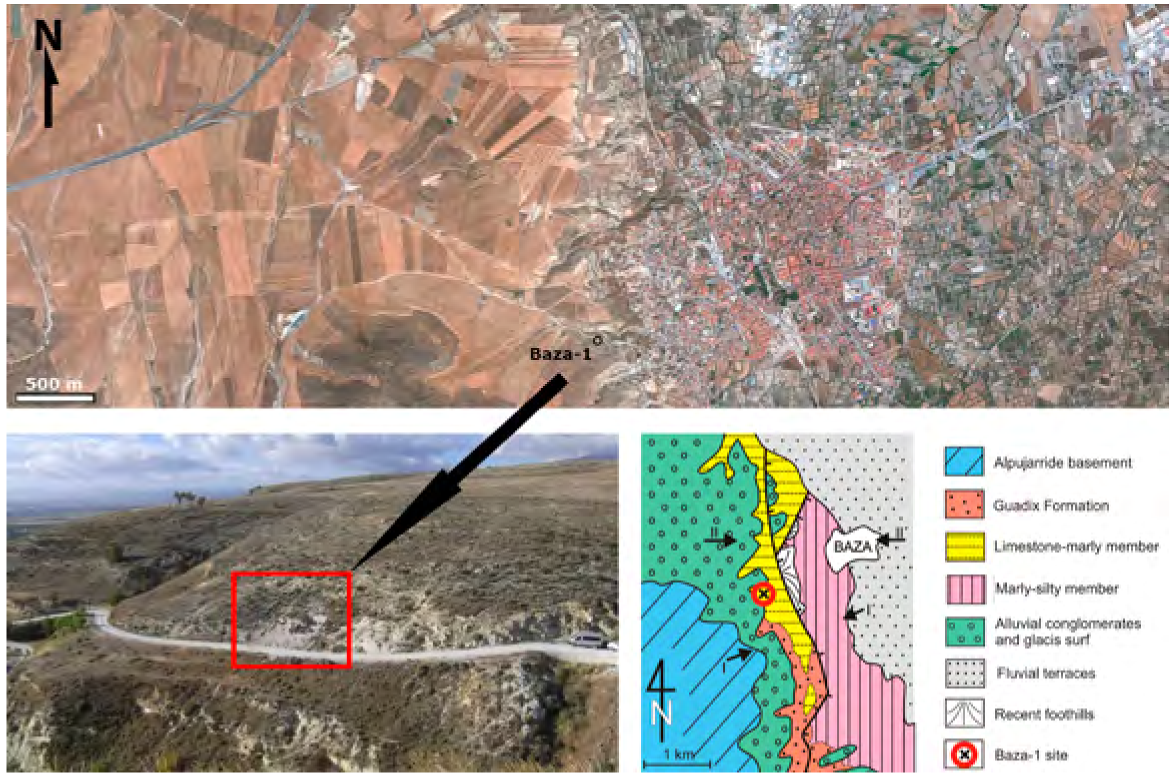


Figure 1. Above: location of the Baza-1 site 300 m from the built-up area; below left: view situating the excavation outcrop on the Cuesta del Francés; below right: geological map showing the position of the site on the western uplifted block of the Baza fault.

Figure 2. Front view (looking south) of the Baza-1 excavation section (27/09/2019).

There are other Ruscinian localities in the basin, all with good records of microvertebrates, especially rodents, of which 11 species are represented at the Baza-1 site. They include some of African origin, which arrived in the Iberian Peninsula during the Messinian age, between 5.3 and 7.2 Ma, such as those from the genus *Paraethomys*. However, the distinctive feature of Baza-1 is that it is one of the few palaeontological localities that have so far provided fossils of large mammals. In only 27 square metres that have been partially excavated (Fig. 2), more than 1,000 records of skeletal remains from a rich megafauna have been located, with an abundance of mastodons, represented by two taxa, *Anancus arvernensis* and *Mammut borsoni* (Figs 3, 4 and 5), among which three individuals of each species have been identified. This is why we refer to the Baza mastodon cemetery.

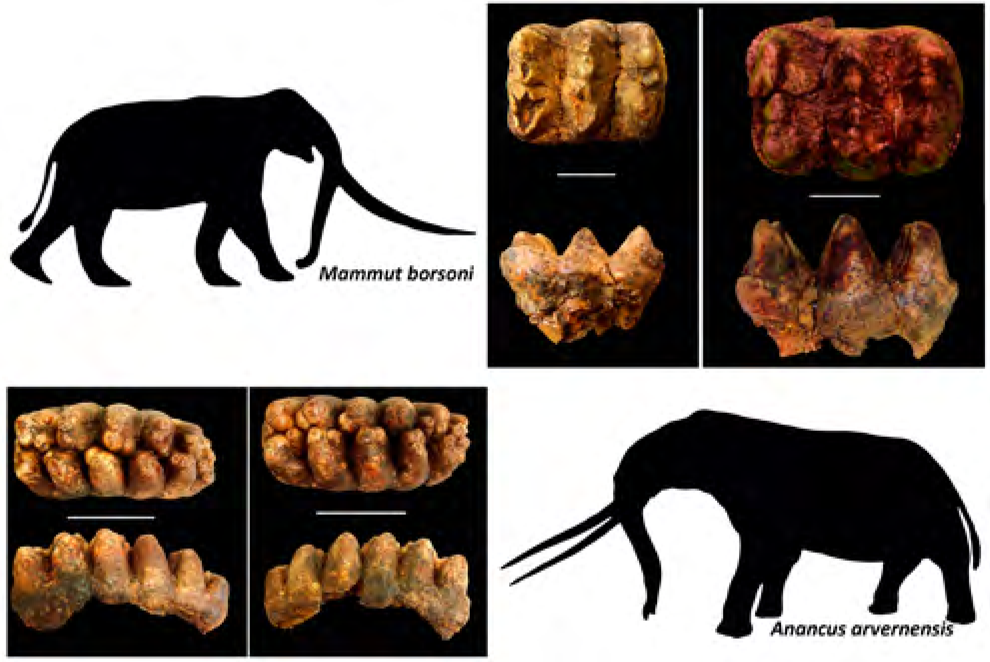


Figure 3. Above: first (left) and second (right) lower molars of *Mammut borsoni* (Scale: 5 cm).

Below: third upper molars of *Anancus arvernensis* (Scale: 10 cm).

Figure 4. Mandibular remains of *Mammut borsoni* in situ, located during the 2015 season.

Figure 5. Palate of *Anancus arvernensis* found in the 2018 season.

In addition to mastodons, other remains of different species have been found. These include rhinoceroses (*Stephanorhinus cf. jeanvireti*) (Fig. 6), small three-toed horses (*Hipparion* sp.), two folivorous (leaf-eating) bovids, one large, called Alephis sp., and one a medium-sized antelope, a small pig and two species of carnivores, together with an extensive record of tortoises. Moreover, these are also supplemented by remains of plants, woody trunks and fossil leaves.

The Baza-1 site constitutes an exceptional palaeobiological archive, for in only 27 square metres that have been partially excavated there is an extraordinary density of fossils, with a unique record of vertebrates, which will increase in the next few years with further seasons of excavation, including fish, amphibians, reptiles, birds and mammals. To this must be added the extensive record of flora located there. These finds will make the Baza palaeontological locality one of the reference sites for the continental Pliocene in Europe.

Figure 6. Jaw of a rhinoceros (*Stephanorhinus cf. jeanvireti*) in situ, in the process of extraction, during the 2017 season.

LIFE TWO MILLION YEARS AGO: THE FONELAS P-1 PALAEONTOLOGICAL SITE

SGI 08

A long, long time ago, the landscape around us, here in the north of Granada, was very different. The western sector of the Granada Geopark (the Guadix Depression) was a vast plain between mountains, crossed by a river, the palaeo-Fardes. At that time, the plain was inhabited by a clan of giant short-faced hyenas. The concentration of skeletal remains of the animals they fed on (the herbivores) and of the others they competed with (the carnivores) produced this palaeontological site, called **Fonelas P-1**. We know that all this happened approximately two million years ago, during the Early Pleistocene, from analysis of the fossils and palaeomagnetic dating studies.

WHO WERE THE PLAYERS IN THIS LOST ECOSYSTEM?

Fonelas P-1 vertebrates (Figures 1, 3 and 4)

Colubridae gen. indet., *Eurotestudo* sp., *Titanochelon* sp., Aves gen. indet., *Mimomys* sp., *Castillomys* sp. cf. *C. rivas*, *Apodemus* sp., *Stephanomys* sp., *Eliomys* sp., *Prolagus* sp. cf. *P. calpensis*, *Oryctolagus* sp., *Erinaceus* sp. cf. *Erinaceus europaeus*, *Meles iberica* (ex gr. *M. thorali*), *Vulpes alopecoides*, *Canis accitanus* (ex gr. *C. arnensis*), *Canis etruscus*, *Canis* sp. cf. *C. falconeri*, *Lynx issiodorensis valdarnensis*, *Acinonyx pardinensis*, *Megantereon cultridens roderici*, *Homotherium latidens*, *Hyaena brunnea*, *Pachycrocuta brevirostris*, *Ursus etruscus*, *Croizetoceros ramosus fonelensis*, *Metacervoceros rhenanus philisi*, *Eucladoceros* sp., *Gazellospira torticornis hispanica*, *Leptobos etruscus*, *Praeovibos* nov. sp. aff. *P. priscus*, *Palaeotragus* (sin. *Mitilanotherium*) sp., *Potamochoerus magnus*, *Capra baetica*, *Equus major*, *Stephanorhinus etruscus* and *Mammuthus meridionalis*.

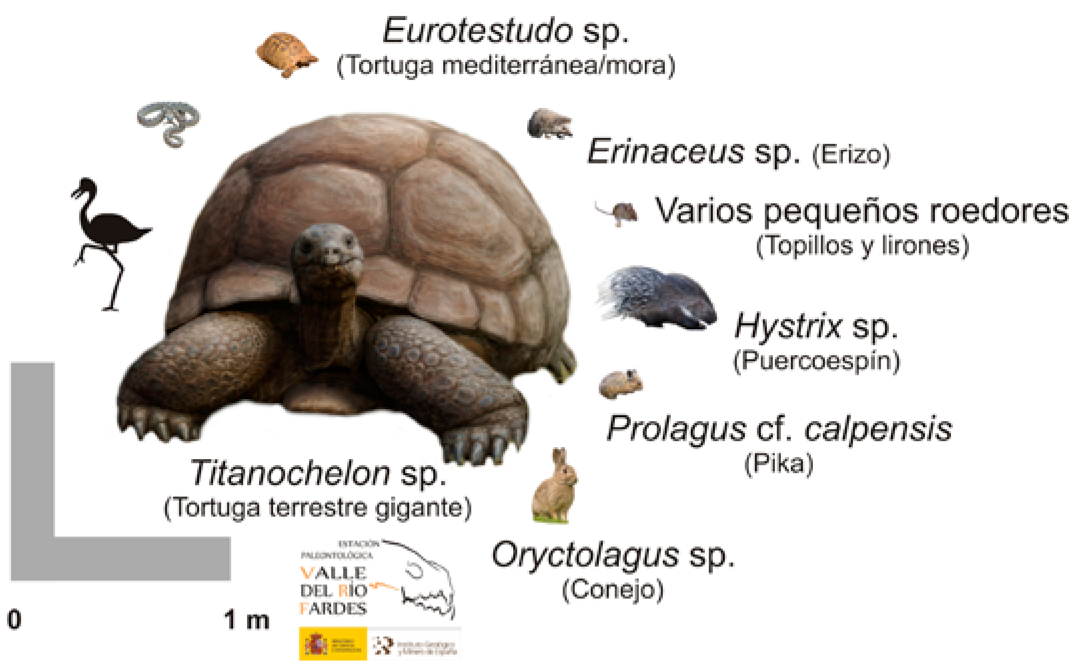


Figure 1. Small mammals, reptiles and birds at Fonelas P-1.

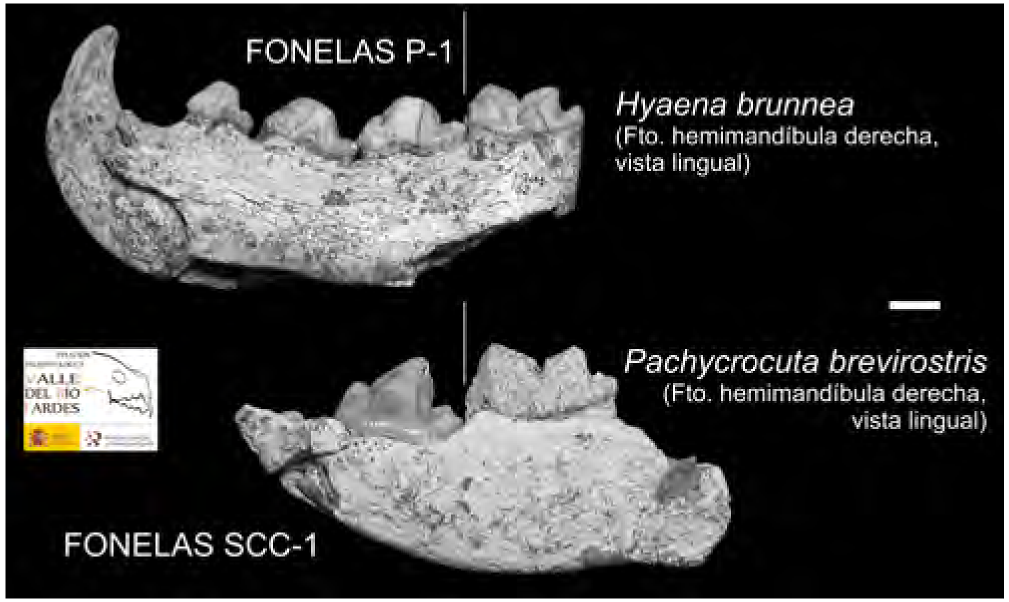


Figure 2. Fossils of the two types of hyenas that coexisted in Granada Geopark two million years ago (graphic scale 1 cm).

These enormous hyenas (*Pachycrocuta brevirostris*), newly arrived in that period from Africa, settled in what is now Fonelas, in two places in the territory: Fonelas P-1 (River Fardes Valley Palaeontological Station) and Fonelas SCC-1. And in both places they coexisted with other hyenas, also of African origin: the present brown hyenas (*Hyaena brunnea*; see Figure 2).

Thanks to the feeding behaviour of the short-faced hyenas, scavengers that consumed remains of the carcasses of many animals in the ecosystem and concentrated the bones of those animals in their feeding places/dens, we have the best possible information on life in this period of time, and we can see that the biological diversity was spectacular.

The Fonelas P-1 palaeontological site corresponds to the sedimentation on a floodplain located in the vicinity of an abandoned meander, within a fluvial system. On this surface, on the dry plain, the clan of hyenas made their home for a few generations (being born, dying, feeding and concentrating animal bones). The thousands of bones carried by them (Figure 5) were buried by trampling and by direct rainfall that they sealed in the site, and subsequently by sedimentation of the materials that overflowed from the main channel onto the floodplain.

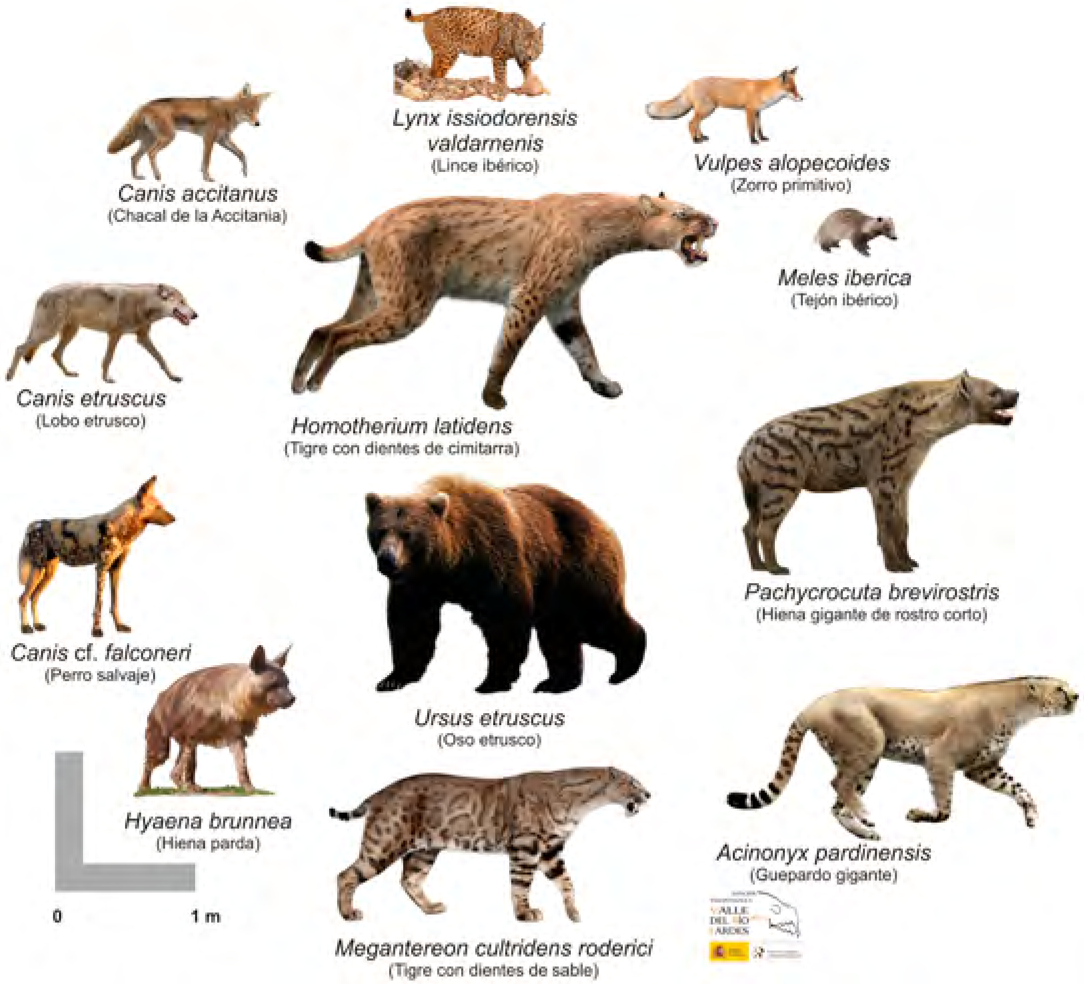


Figure 3. Fonelas P-1 carnivores: mustelids, canids, felids, hyenids and ursids.

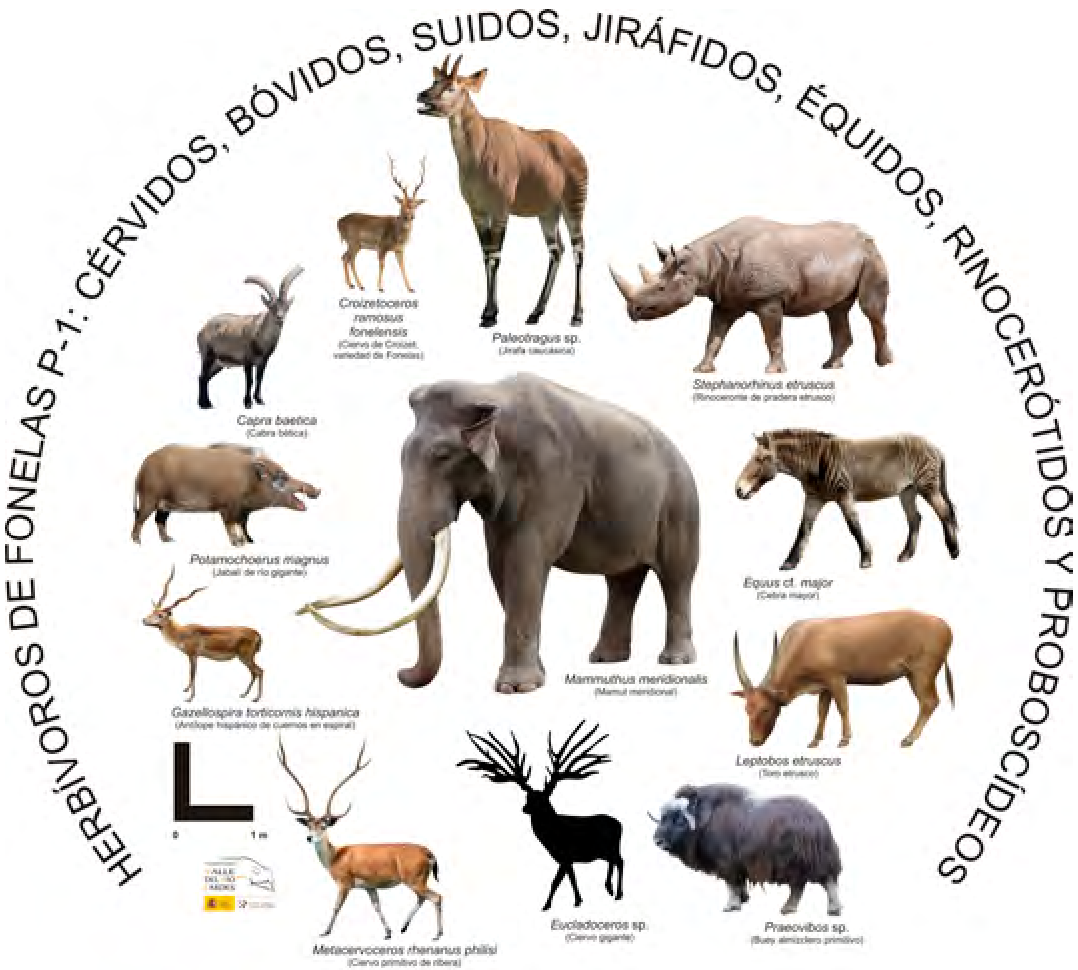


Figure 4. Fonelas P-1 herbivores: cervids, bovids, suids, giraffids, equids, rhinocerotids and proboscideans.

Through its faunal content (identified genera and species) and analysis of its distribution in time and space, Fonelas P-1 has made it possible to group the movements of Asian and African fauna that partially renewed European ecosystems at the beginning of the Quaternary into a single dispersal event, between 2.1 and 2.0 Ma. Indeed, the assemblage of fauna identified at this site indicates that numerous animals colonized the western European continent earlier than was previously thought, incorporating both African and Asian elements into this unique migratory event.

Fonelas P-1 is therefore the reference site nowadays for palaeontological research on the basal Early Pleistocene, because of a range of scientific evidence: enormous diversity in carnivores and herbivores, the first known population of ibex (Capra baetica) on the planet, the first report of *Leptobus etruscus* in the Iberian Peninsula, the earliest European records of Pachycrocuta brevisrostris and *Canis etruscus*, the most recent report of the giraffid *Palaeotragus* (syn. *Mitilanotherium*) in Western Europe, the first reports of *Potamochoerus* and *Hyaena brunnea* outside Africa, and the presence of new species and varieties of the genera *Meles*, *Canis*, *Gazellospira*, *Croizetoceros*, *Praeovibos*, *Palaeotragus*, *Potamochoerus* and *Capra*.

Finally, an outstanding feature of the site is the identification of a Lazarus taxon, in the form of the giant tortoises of the genus *Titanochelon*. They were assumed to have become extinct in Europe 3.3 million years ago, and therefore constitute the last presumed representatives of this type of reptile. Their identification at 2.0 Ma in Fonelas P-1 indicates that in the Early Pleistocene, in the SE of the Peninsula, there was still a resident population of these ancestral animals, whose environmental requirements are associated with a tropical or subtropical climate, but under no circumstances with cold conditions or glacial periods.

Come and discover it; get to know it. Fonelas P-1 is a fascinating palaeontological site that is part of National Heritage. It is fully equipped with museum facilities and open to visitors

IT IS YOURS: ENJOY NATURE AND YOUR HERITAGE

Figure 5. Characteristic set of fossilized bones at Fonelas P-1 (skulls of *Gazellospira* and *Metacervoceros* and long bones, notably including those of *Mammuthus* calves, all partially consumed by hyenas).

Datos patrimoniales de Fonelas P-1

- Código Geosite [Proyecto Global Geosites; Ley de Patrimonio Natural y Biodiversidad (Ley 42/2007)]: VP014.
  Dominio geológico (GEODE): Cuencas del Guadalquivir y neógenas intramontañosas.
  Unidad geotectónica 2º orden: Cuencas neógenas intramontañosas.
  Contexto Ley 42/2007: Yacimientos de vertebrados del Plio-Pleistoceno español.
  Unidad geológica Ley 42/2007: Estructuras y formaciones geológicas de las cuencas cenozoicas continentales y marinas.
- Código LIG (Estrategia andaluza de gestión integrada de la Geodiversidad, Consejería de Medio Ambiente, 2010): AND303.
- Código LIG Geoparque de Granada: **LIG GG-08**.

Propiedad: Instituto Geológico y Minero de España-CSIC, Ministerio de Ciencia (Patrimonio del Estado).
Nombre del conjunto (Unidad IGME): **Estación paleontológica Valle del río Fardes** (EPVRF).
Extensión/superficie: 25 hectáreas.
Especificidad: Zona de reserva geológica en la Hoya de Guadix.
Utilidad/usos: Geoconservación, Investigación + Divulgación + Docencia.
Tipos de patrimonio:
Natural:
- Geológico (paleontológico -40 especies de vertebrados extintos, de las cuales 25 de grandes mamíferos-, estratigráfico, sedimentológico, geomorfológico). Continuidad lateral: Si, a dos kilómetros al NE cambia de denominación a Fonelas SCC-1.
- Biológico: poblaciones de especies botánicas endémicas en "peligro crítico de extinción" (*Clypeola eriocarpa* y *Limonium majus*). Inventario provisional de 480 especies de fauna (de las cuales 404 de invertebrados) y 297 especies de plantas.
- Cultural:
  Dólmenes.

Infraestructuras que contiene:
- Centro paleontológico Fonelas P-1 (yacimiento del mismo nombre protegido, monitorizado y musealizado en una superficie de 1.020 m^2).
- Módulo divulgativo Historia de la Tierra y de la Vida.
- Ruta geológica de campo EPVRF.
- Pabellón de trabajo en campo y módulo de suministro eléctrico.

Visitable: Si, todo el año.
Gratuito: Si.
Toda la información en: http://www.igme.es/epvrf/estacion

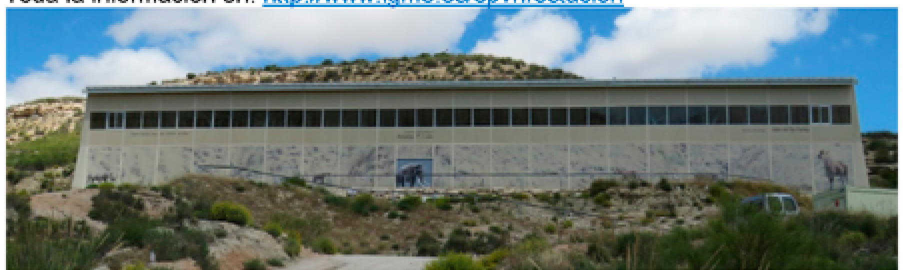


Figure 6: Summary of the heritage and technical data for Fonelas P-1 at the Fardes River Valley Palaeontological Station.

THE ORCE ARCHAEO-PALAEONTOLOGICAL SITES
SGI 61, 62, 63

The town of Orce, located in the northeast of the province of Granada (Fig. 6), is home to one of the most important archaeo-palaeontological records in the world for knowledge of the first dispersal of humans out of Africa and for the reconstruction of the palaeoecological context in which it took place. Its archaeo-palaeontological sites constitute a veritable documentary archive in which various moments and aspects of the everyday life of our ancestors have been preserved. They also offer valuable information on the other species that inhabited the region during the Early Pleistocene. This enables us to state that the Guadix-Baza Basin, in its Orce sector, whose history dates back to one and a half million years ago, includes the oldest sites with human presence in Western Europe.

In this distant past, the Guadix-Baza Basin, and the "Orce Basin" Archaeological Zone in particular, exhibited a breathtaking luxuriance quite unlike the present landscape, which is as rugged as it is engaging, the result of an extremely continental semiarid climate. What were the main reasons for this transformation of the landscape? The answer is the presence and subsequent disappearance of a large lake.

The Baza palaeolake and its wetlands in the Orce sector attracted and catalyzed a biodiversity that seems astonishing today. Throughout its long history sediments gradually accumulated, and in some places on the shore they included remains of human activities and/or fossils of the other species that inhabited the area around Orce. This being so, the set of macrovertebrates is made up of species that may now strike us as exotic and others that are more common: sabre-tooth cats, hyenas, hippopotamuses, horse, deer, bovids, mammoths, rhinoceroses, wild dogs, wolves... and humans. Some were indigenous, others came from elsewhere, from Africa and Asia, including our ancestors.

The list of macrovertebrates recorded at the Venta Micena, Barranco León and Fuente Nueva 3 sites is as follows: *Mammuthus meridionalis*, *Stephanorhinus etruscus*, *Equus altidens*, *Equus suessenbornensis*, *Hippopotamus antiquus*, *Bison* sp., *Hemibos* sp. aff. *Hemibos gracilis*, *Soergelia minor*, *Ammotragus europaeus*, *Praeovibos* sp., *Hemitragus albus*, Bovidae indet. (tamaño muflón), *Praemegaceros* cf. *verticornis*, *Metacervocerus rhenanus*, *Homotherium latidens*, *Megantereon cultridens*, *Panthera* cf. *gombaszoegensis*, *Lynx* cf. *pardinus*, *Pachycrocuta* *brevirostris*, *Lycaon lycaonoides*, *Canis mosbachensis*, *Vulpes alopecoides*, *Ursus etruscus*, *Martellictis ardea*, *Meles meles* and *Homo* sp.

However, another geological phenomenon had to occur for us to be able to access the rich heritage of the Orce sector today: the capture of the Guadix-Baza Basin by the River Guadalquivir, via the Guadiana Menor (Chapter 7). This drastic modification, in these wastelands, led to the emergence of gullies, canyons and ravines which have brought to light strata that would otherwise have remained hidden and unknown (Fig. 6).

Figure 6. Aerial view of part of the archaeological zone of the Orce sector (Llanos de Almaida and Cañada de Vélez).

There are four sites that stand out in the Archaeological Zone of the Guadix-Baza Basin in its Orce sector: two, Barranco León and Fuente Nueva 3, contain evidence of human activities together with those of other animal species; the others, Fuente Nueva 1 and Venta Micena, only the latter.

FUENTE NUEVA 1 has a slightly earlier chronology that the other localities (c. 2 Ma) and is notable for the large concentration of bone cores (horns) of two species of gazelle, *Gazellospira torticornis* and *Gazella borbonica*.

VENTA MICENA ((Fig. 7) is one of the best-known sites in the palaeontological literature of the Eurasian Early Pleistocene, with an age of 1.5 Ma. To the large quantity and variety of elements in taxonomic and anatomical terms must be added the excellent state of preservation of the assemblage, thanks to the characteristics of the so-called Venta Micena Level, which records a density of more than 200 elements per m2. Some species were indigenous, but others, including the humans, came from Asia and Africa. On the other hand, this site has been crucial in characterizing the scavenging and bone-cracking behaviour of the giant short-faced hyena (*Pachycrocuta brevirostris*).

Figure 7. Accumulation of fossil remains at the Venta Micena site.

BARRANCO LEÓN 5 (Fig. 8) is notable for the presence of humans (*Homo* sp.), and in particular of a deciduous (milk) molar belonging to a child of approximately ten years of age (Fig. 9).

Figure 8. Barranco León 5 site.

Figure 9. Human deciduous tooth from Barranco León 5.

This is not the only human evidence; there are also recorded traces of the everyday activities of the human groups from around 1.4 Ma, basically stone working and the processing of ungulate carcasses: stones for striking bones and obtaining the marrow and for reduction of workable rocks to stone flakes with sharp edges for stripping flesh (Fig. 10).

Figure 10. Knapped stone flakes from the Fuente Nueva 3 site. Source: Barsky *et al*. (2015). .

We also find those futuristic shaped stones (they do not appear again in Europe until 400,000 years later) called *spheroids* (Fig. 11).

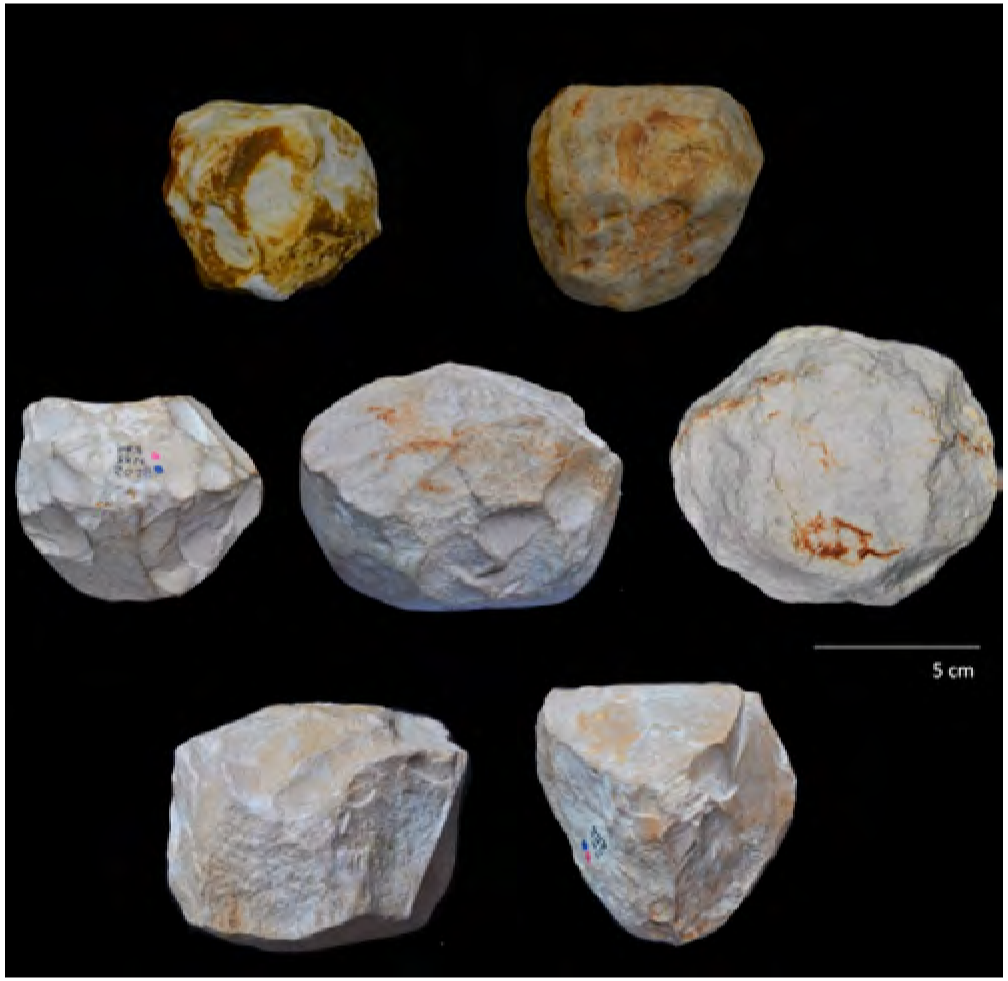


Figure 11. Spheroids found at the Barranco León 5 site.
Source: Titton et al. (2020).

Finally, **FUENTE NUEVA 3**, which has a similar chronology to the previous site, is distinguished by the preponderance of large animals, and in particular mammoths, as well as human evidence in the form of lithic industry. Outstanding among the wealth of heritage at this site are two tusks from a male proboscidean measuring four metres in length (Fig. 12). The site must have functioned as a natural trap into which these Pleistocene giants fell and were later utilized by humans and other scavengers, mainly by the above-mentioned *Pachycrocuta*.

Figure 12. View from the upper part of the Fuente Nueva 3 site showing the tusks of the large mammoth known as the "Titan of the Pleistocene".

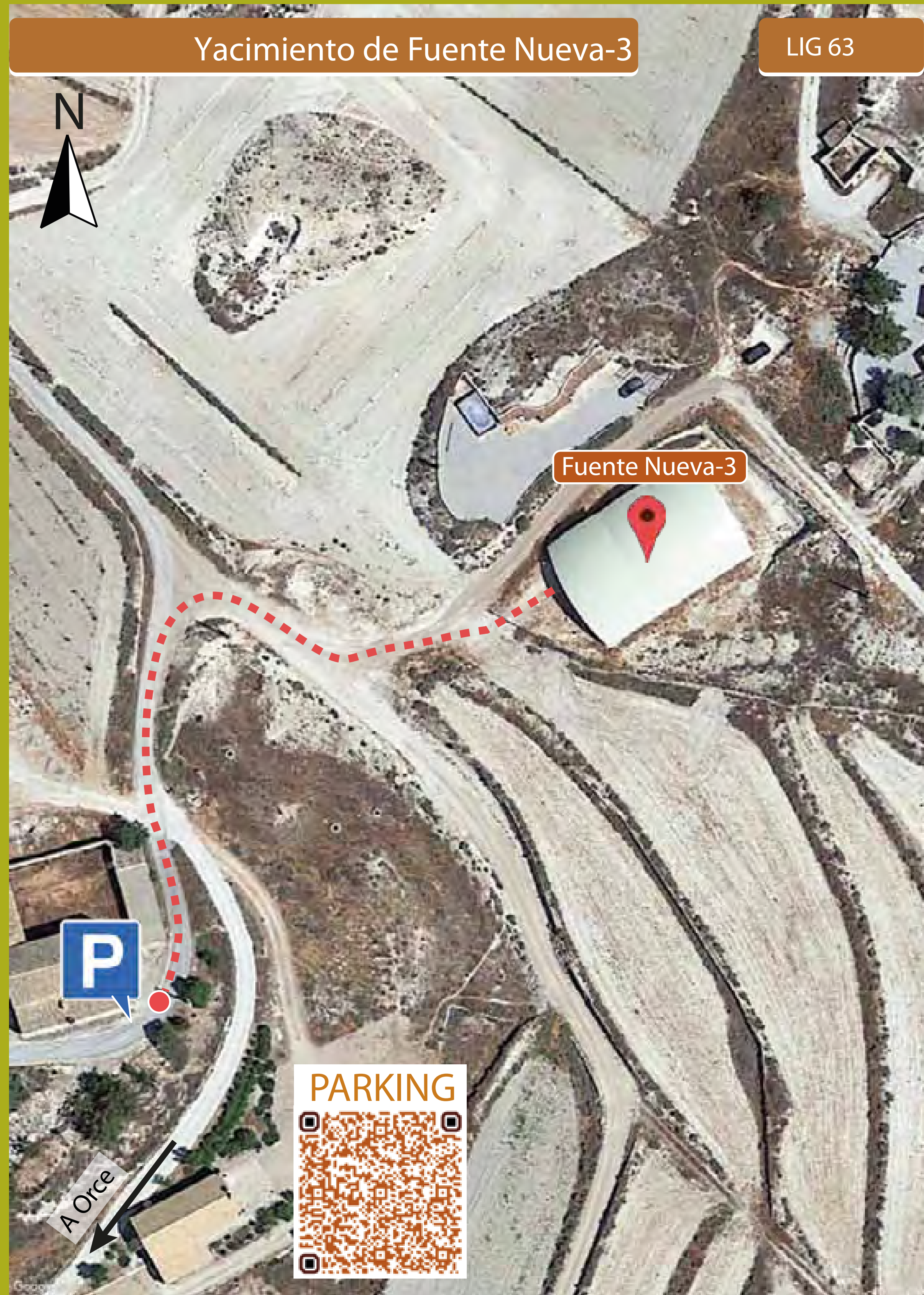
As well as the spectacular macrovertebrate remains, there are a huge quantity of microvertebrates recorded at these sites, including fish, which are crucial for climatic and chronological reconstructions. Thus, almost invisible elements make it possible to generate fundamental knowledge for understanding this remote past. Amphibians and reptiles have enabled us to estimate temperatures (with much milder winters than those we have now) and rainfall (more than double that of today) during the period when the Barranco León and Fuente Nueva 3 sites were formed. Rodents have helped us to pinpoint the time when our ancestors lived in these two places (1.4 million and 1.2 million years respectively).

Other vertebrates at the Orce sites are the following:

> *Allophaiomys* aff. *lavocati*, *Allophaiomys* sp., *Apodemus flavicollis*, *Apodemus mystacinus*, *Castillomys rivas*, *Hystrix* sp., *Mimomys savini*, *Oryctolagus* cf. *lacosti*, *Prolagus* sp., *Galemys* sp., *Sorex minutus*, *Sorex* sp., *Asoriculus gibberodon*, *Crocidura* sp., *Erinaceus* sp., *Chalcides* sp., *Timon* cf. *lepidus*, *Dopasia* sp., *Malpolon monspessulanus*, *Natrix maura*, *Natrix natrix*, *Rhinechis scalaris*, *Testudo* sp., *Discoglossus* cf. *jeanneae*, *Pelobates cultripes*, *Bufo bufo*, *Bufo calamita*, *Hyla meridionalis*, *Pelophylax* cf. *perezi*, *Squalius* aff. *cephalus*, *Squalius* aff. *pyrenaicus*, *Luciobarbus* aff. *sclateri* and *Luciobarbus* aff. *bocagei*.

Although all this archaeo-palaeontological evidence is of paramount interest for the history of humanity, we cannot omit other sources of information contained in the sediments, bones and teeth, which, properly analysed and interpreted, contribute elements of the first importance to reconstructions of the past.

Orce already has five decades of research under its belt. In the past, Tomás Serrano, the owner of this fertile land of Venta Micena, used to find stones that looked to him like bones. In the Garden of the Hesperides, which Strabo located in the south of the Iberian Peninsula, grew the tree on which the golden apples that bestowed immortality ripened. In a sense, after one and a half million years, we can say that the heritage of this sector of the basin and of the Granada Geopark in Orce is immortal. But in order for it to be so, research must continue to contribute to universal knowledge and to the creation of value for the society that sustains it.



7

THE CAPTURE OF THE BASIN AND THE PRESENT LANDSCAPE

The Guadiana Menor in the vicinity of the capture area of the basin

ALBERTO TAUSTE

During the endorheic continental stage of the Guadix-Baza basin (Chapter 4), in the territory of the Granada Geopark, the main river (the palaeo-Fardes) and its tributaries had no outlet to the sea. Under these conditions, instead of producing deep valleys or ravines, the rivers gradually filled in depressed areas with sediments and smoothed out the existing relief. In this way, a surface developed with a very gentle slope from the foot of the mountains towards the centre of the basin, known as a **glacis**, and a landscape similar to the present African savanna was created. That landscape, characterized by a large plain crossed by a main river and its tributaries, and a large lake in the eastern part of the territory, lasted for millions of years (the Pliocene and much of the Quaternary) (Fig. 1).

All this changed approximately half a million years ago, when the most important geological event that has happened here for millions of years occurred: the capture of the Guadix-Baza Basin by the River Guadiana Menor. At that moment, the rivers in the territory found an outlet to the Atlantic Ocean via the Guadiana Menor. The consequences were dramatic, as the Baza lake soon emptied, the sedimentation in the basin gradually disappeared and the sediments that had been accumulating in this area for over 5 million years began to be rapidly eroded. This last stage of the geological history of the Geopark, in which we still find ourselves, is described in detail below.

Figure 1 (next page). **A**. Reconstruction of the former endorheic basin in which the palaeo-Fardes river and the Baza palaeolake are represented. From the last part of the Late Miocene until approximately half a million years ago, the waters of the palaeo-Fardes river and its tributaries had no outlet to the sea and flowed into the Baza palaeolake.

B. Reconstruction of the moment when the basin was captured, approximately half a million years ago. A small tributary of the Guadalquivir, by headward erosion, reached the watershed between the Guadalquivir and Guadix-Baza basins.

C. From that moment, this small tributary became the present Guadiana Menor. The territory of the Geopark was incorporated into the Guadalquivir basin, and the waters (and sediments) drained towards the Atlantic Ocean. For this reason, practically all the Granada Geopark still belongs to a single drainage basin, the Guadiana Menor Basin, with a single outlet for the runoff waters via that river. It is surprising to find that the River Almanzora, with a much more direct course towards the Mediterranean, lost the battle to capture the basin and has still not managed to cross the watershed.

Figure 2. Panoramic Google Earth view looking south with the three main landscapes of the Granada Geopark: (1) **mountains** (basement), (2) **glacis** and (3) **river valleys**, including the badlands relief.

A major part of the large plain (glacis) that is still preserved can be recognized in the image. You cross the glacis when you take the northern branch of the A92 between Guadix and Baza, for example. If you look at it carefully in panoramic view you can see that it actually has a slight slope, with altitudes from around 900 metres in the central parts of the basin to over 1000 metres in the vicinity of the mountains.

Following the capture of the Guadix-Baza Basin, erosion began to predominate over sedimentation in the territory of the Geopark. The sedimentary basin ceased to be active and became the current drainage basin of the Guadiana Menor (Figs. 1B and 1C). Since then, that plain (glacis), which dominated the landscape for several million years, has been undergoing erosion (Fig. 2). Traces of that former landscape can still be recognized at the edges of the basin, between the mountains and the central part of the Geopark. Below this surface the river valleys of the Granada Geopark have developed. The main river, the Guadiana Menor, and its tributaries (Rivers Baza, Guardal, Fardes, Castril, Guadalentín, etc.) have downcut by eroding the sediments that filled the basin, forming the most characteristic and spectacular landscape of the Geopark, its **badlands**.

After the capture, sedimentation was limited to alluvial deposits close to the uplands near the basin margins and to deposits on valley bottoms, which have gradually generated several levels of **river terraces**. Moreover, the presence of thermal springs has produced several travertine platforms on some of those terraces, such as those at the **Alicún de las Torres** and **Zújar Thermal Baths**, which, along with the badlands and some particularly remarkable valleys such as those of the **River Gor** and **River Guardal**, represent the main sites of geological interest (SGIs) described below.

When the capture of the basin took place and the erosion that created the Geopark's characteristic landscape began

At present, the precise moment when the capture took place is not known, but there is a great deal of evidence pointing to an age of around half a million years.

The glacis surface formed on sedimentary rocks of very different ages. At some points it is located on the most recent sediments that filled the basin, but at others, as in Baza and Zújar, it lies over sediments that are more than two million years old. Therefore, to determine the age of this crucial moment in the history of the Geopark we need to take account of the age of the most recent endorheic sediments and of the oldest exorheic sediments. In this way we will be able to obtain a maximum and minimum age for the capture, and the narrower this interval is the more precise the result will be.

THE MOST RECENT ENDORHEIC SEDIMENTS

In the endorheic sedimentary infill of the Guadix-Baza basin more than 150 palaeontological sites of fossil vertebrates have been located. Most of them have been known for more than 30 years and their ages have been reviewed in numerous scientific articles. Almost all researchers that have worked on them agree that the most recent are those of Solana del Zamborino, Cúllar-Baza and the Loma Quemada, Puerto Lobo and Huéscar 1 group. Their ages range from 750,000 to 500,000 years. An exception is the Solana del Zamborino site, to which some authors assign ages between 300,000 and 480,000 years, while others consider it to be older. .

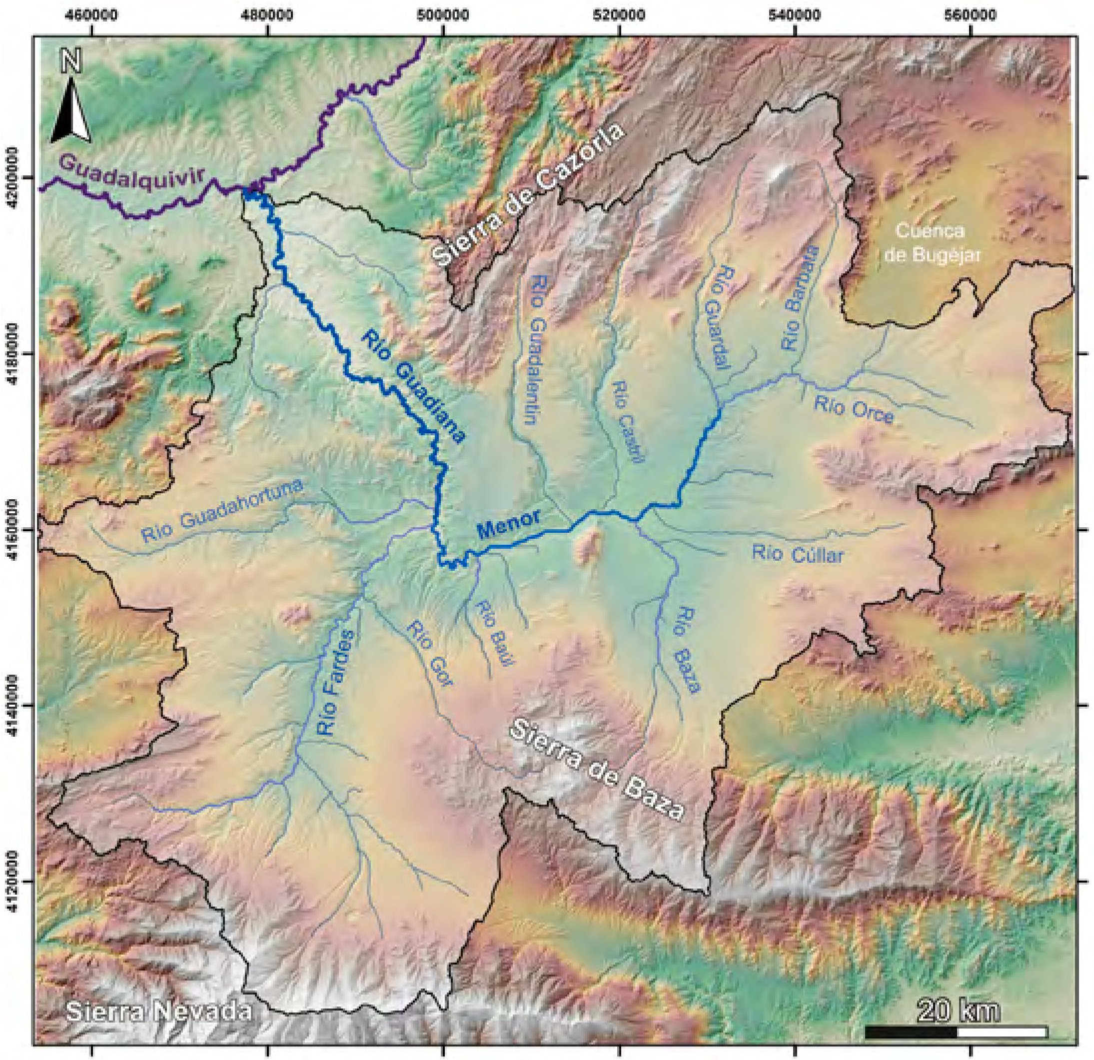


Figure 3. Drainage basin of the Guadiana Menor.

THE OLDEST EXORHEIC MATERIALS

The oldest exorheic materials dated up to now are the travertines of the Zújar thermal baths, at 240,000 years. These deposits rest on even older river terraces and travertine platforms, which are downcut more than 250 metres below the glacis, within the present Guadiana Menor valley (see Figure 8B in the section devoted to the Alicún de las Torres and Zújar Thermal Baths). This means that when they were formed, the basin had already been exorheic and subjected to erosion for a long time.

Taking the foregoing data into account, **the capture must have occurred approximately half a million years ago**. Nevertheless, although there was a moment when the basin was captured, its effects on sedimentation and on the breakup of the glacis surface in sectors remote from the capture zone, or in areas affected by active faults that produced small depressions with sedimentation, must have been diachronic. This could be what happened at Solana del Zamborino, which, being located on the downthrown block of an active fault, could have accommodated sedimentation once the capture had taken place.

As soon as the basin was captured, the sediments that had accumulated in it for millions of years were eroded and transported by the local rivers to the Guadiana Menor, and later to the River Guadalquivir, which finally carried them to the Atlantic Ocean (Figs 3 and 4).

Figure 4. Route of water and sediment from the Granada Geopark to the Atlantic Ocean.

THE BADLANDS OF THE GRANADA GEOPARK

SGI 01, 02, 03, 04, 05, 44, 52, 58

The **badlands landscape** is undoubtedly one of the hallmarks of the territory of the Granada Geopark. Located in the central part of the Geopark, away from the main roads, it is a rugged landscape, made up of thousands of ravines of various sizes, which have been formed by water erosion during the last half a million years. Visitors can see that geology is alive in this region and can imagine how the relief has evolved in the most recent past and how it will evolve in the coming millennia (Fig. 1).

There are places on the planet that are famous for this type of landscape. Located mostly in the American West, they attract hundreds of thousands of visitors every year. It was precisely in that part of the world that the first colonists of those lands coined the term *badlands* to refer to an arid territory, wild and hostile to inhabit, cultivate or simply traverse. However, far from the original negative connotations of the term, this landscape is arousing increasing interest, among both tourists, for its beauty, and scientists, for its biodiversity and geodiversity. Although the term *badlands* is accepted by the international scientific community, in Spain the expression *paisaje de cárcavas* ("gully landscape") is also used.

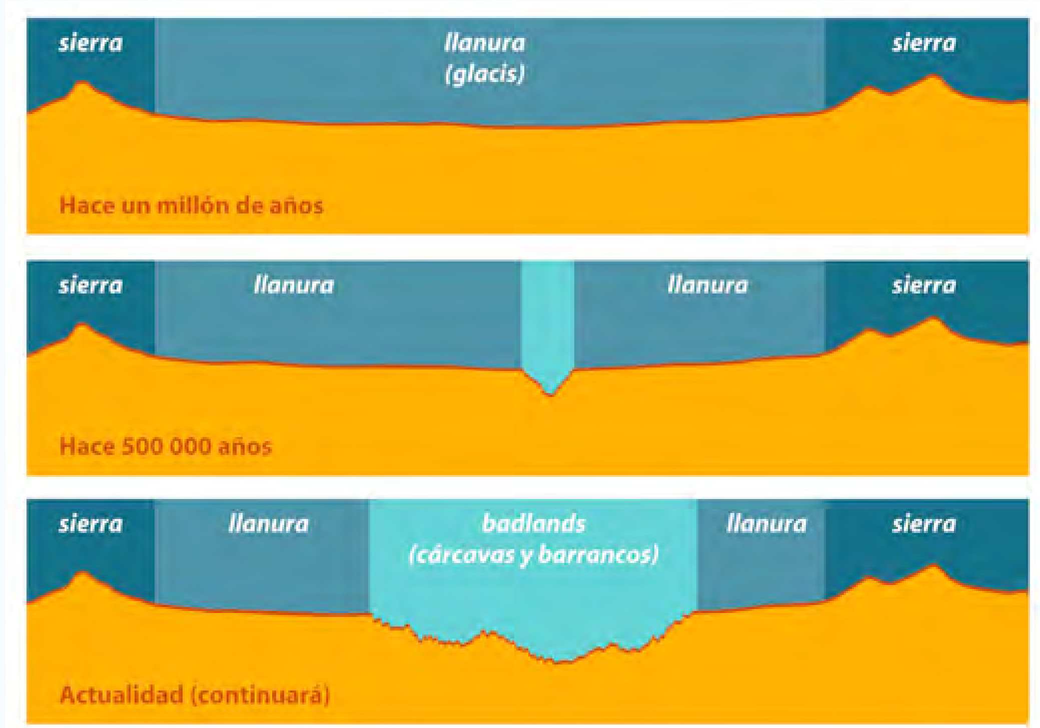


Figure 1. **A**. Schematic illustration of the development of the badlands landscape in the Granada Geopark. This landscape began to form only half a million years ago. Previously, there was a large plain or *glacis*, surrounded by mountains, which occupied practically the entire territory of the Granada Geopark. Half a million years ago, a small river, a tributary of the Guadalquivir (the palaeo-Guadiana Menor), entered this territory, becoming the present Guadiana Menor. From then on the "great plain" (*glacis*) began to be eroded.

B. Example of badlands landform in the vicinity of Bácor-Olivar.

Where and how do badlands form?

There are many factors that influence the formation of this landscape, but the two main ones are the ground type (sediments and rocks) and the climate.

GROUND TYPE: badlands are formed due to erosion by rainwater on grounds that are essentially impermeable and soft and therefore easily erodible. Grounds consisting of sediments of the clay "family" are the most suitable. These impermeable substrates cause rainwater to run over the surface instead of infiltrating it, favouring erosion.

CLIMATE: although it is not always the case, badlands form mainly in semiarid climates, where the low rainfall tends to be concentrated in a few days per year, with episodes that can be very intense.

Some studies indicate that annual rainfall of around 300 litres per square metre is the most conducive to the successful development of this landscape. This quantity of water inhibits the growth of vegetation, which serves to protect the ground against erosion. Higher rainfall encourages the development of vegetation, which impedes erosion, and lower amounts have less erosive capacity. Indeed, average annual rainfall in the Granada Geopark is close to that key amount of 300 litres per square metre.

In the Granada Geopark there is a third factor that influences the large-scale development of badlands: the **difference in mean altitude** between the badlands territory and the River Guadalquivir valley, which is where all the rivers in the Geopark flow to via the Guadiana Menor (Figs 2 and 3).

The set of channels (streams, gullies and ravines) through which the water flows constitute the **drainage network**. In badlands landscapes this drainage network is very dense, with a tree-like morphology, including a trunk, some main branches and numerous secondary branches (Fig. 4). In the Granada Geopark, the main watercourse is the River Guadiana Menor and some of the main branches are the Rivers Fardes, Gor, Baza, Cúllar, Orce, Barbata, Guardal and Castril.

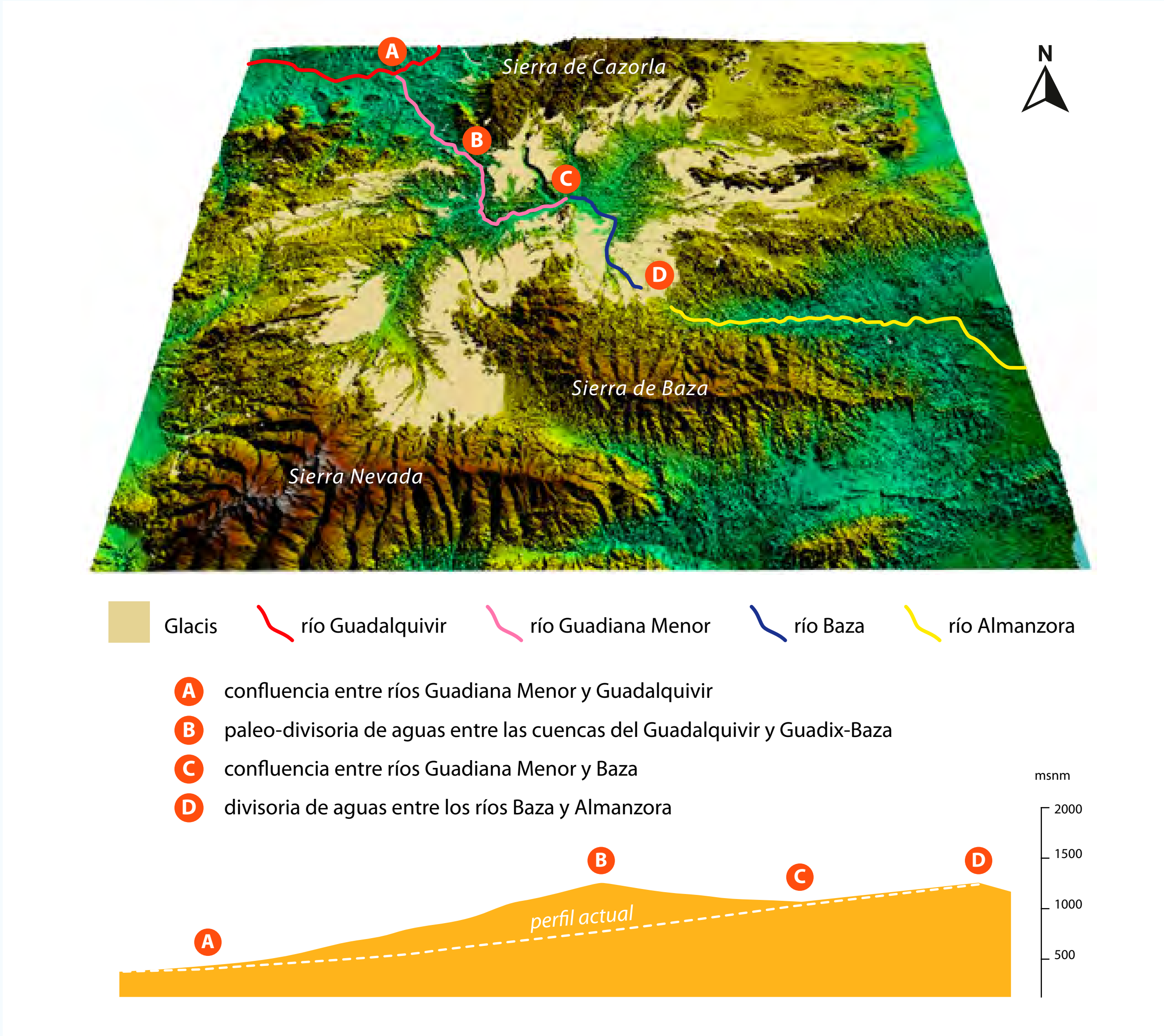


Figure 2. Above: This digital model of the terrain shows the current courses of the Rivers Guadiana Menor, Baza and Almanzora. Circle B represents the approximate position of the palaeo-watershed between the Guadalquivir and Guadiana Menor basins half a million years ago.

Below: Approximate reconstruction of the topographic profile corresponding to the palaeo-watershed (vertical scale x5). Note how the great plain that dominated the territory lay some 500 metres above the confluence of the Guadalquivir and the young Guadiana Menor. When the River Guadiana Menor reached the great plain, on an erosional southward journey from the Guadalquivir, it joined two territories with a large topographic difference in height. Therefore, the new drainage network, which had just come into existence in the region, had a large gradient and high erosional power, producing deep valleys which evolved into our current landscape. And they are still doing so today.

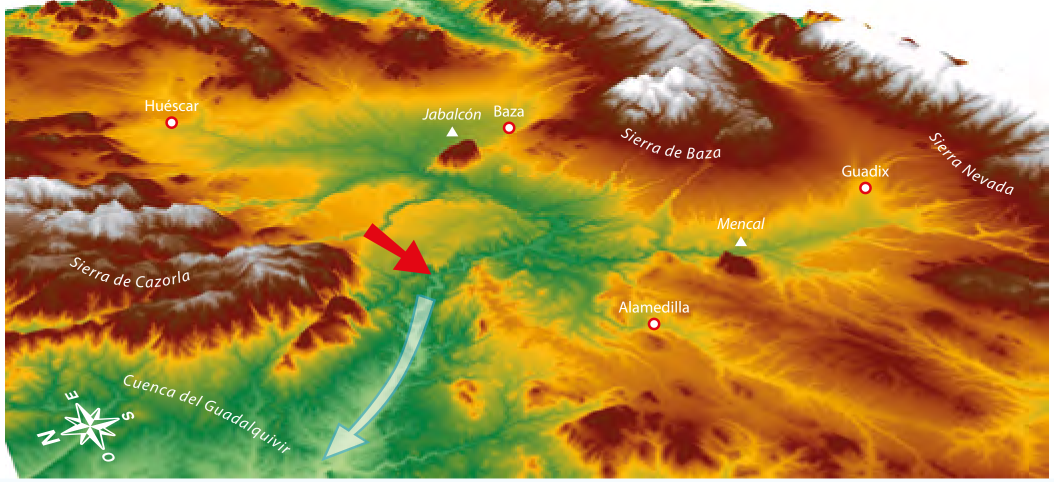


Figure 3. The red arrow indicates the approximate point where the capture of the Guadix-Baza Basin and its incorporation into the Guadalquivir Basin took place. The former River Guadiana Menor started with a difference in elevation of over 500 m relative to the watershed between the Guadalquivir and Guadix-Baza Basins, giving great energy to the headward erosion. This is also why when the basin was captured by the Guadalquivir drainage network, the glacis began to break up very rapidly, as it was topographically very high relative to its new base level.

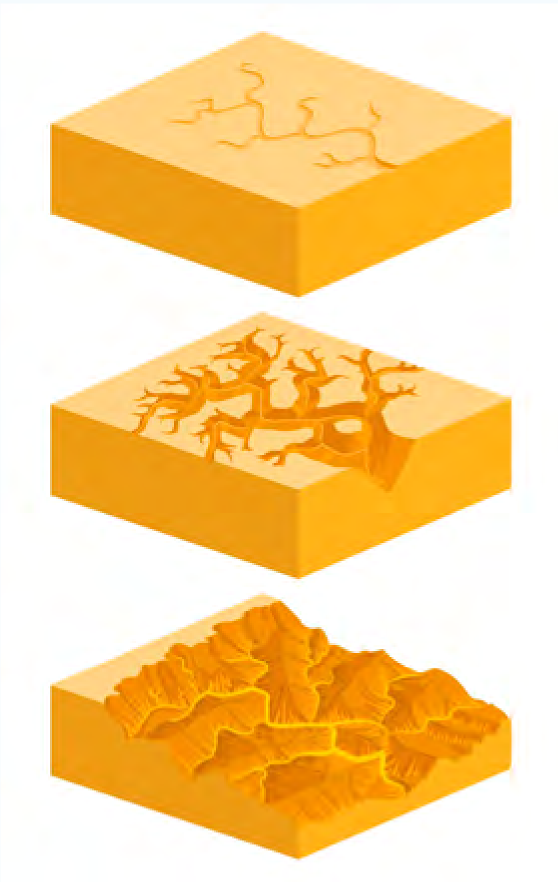


Figure 4. Evolution of the badlands landscape.

In impermeable materials, which are very abundant in the endorheic sediments of the Granada Geopark, the rainwater runs over the surface and is concentrated in small rills. Downstream, the flow and erosive capacity of the rills will increase. Over time, these little streams turn into gullies, growing larger and larger, until they become the spectacular ravines that dominate the badlands landscape of the Geopark.

Variety in the badlands landscape of the Granada Geopark

The badlands that are spread over much of the Granada Geopark share general features, such as sparse vegetation, rugged topography, abundant ravines (a dense drainage network), steep slopes and a soft substrate. But despite their similarities, a more detailed look enables us to see some features that make them different and unique. The differences between them are controlled by the type and mixture of sediments that predominate in each area, which in turn produce different colours and shapes in the relief. The grain size of the sediments, from sands to clays, or the presence of harder layers that are more difficult to erode (limestones and conglomerates) interspersed between the softer layers of marls, sands or shales, produce variations in the badlands landscape within the Granada Geopark (Figs 5–10):

Figure 5. **A**. The western sector of the Geopark has mainly reddish colours. **B**. The eastern sector of the Geopark has mainly whitish colours.

LACUSTRINE AND MARINE SEDIMENTS

With a predominance of marls in the substrate and of whitish colours. This group includes the Dehesas de Guadix badlands in the western sector (SGI 03) and the Castilléjar and Galera badlands in the eastern sector (SGI 58). .

Figure 6. Above: Dehesas de Guadix badlands.
Below: Badlands between Galera and Castilléjar.

FINE DETRITAL SEDIMENTS

Clays and silts. Badlands on sediments of this type are well developed in various places within the Geopark. Worth highlighting among them are those in the Gorafe and Bácor-Olivar sector, where greyish-brown colours predominate, and the Negratín and Guadiana Menor sectors, where the predominant tones are reddish-brown. In this type of sediment, abundant ravines usually develop, separated by sharp interfluves.

Figure 7. Above: Gorafe and Bácor-Olivar badlands.
Middle: Negratín badlands.
Below: Guadiana Menor badlands.

BADLANDS AND STRUCTURAL RELIEFS

The presence of more resistant rock layers alternating with the softer ones favours the development of a landscape reminiscent of the Colorado River Canyon in Arizona (United States). It is called tabular or stepped relief, where the horizontal arrangement of the layers may continue for miles. In the western sector of the Granada Geopark these more erosion-resistant levels are layers of conglomerates, and in the eastern sector they are predominantly of limestones.

Figure 8. Shelves, ledges and slopes typical of structural reliefs.
Above: structural reliefs in fluvial sediments in the Desierto de los Coloraos (Gorafe).
Below: structural reliefs in lacustrine sediments in the eastern sector (Orce).

LAND FORMATION BY PIPING OR TUNNEL EROSION

The surface presence of sands, mudcracks, small fractures and holes facilitates the infiltration of part of the rainwater and the formation of underground conduits which eventually collapse and turn into gullies, with spectacular vertical development.

The process begins with the infiltration of part of the rainwater in one of the following situations: presence of permeable sandy strata, existence of mudcracks in clayey or marly grounds, small fractures, cracks in the slopes (due to instability produced by gravity), animal holes or plant roots.

The finest particles are swept away by the water, forming underground conduits that gradually increase in size (erosion tunnels or pipes). The growth of these erosion tunnels eventually produces subsidence in the terrain, leading to the creation of surface gullies, which evolve by surface water erosion like other badlands (Figs 9 and 10).

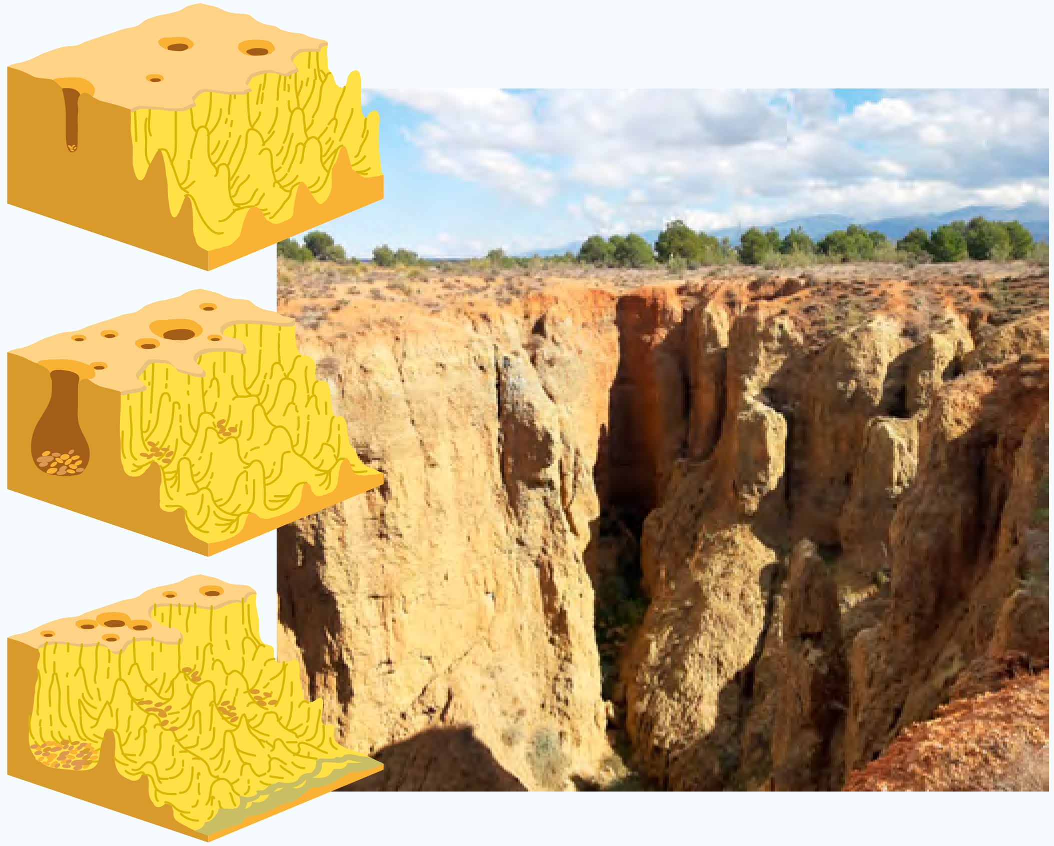


Figure 9. Model of the development of tunnel erosion or piping.

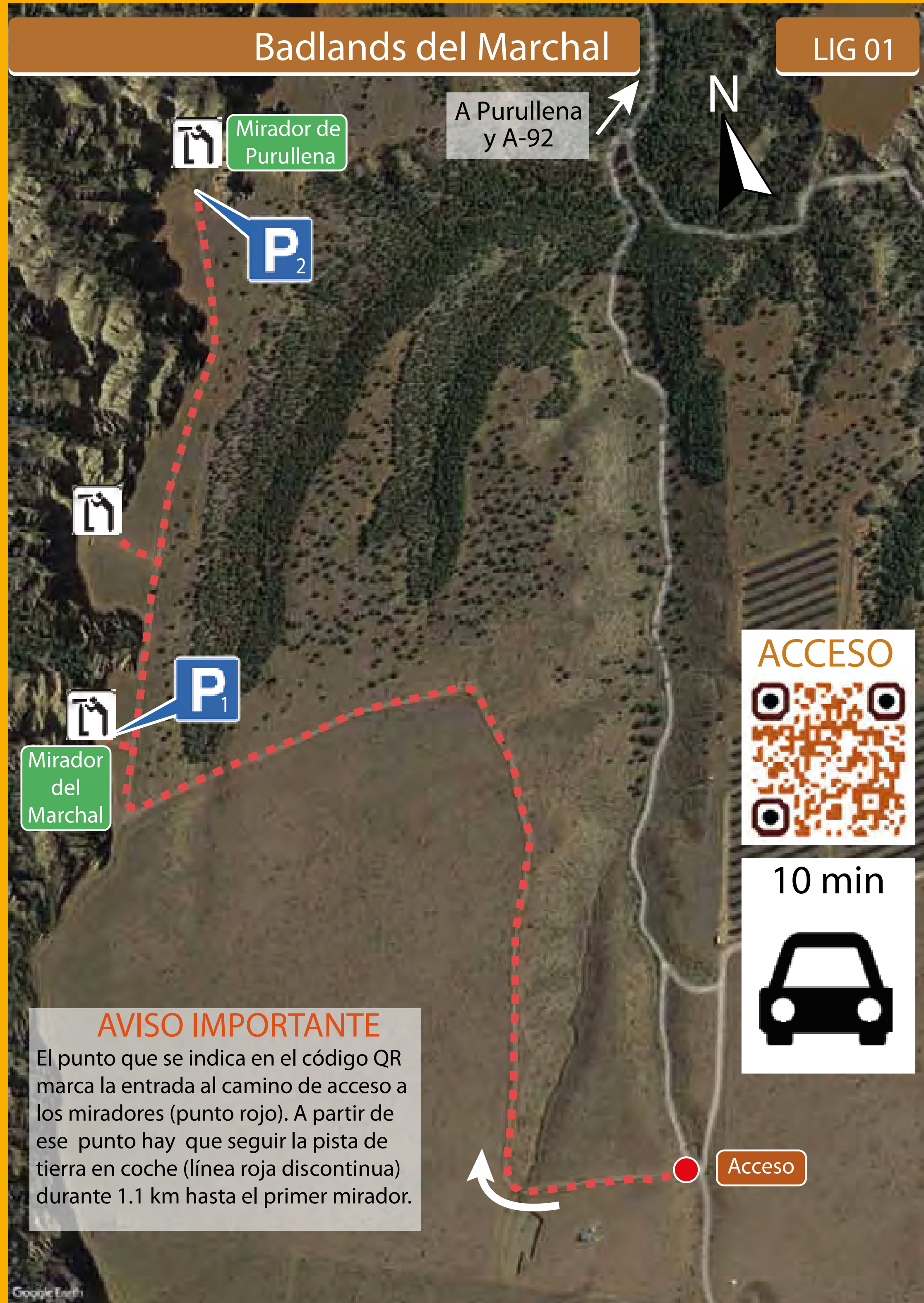
Figure 10. In these sectors we can see that the gullies do not have the typical appearance with sharp crests, but rather more or less rounded areas separating the ravines, semicircular heads of ravines and abundant hills in the shape of residual mounds.

DID YOU KNOW...?

Some scientific studies have shown that the erosional power of the piping process is much greater than was thought. The process is facilitated by (1) the occasional and/or cyclical occurrence of torrential rain, (2) dry periods that favour the appearance of cracks in the substrate, and (3) the alternation of horizontal layers with lithologies of different permeability and cohesion.

These features are common in many sectors of the Granada Geopark, and this favours the development of piping landscapes.

Another outstanding place to observe the badlands landscape generated by the piping process is the Cerro Kabila Viewpoint and its surroundings, in Benalúa (see location map).

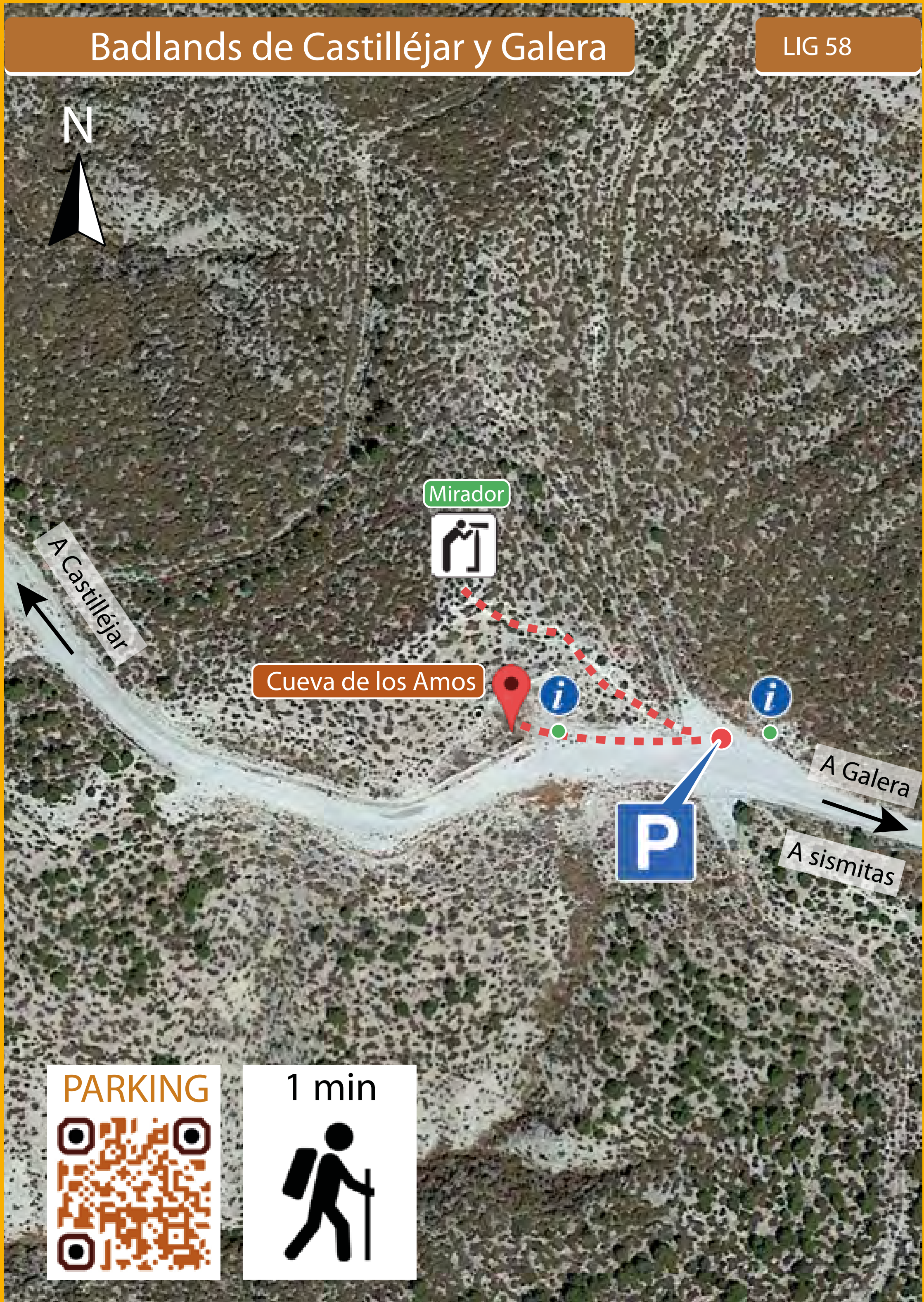


Badlands de Dehesas de Guadix
LIG 3
Paisaje de Badlands
N
Dehesas de Guadix
A Villanueva de las Torres
P
Mirador de San Bernardino
A Alicún de Ortega
A Pedro Martínez
PARKING

Badlands de Gorafe y Bácor-Olivar
LIG 04
N
Mirador de Don Diego
P
A N-342
PARKING
1 min


Badlands del Negratín
LIG 05
N
Mirador
P
A A-315
A A-315
PARKING
2 min


Badlands de Benalúa
LIG 44
N
Mirador
del Cerro Kabila
P
AVISO IMPORTANTE
El punto que se indica en el código QR marca la entrada a la calle de acceso al mirador (punto rojo). A partir de ese punto hay que tomar la calle de la derecha y seguir en coche durante 400 metros (línea roja discontinua) hasta el parking, desde donde se sube a pie al mirador.
Benalúa
Acceso
ACCESO
2 min



GEOPARQUE GRANADA

THE RIVER GOR

A RECENT HISTORY OF EROSION AND SLOPE INSTABILITIES

SGI 25

Between the towns of Gor and Gorafe, where the road begins its descent from the surface of the glacis to the bottom of the River Gor ravine, the greatest concentration of megalithic monuments in the area can be found. At this point the Gor valley increases abruptly in width from 400 m to 750 m (Fig. 1).

There is also a sudden increase here in the thickness of the Plio-Quaternary sedimentary infill, which goes from a few metres to almost 200 metres.

In this place we find the answers to the following questions: *What causes this change in the thickness and incision of the Gor valley?* and *What surface processes induce this increase in the cross-section of the Gor valley*?

As we can see in the geological section in Figure 2 (along the bottom of the ravine), the sedimentary infill of the Guadix-Baza Basin is made up of coarse-grained alluvial sediments in the upper parts (conglomerates, gravels and sands) that transition to finer materials (sands, silts and clays). This abrupt change in the widening of the Gor valley may be due to a change in the relief of the basement or to the existence of a fault. Both hypotheses would explain the sudden descent of the ancient rocks of the substrate (Fig. 2).

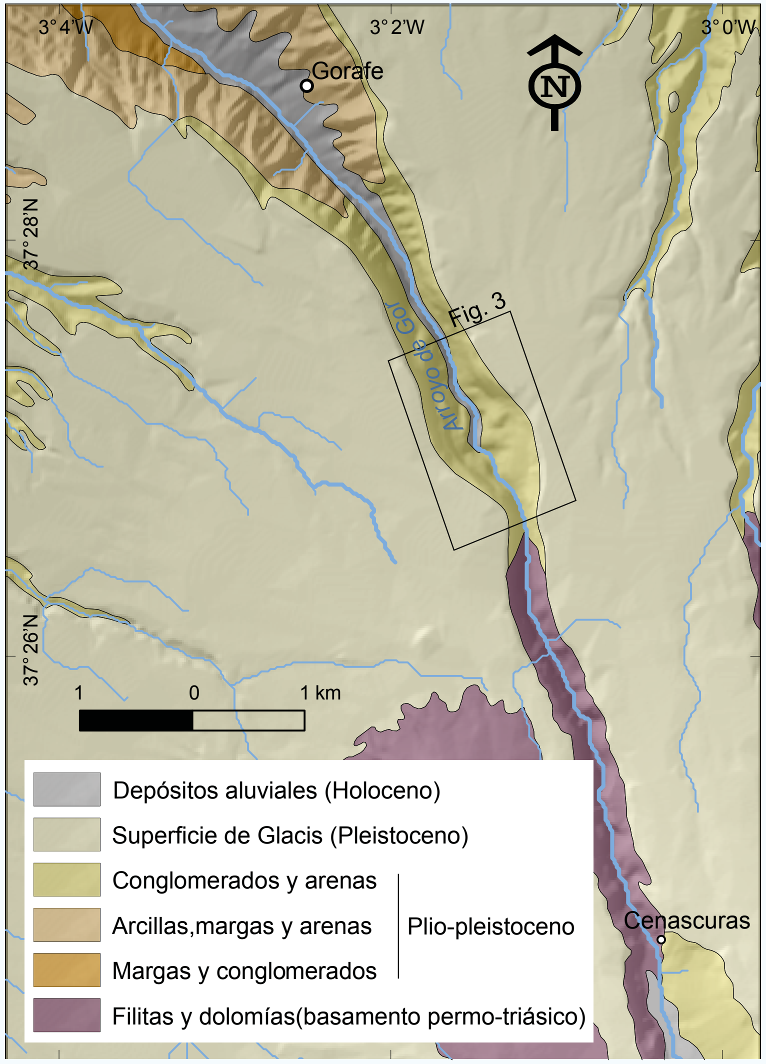


Figure 1. Geological map of the Gor valley and its surroundings showing the increase in downcutting in the boxed area (Fig. 3), and also the widening of the valley's cross-section.

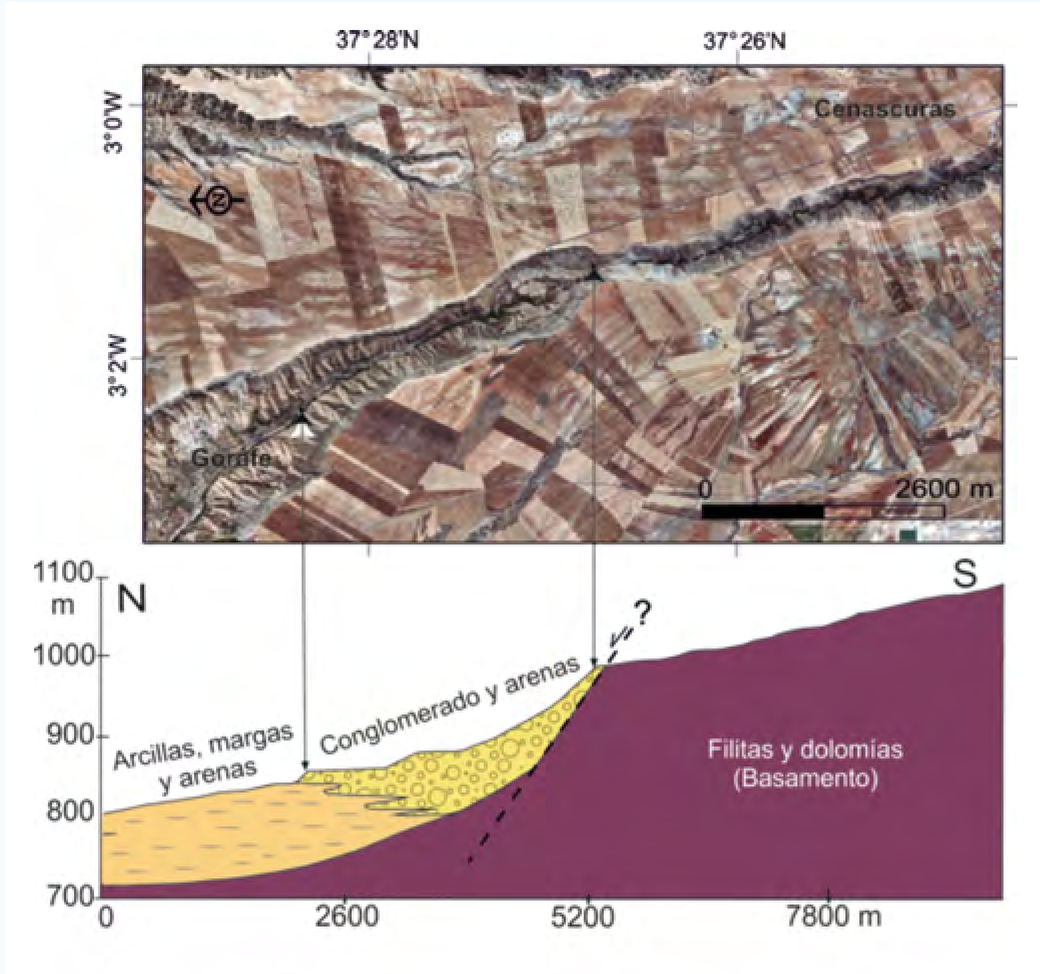


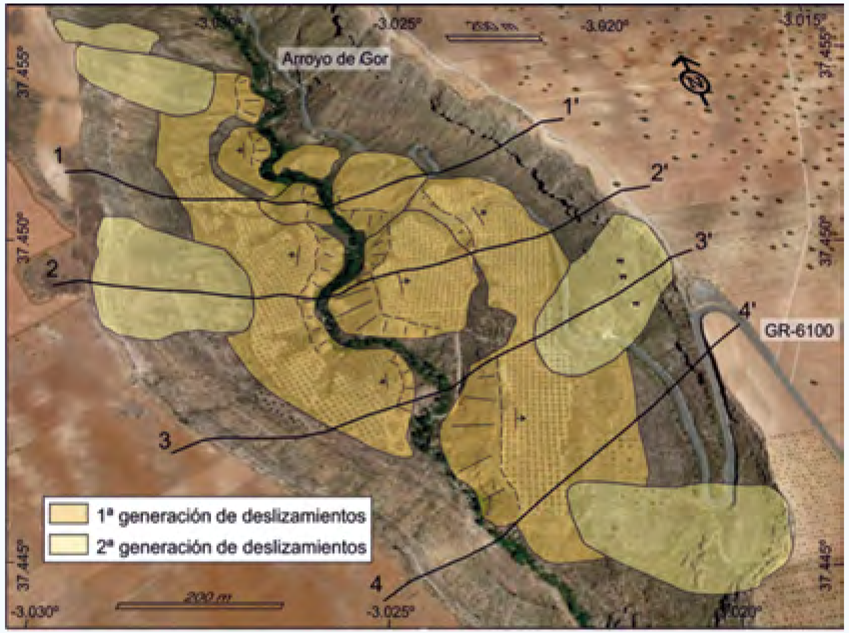
Figure 2. Geological section along the line of the River Gor.

Slope instabilities as incision and erosion mechanisms of the bed of the River Gor

On the slopes of the River Gor there are numerous lobes with a lenticular geometry in plan view. In some cases, moreover, a slight rotation of the layers can be observed within these lobes. Both features are evidence of the existence of blocks that have slid down the slope (Fig. 3). The surfaces on which these slope movements occur are curved. This curved geometry is induced by the rotational component of the layers (Figs 4 and 5).

The topographically lowest landslides are the oldest, although the current erosion of the River Gor still keeps them active. The movement of the lower landslides undermines the topographically higher ones, which are consequently also reactivated. This sequential movement creates tensions in the upper part producing semicircular cracks in the terrain.

The mechanism by which the valley is widened is shown schematically in Figures 3 and 4. The rotation of some of the dolmens built on the sliding mass shows that this slope creep movement has remained active for the past 6,000 years. The driving force behind this movement is the erosion produced by the River Gor at the foot of the landslides. Moreover, reduction of the resistant properties of the clayey strata at the base of the sedimentary sequence through water saturation during rainy periods also accelerates these movements.



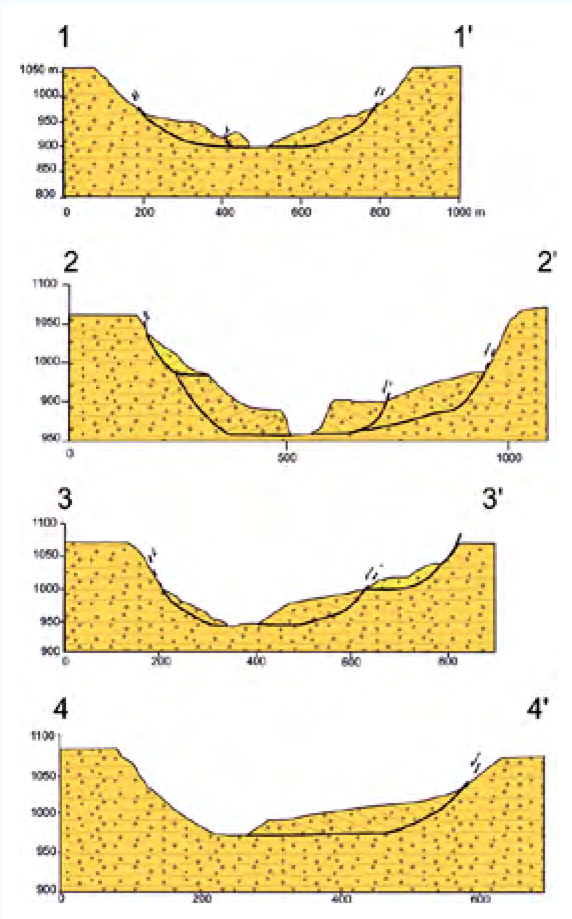


Figure 3. Rotational landslides in the River Gor valley.

Cross profiles showing the geometry of the landslides in the River Gor valley.

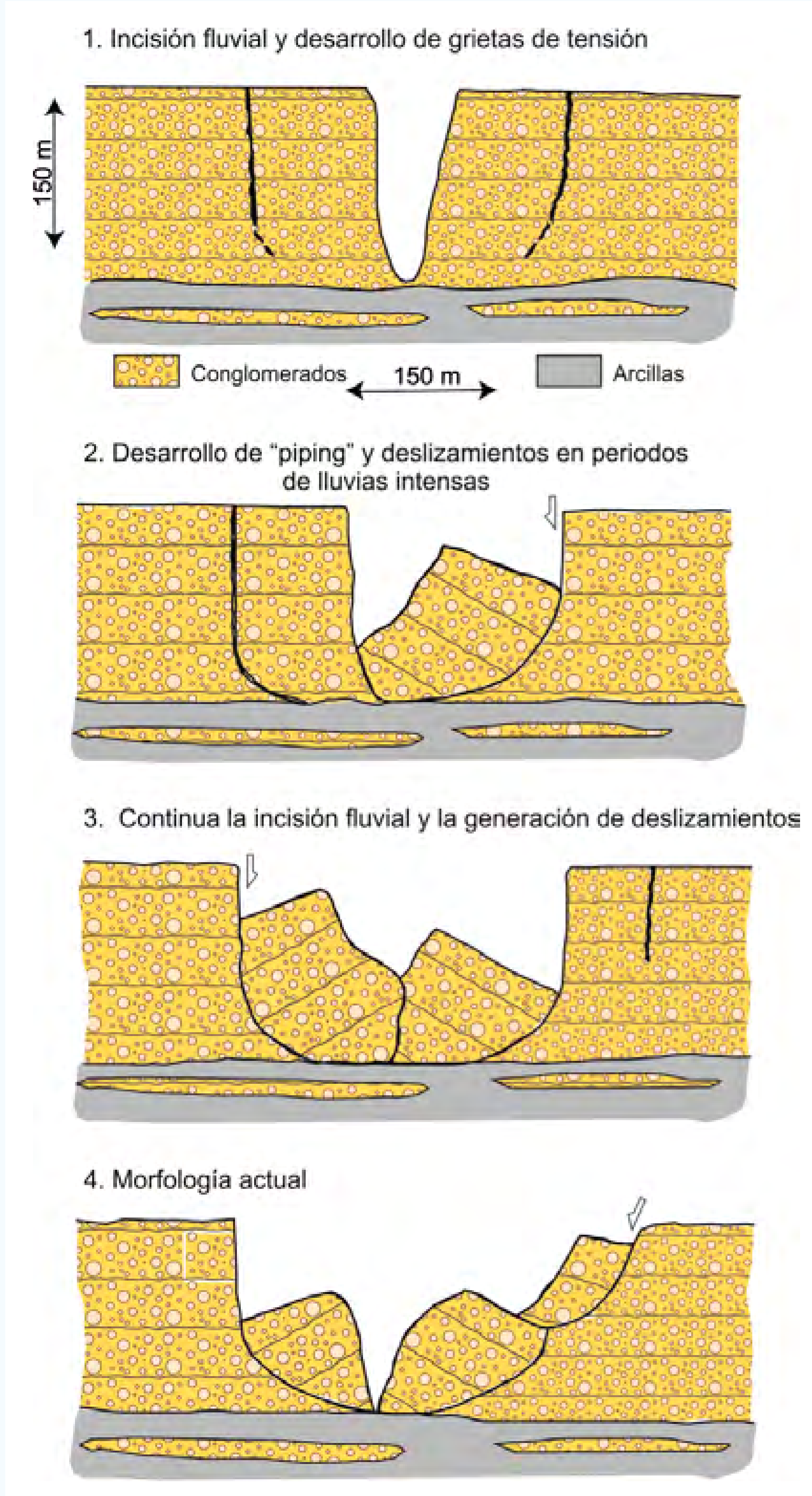
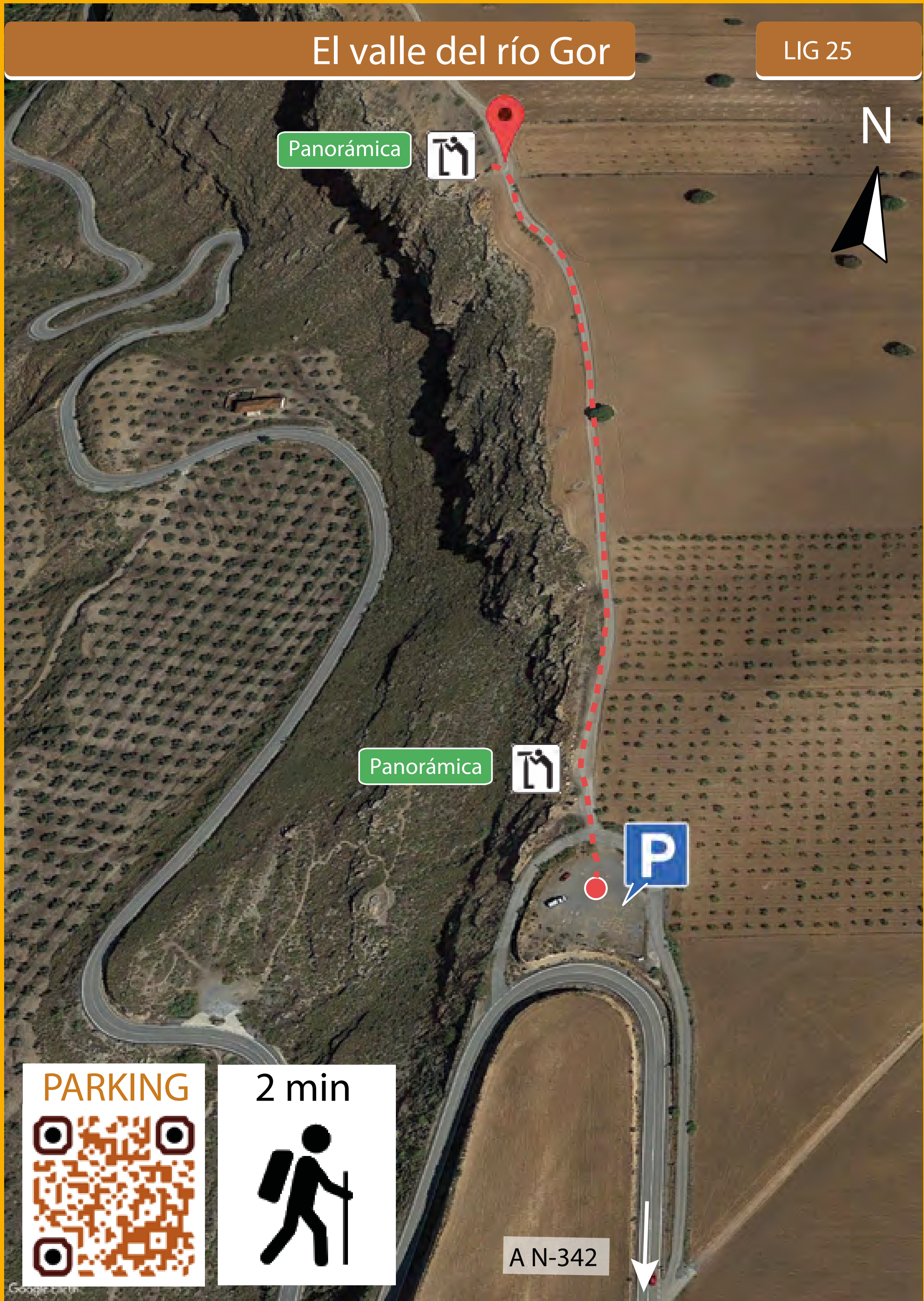


Figure 4. Schematic representation of rotational landslides in the River Gor valley.



GEOPARQUE GRANADA

ALICÚN DE LAS TORRES AND ZÚJAR THERMAL BATHS

HOT SPRINGS, TRAVERTINES AND THE TORIL AQUEDUCT

SGI 20, 42

In the Granada Geopark there are numerous springs associated with carbonate-rock aquifers, and a few of them are thermal springs. Three are used as spas: the Alicún de las Torres Baths (Fig. 1), the Zújar Baths and the Graena Spa.

Because of their geodiversity, the Alicún de las Torres and Zújar baths are described below, although the general hydrogeological issues described for them are similar and also enable us to understand the nature of the Graena spring.

Brief historical notes

The Alicún de las Torres and Zújar Thermal Baths were declared to be of public benefit in 1869, but use of their waters dates back at least to Roman times. However, in view of the abundant archaeological remains that are more than 3,000 years old in the vicinity, these thermal waters were probably exploited earlier.

At the Zújar Baths quite sophisticated facilities were already built for their use in the Roman period and

Figure 1. Thermal waters flowing along the Toril aqueduct at the Alicún de las Torres Baths. This area is known as "The Green Waterfall".

were maintained and updated in the Middle Ages and subsequently. A period of great splendour for the Zújar Baths came in the eighteenth century, when a building that was to be a hotel as well as a spa was constructed. It even acquired a casino, and also rural apartments outside the grounds to accommodate people who could not afford the hotel. Today, alongside the facilities that were submerged by the waters of the Negratín Reservoir, there is a restaurant, whose terrace has magnificent views of the reservoir (Fig. 2). The thermal waters, which flowed naturally in the past, are now pumped to a narrow, elongated pool above the area flooded by the reservoir, in a setting with spectacular scenery and geological diversity. Some two kilometres to the west of the historical baths a new, sophisticated spa has been built, also utilizing the thermal waters by pumping them through boreholes.

In the case of the **Alicún de las Torres Baths**, after a long period with basic facilities dating from the Roman era and even near-abandonment after the medieval period, from the beginning of the nineteenth century they had facilities capable of accommodating more than 100 people (Fig. 3). Today, the Alicún de las Torres Spa has a hotel and a complex of pools, restaurant and barbecues. Since January 2008 it has been designated an Asset of Cultural Interest because of the archaeological area in its surroundings.

Figure 2. Panoramic view of the Negratín Reservoir looking west. The former Zújar baths have emerged as the water level of the reservoir has dropped dramatically.

Figure 3. Panoramic view of the Alicún de las Torres Spa Hotel from the upper travertine platform. In the centre to the right the first section of the Toril aqueduct can be seen.

Origin of the thermal waters in the Granada Geopark

The geochemical and hydrogeological studies conducted on the waters of the Alicún de las Torres and Zújar springs indicate that they largely come from the Sierra de Baza, since the rainwater infiltrated into the Cerro de la Raja and Jabalcón is insufficient to supply the flow rates of close to 100 litres/second in both areas (Fig. 4).

The temperature of the water in the springs is around 35 °C. However, the studies performed on the geochemistry of the water at Alicún de las Torres and the temperature measured in boreholes at a depth of 120 metres around the Zújar baths indicate that the temperature of the water in the reservoir it comes from is over 50 °C. These waters have circulated at depths of several hundred metres, where the geothermal gradient gives them a thermal character (Fig. 5). During their ascent to the surface, they have been partially cooled and mixed with colder waters, but the ascent is fast enough to keep the temperature at 35 °C.

This ascent is possible due to the state of confinement of deep waters, which circulate under pressure beneath impermeable layers until they encounter highly fractured fault zones that provide them with an escape route to the surface (Figs 5 and 6).

Figure 4. Panoramic view of Cerro de la Raja. The thermal waters come to the surface through the fault that forms the small mountain front of Cerro de la Raja.

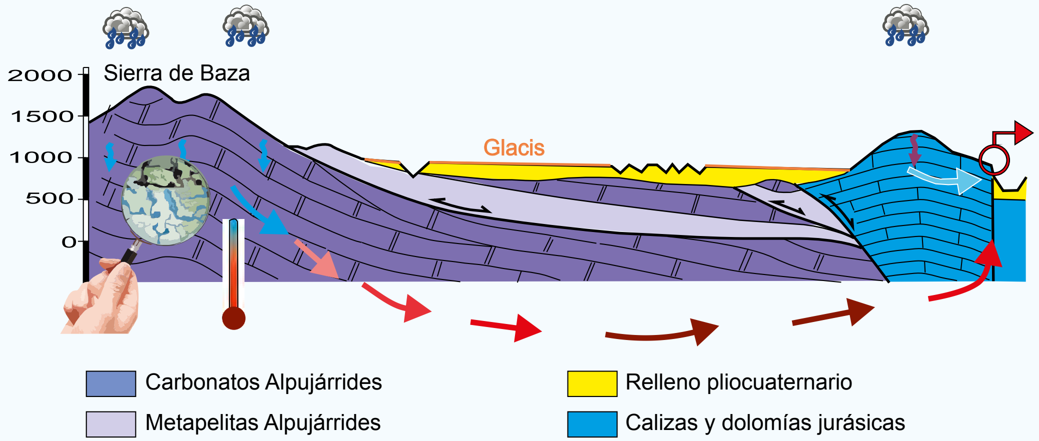


Figure 5. The geothermal gradient is the increase in temperature with depth. In the Earth's crust it usually increases by 1 °C every 33 metres (around 30 °C for every kilometre we descend).

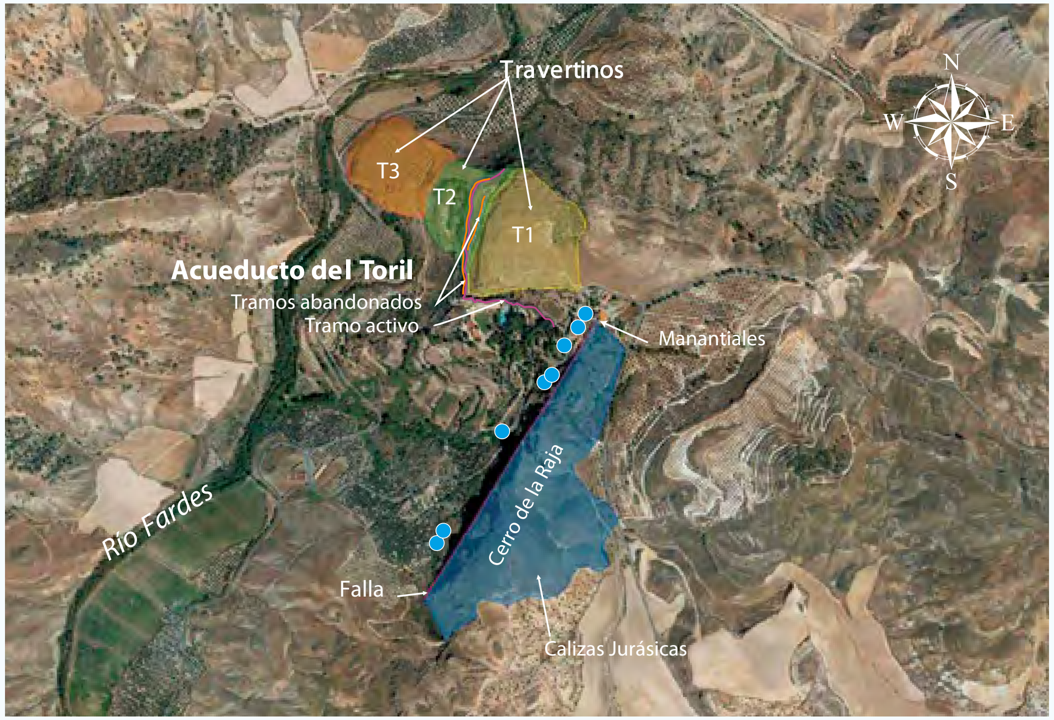


Figure 6. Location of the thermal springs at the Alicún de las Torres Baths (blue dots). The springs are aligned along the Cerro de la Raja fault. The three main travertine platforms and the Toril aqueduct are depicted.

The travertines

The thermal waters of the Alicún de las Torres and Zújar spas are highly mineralized. This means that they carry various dissolved chemical components that can precipitate and form minerals and rocks. Some of these components are dissolved salts: sulphate, chloride, bicarbonate and calcium. When the water emerges from the springs, these last two chemical components are precipitated in the form of calcium carbonate, and this process is responsible for forming a rock called *travertine* (Fig. 7).

Figure 7. When the waters of the Alicún de las Torres and Zújar springs emerge at the surface, they cool and decompress. This leads to a loss of the carbon dioxide gas that they carry in solution, an increase in pH and a disequilibrium in the degree of calcite saturation. The result is that some of the salts they carry in solution precipitate in the form of calcium carbonate. The precipitation of calcium carbonate occurs in turbulent areas, where the water flows fast and there is abundant vegetation. Consequently, the precipitates envelop the stems and branches of the plants, fossilizing them and giving rise to travertines.

How long have the thermal springs existed?

When did the travertines form?

In the vicinity of the Alicún de las Torres and Zújar springs there are very old travertines intercalated between sediments from the endorheic stage. This means that before the capture there were already thermal springs in the region. However, the best travertine outcrops formed when the basin was already exorheic.

These travertines form almost horizontal platforms staggered at different heights (Figs 6 and 8). For their formation they took advantage of the flat and almost horizontal morphology of river terraces previously generated by the Rivers Fardes and Guadiana Menor.

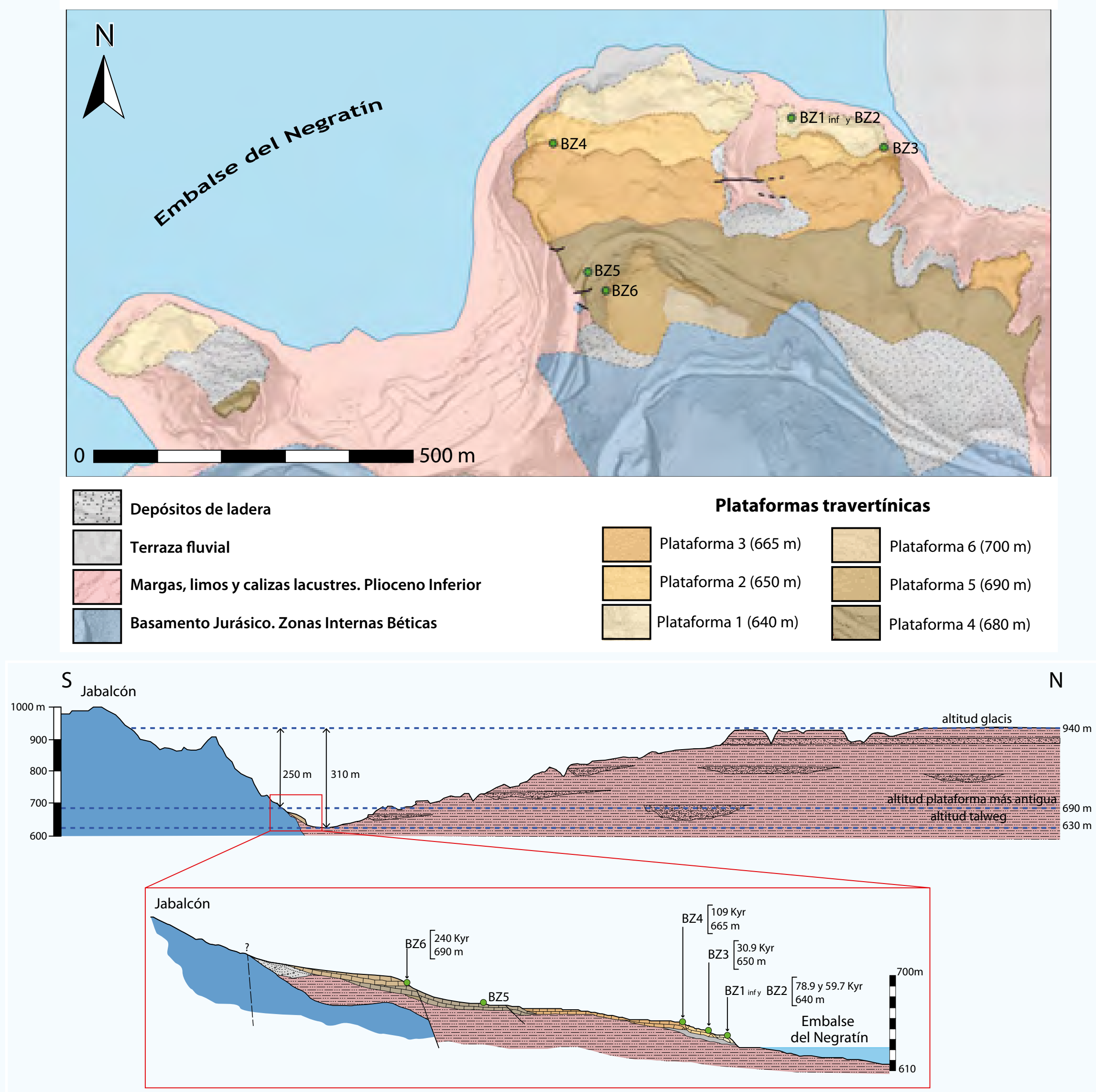


Figure 8. **A**. Geological map of the Zújar travertine terraces in the Negratín Reservoir tail sector.

B. Schematic cross-section showing the downcutting of the Zújar travertine terraces and their position in relation to the glacis (see the discussion of the age of the capture in the introduction to this chapter). The lower drawing shows a geological section of the travertine platforms.

The Toril aqueduct

Nowadays, much of the water that emerges from the thermal springs of the Alicún de las Torres baths is directed along an irrigation channel, known locally as the "Toril aqueduct". Its course runs topographically alongside the highest travertine platform in the area and directly over the intermediate platform (Figs 9, 10 and 11).

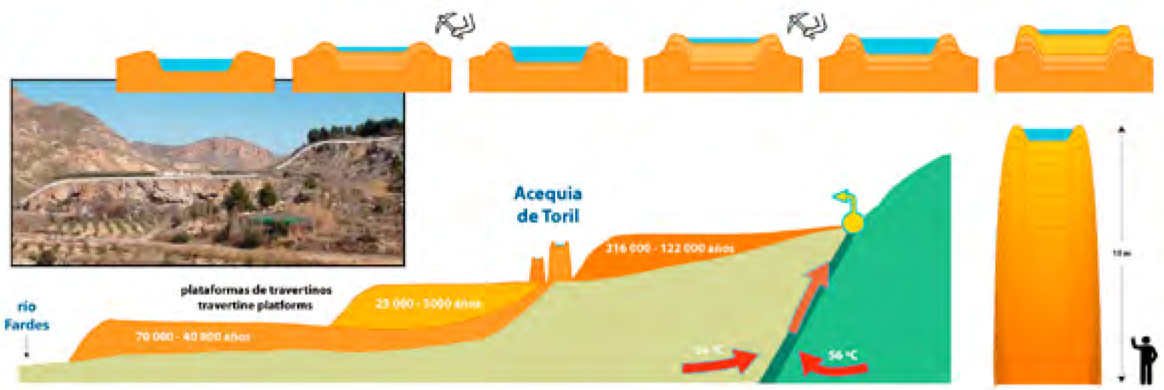


Figure 9. The figure explains how extraordinary this aqueduct is. Initially, human beings dug its channel several metres below its present level. The gradual accumulation of calcium carbonate in the channel, resulting from the special physical and chemical characteristics of the water, has caused the raising of the aqueduct and the formation in some areas of a wall up to 15 m high and over 4 m wide. According to scientists and datings made in the travertine of the aqueduct, its age, that is, the age at which the waters started to be diverted and the wall on which the water runs today began to form, is over 3,000 years.

DID YOU KNOW...?

One of the unique features that make this place so special is that visitors can witness the live formation of a sedimentary rock, specifically travertine, growing at unusual speed. On the walls of the channel the fossilization and petrification of plants can be recognized, in various stages, until they turn into travertine rock (Fig. 11).

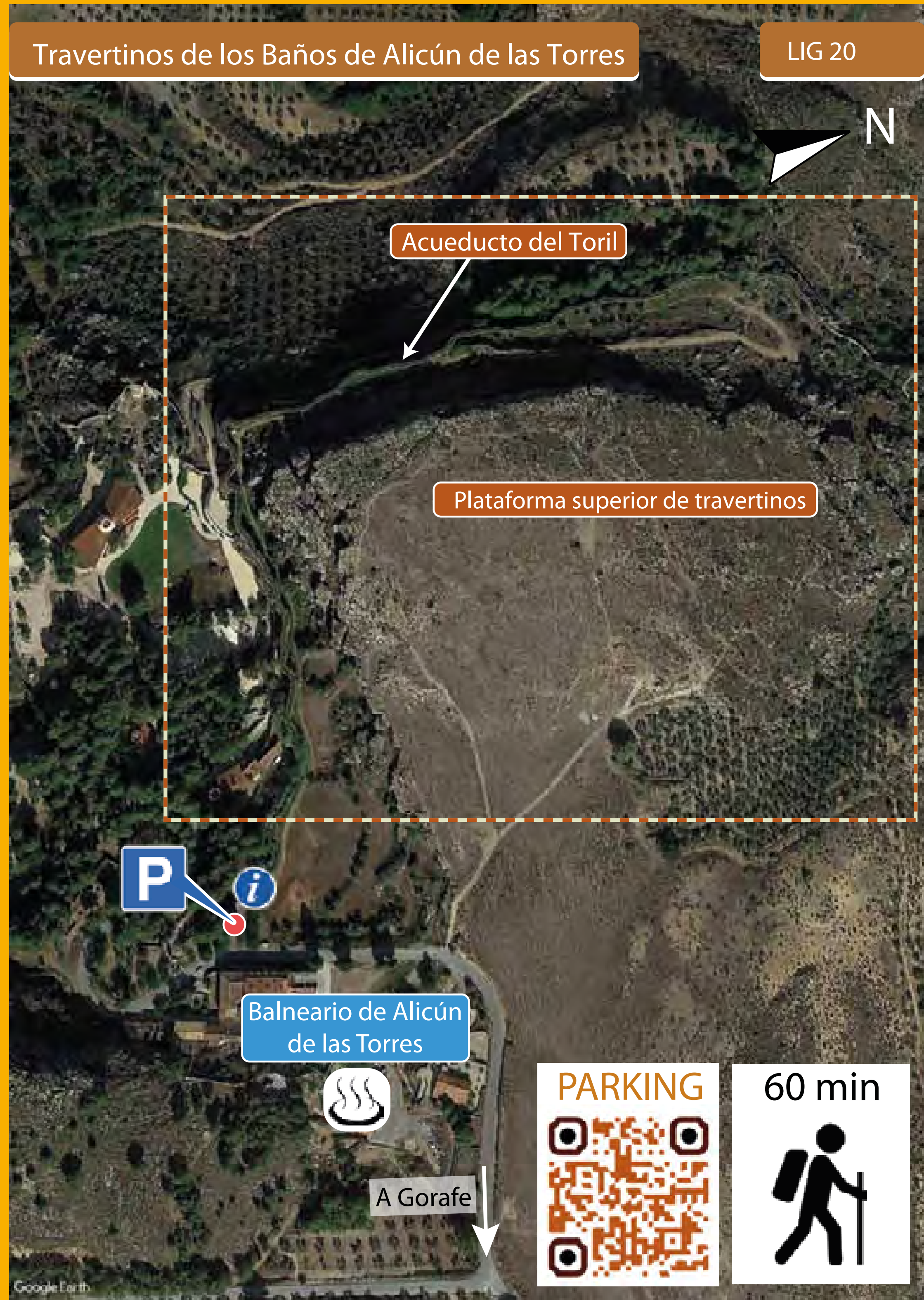
Figure 10. Panoramic view of the travertine wall that constitutes the Toril aqueduct. The rocks that can be seen in the foreground on the left belong to the highest travertine platform in the sector, which is 205,000 years old.

DID YOU KNOW...?

You can find out the **age of travertines from analysis of certain radioactive isotypes**, the most commonly used in this type of rock being those of uranium and thorium. When calcite crystals form, they incorporate small quantities of the unstable isotope 234U, which decays at a constant rate into the stable isotope 230Th. At the Alicún de las Torres spa the oldest age of the upper terrace is 205,000 years, and at Zújar 240,000 years. For the Toril aqueduct, because of its young age, it has also been possible to use 14C, which indicates that this spectacular construction is only a few thousand years old.

Figure 11. Growth of plant communities on the walls of the Toril aqueduct. This aqueduct is a veritable vertical garden, where the plants grow on rocks that do not need millions of years to form. The porosity of the travertine rock of which the aqueduct is composed enables it to be always moist and allows communities of plants perfectly adapted to the salinity and temperature of these waters to grow. One of them is the endemic species Limonium alicunense, recognizable by its small purplish flowers, which only grows here. The precipitation of calcium carbonate around the stems and leaves of the plants also gives us a delightful fossilized garden where we can see which plants have been living in the area for hundreds of thousands of years.

The origin of the aqueduct is clearly human, but its growth is natural, due simply to the precipitation of calcium carbonate around the plants (Fig. 11). All it has required from humans is maintenance by partial cleaning of the channel, which they have been doing for thousands of years. Today, however, it is not known for certain what this structure was used for, since the high salinity of the water is not ideal for irrigation. For this reason, although it is currently used for that purpose, some argue that it may have had a ceremonial origin. In the area around the thermal springs of Alicún de las Torres a rich set of archaeological sites has been documented. Various authors have studied the evidence of megalithic monuments and have described Chalcolithic and Palaeolithic sites.



GEOPARQUE GRANADA

SOURCE AND VALLEY OF THE RIVER GUARDAL

SGI 72

The valley of the River Guardal, from its source (Fuentes del Guardal) to the vicinity of the town of Castilléjar (Fig. 1), offers us extraordinary geodiversity, combining geological, geomorphological and hydrogeological aspects in an exceptional scenic and natural setting. In this section we are going to focus on its source and on the segment that runs through the villages of Duda and La Parra (Huéscar).

The source springs of the River Guardal (Sierra Seca)

The predominance of limestone rock in the mountains of the district of Huéscar produces a distinctive landscape called karstic landform, resulting from processes of dissolution and precipitation of carbonate rocks. On the peaks of the Sierra Seca (Fig. 2), the action of water and snow has created a notable array of *dolines* (depressions formed by dissolution of the rock). Some larger depressions, called *poljes*, have also formed, with sinkholes (*ponors*) through which rainwater infiltrates. Under these conditions, water from rain and melted snow infiltrates easily and rapidly, taking advantage of the rock fractures. During its underground journey to the springs it dissolves the rock and forms caves (Fig. 3). These springs are characterized by large and abrupt variations in flow known as *reventones* (“bursts”).

Figure 1. Panoramic view of the valley of the River Guardal from its source (Guardal Springs) to the area of Duda Bridge".

Calling these sudden rises in water level *reventones* comes from the Chorros del Río Mundo spring in the province of Albacete. In the Granada Geopark there is another example, less well known but very similar to the Chorros del Río Mundo. This is Fuente Alta ("High Spring"), which gives rise to the source of the River Guardal on the eastern slope of the Sierra Seca (Fig. 2). On the peaks of the Sierra Seca, the rains from the Atlantic or the Mediterranean bring large volumes of water in short periods of time. As with the source of the River Mundo, the Sierra Seca limestones are dotted with dissolution structures through which water can reach the aquifer and flow rapidly through the interior. This causes sudden large increases in flow from the springs of just a few days' duration. But the water not only emerges from the permanent spring but also activates other points that used to be springs in the geological past (palaeo-springs) but are now almost always dry. Sometimes, these palaeo-springs are mouths of caves that can be explored (Fig. 3). At Fuente Alta, the flow can increase in a few hours from 100 to over 15,000 litres/second and the duration of these floods is often only three or four days. When this happens, the water emerges in large quantities through the mouths of the two caves above the permanent spring. A temporary water outlet of this kind is usually called a *trop plein* in the scientific literature in Romance languages and an *overflow spring* in English.

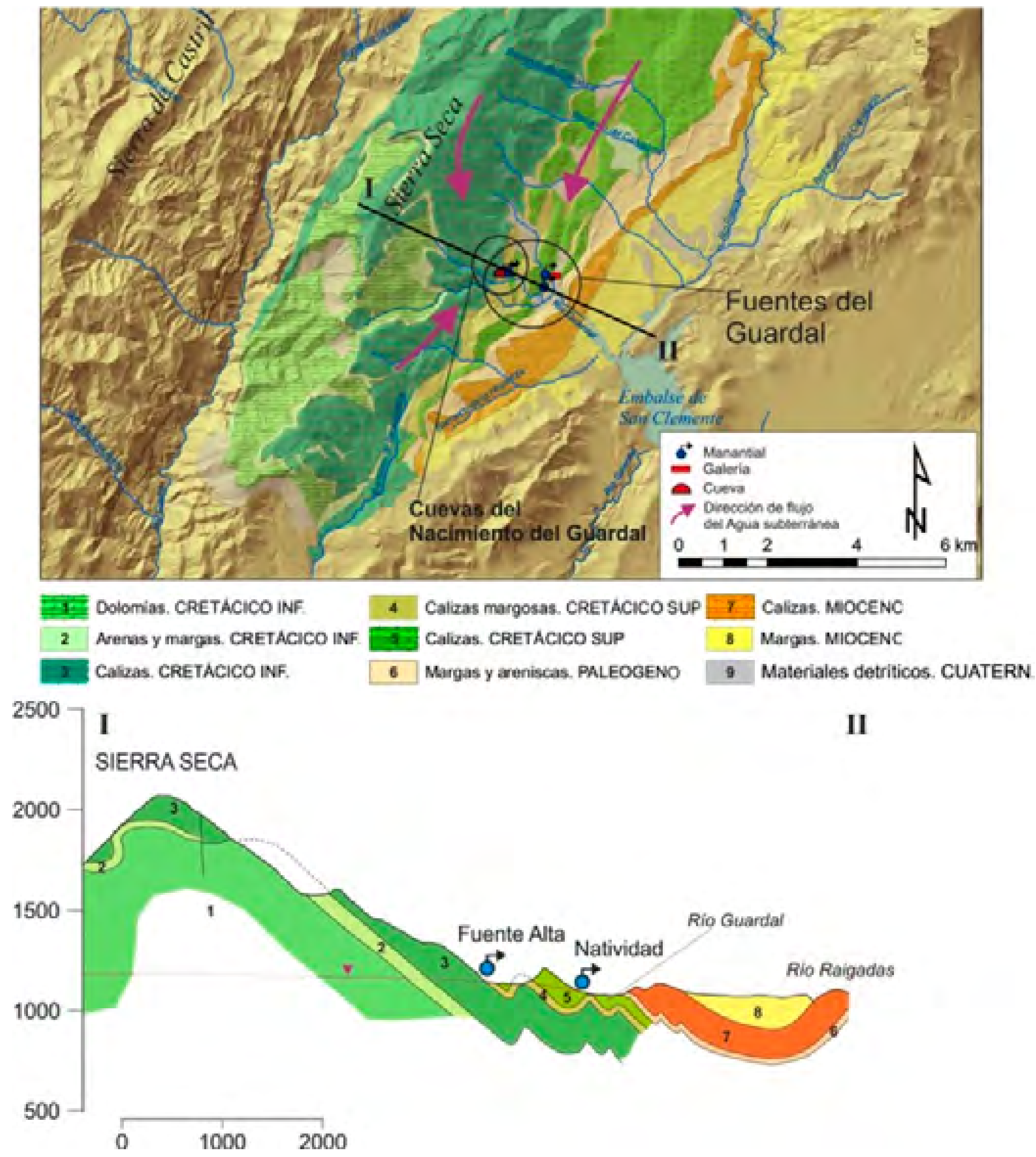


Figure 2. Geological context of the Guardal springs and the caves of the Source of the River Guardal.

Below: Hydrogeological cross-section of the area of the springs that give rise to the Source of the River Guardal (based on the geological cartography of Lupiani et al., 2007).

Figure 3. The Lower Cave of the Source of the River Guardal.

The River Guardal canyon

The great majority of the valleys in the Granada Geopark, except for the upper courses of some rivers downcut into basement rocks of the Guadix-Baza Basin, are located below the glacis surface. These valleys began to form when the endorheic basin was captured. Many of them that have downcut into soft sediments have a characteristic V-shaped cross profile (Fig. 4), and their sides have developed countless gullies and ravines that make up the badlands landscape. In the larger valleys, this configuration has evolved to form wider, flat-bottomed valleys.

The River Guardal valley, in the vicinity of Duda, represents an exception in this set of valleys generated below the glacis surface in soft sediments. The fact that the River Guardal runs across resistant limestone rocks in this section explains the development of a spectacular canyon, with vertical walls. Specifically, the river has excavated the Jurassic limestones and dolostones of the Sub-betic, whose resistance has shaped this spectacular valley (Fig. 5).

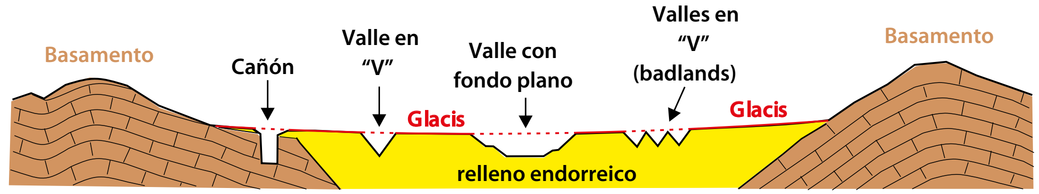


Figure 4. Most of the river valleys generated after the capture share two features. On the one hand, they are downcut into soft sediments from the endorheic stage. On the other, if we take an imaginary cross-section of these valleys, most of them have a characteristic V shape (this shape is very clear in the valleys of the badlands landscape), while others have a wider, flat-bottomed shape. The flat-bottomed shape predominates in valleys of a certain magnitude, such as those of the main rivers in the territory. However, the River Guardal, in a section of several kilometres in a downstream direction from Duda, has a narrow, deep valley with vertical walls. This valley morphology is known as a canyon.

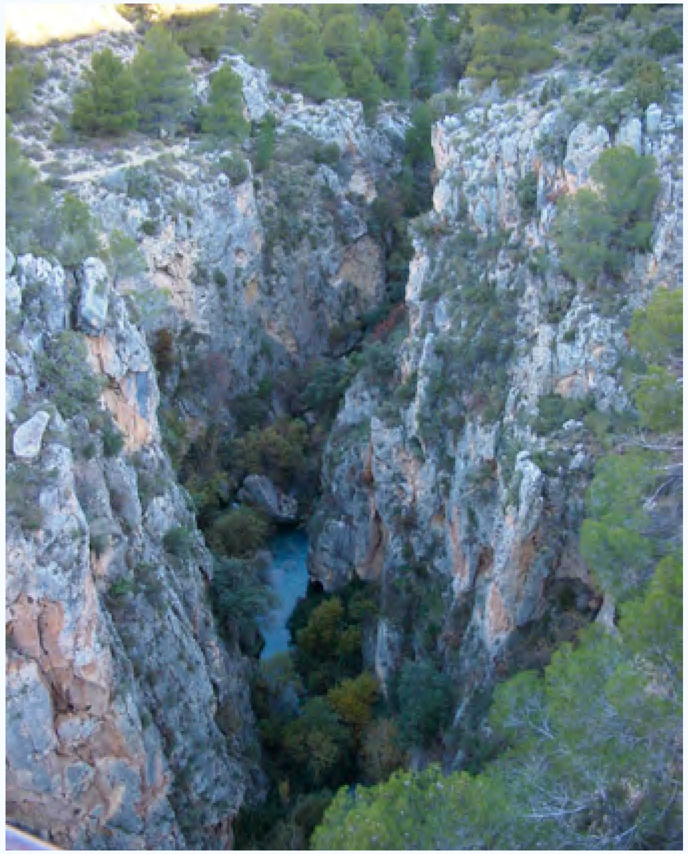


Figure 5. Valley with vertical walls (Guardal canyon) formed in basement limestones and dolostones. This section we are describing shows the severe downcutting of the River Guardal, generating an impressive canyon with vertical walls more than 100 metres high.

How was the River Guardal canyon formed?

Normally, karst canyons are formed by the dissolution of rocks such as limestones and dolostones. The lowering of the water table is crucial to their development (Fig. 6). However, in the case of the River Guardal canyon the limestone has also been severely eroded by the action of water; in other words, not only has dissolution been involved, but also they have been eroded by the energy of the water in this section of the river. This erosive action of water was due to the fact that the limestone once represented an obstacle encountered by the course of the river. Consequently, the river began to downcut first into detrital rocks of alluvial fans, derived from the surrounding mountains, and subsequently into the limestone located beneath them. In this case, therefore, we should refer to a fluvio-karst canyon, indicating that it was produced by the combined action of erosion by the river and dissolution of the carbonate rocks.

The downcutting of the valley in this section may also have been favoured by the presence of fractures in the rock, creating areas of weakness that were easier to erode and dissolve.

In the River Guardal valley you can also see **travertines**. There are several outcrops of travertines in the section of the valley we are describing. One of the most attractive is located below the village of Duda (Fig. 7), where they form a large petrified cascade from a waterfall that existed in the past. These travertines are associated with a spring from the Sierra de Duda, whose water carried a large quantity of dissolved calcium carbonate.

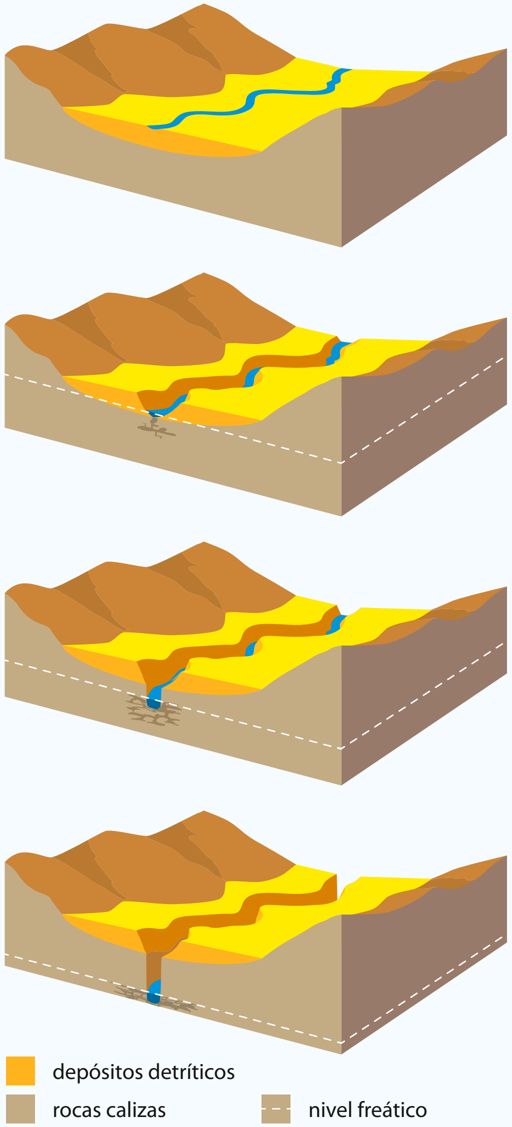


Figure 6. The upper part of this section of the River Guardal valley is excavated in detrital deposits of alluvial fans originating from the Duda, Cerro del Cubo and Loma del Perro mountain ranges. In that higher stretch of the river the walls are not vertical and a typical V-shaped valley developed. Downstream, when the river bed reached the limestone rocks, the resistance of the rocks allowed a valley with vertical walls to develop.

As well as water erosion, the height of the water table played a part in the evolution of this valley, partially determining dissolution in the vertical plane.

Figure 7. Cascade of travertines below the village of Duda. Panoramic view taken looking NW.

Valle del río Guardal
LIG 72
N
Travertinos
RÍO GUARDAL
AVISO IMPORTANTE
Para acceder al mirador del puente de Duda hay que caminar a lo largo de una carretera, por lo que se ruega precaución.
A Huéscar
15 min
Mirador del puente de Duda
A Fátima
ACCESO
Google Earth

Panoramic view towards the eastern sector of the Geopark from the side of Cerro Jabalcón. In the foreground we can see the transition between the red fluvial sediments characteristic of the western sector and the whitish lacustrine sediments typical of the eastern sector.

8

THE GEOPARK'S VIEWPOINTS

In the Granada Geopark, landscape and geology are inseparable. There are many spectacular viewpoints from which to observe the various geological features that characterize the territory. Some of them also provide exceptional views of other elements that are not exclusively geological, such as interesting urban and cultural landscapes, among which cave house districts and vegas (fertile plains) have pride of place. However, in this last chapter we have selected a set of viewpoints that make it possible to visualize and synthesize, above all, the various geological and geomorphological phenomena described in the previous chapters.

One of the essential factors determining their selection, as well as showing an outstanding example of one of the geological or geomorphological features described in the course of the guide, has been that they can be reached by car, so that they are accessible to most visitors. However, in addition to experience of driving on dirt roads, access to some of the viewpoints may require a 4x4 vehicle. Caution is also advised after rainy periods owing to the state of the roads. Another question that has been taken into account when selecting the viewpoints for this chapter is that they should not be in an urban area. Finally, a point they all have in common is that no geological knowledge is needed to enjoy the outstanding geological landscape that can be seen from them.

All the viewpoints offer magnificent panoramic views of the territory that cannot fail to impress you.

We begin this list with the only viewpoint that offers the possibility of a 360-degree panoramic view of the entire Granada Geopark: the Jabalcón Viewpoint. The other viewpoints will then be described following an order related to the geological history of the territory, from the mountains to the badlands and the river terraces.

As with the Sites of Geological Interest described in the course of the guide, access to the viewpoints can be obtained using a QR code linked to Google Maps.

DISCOVER OUR GEOLOGICAL HERITAGE!

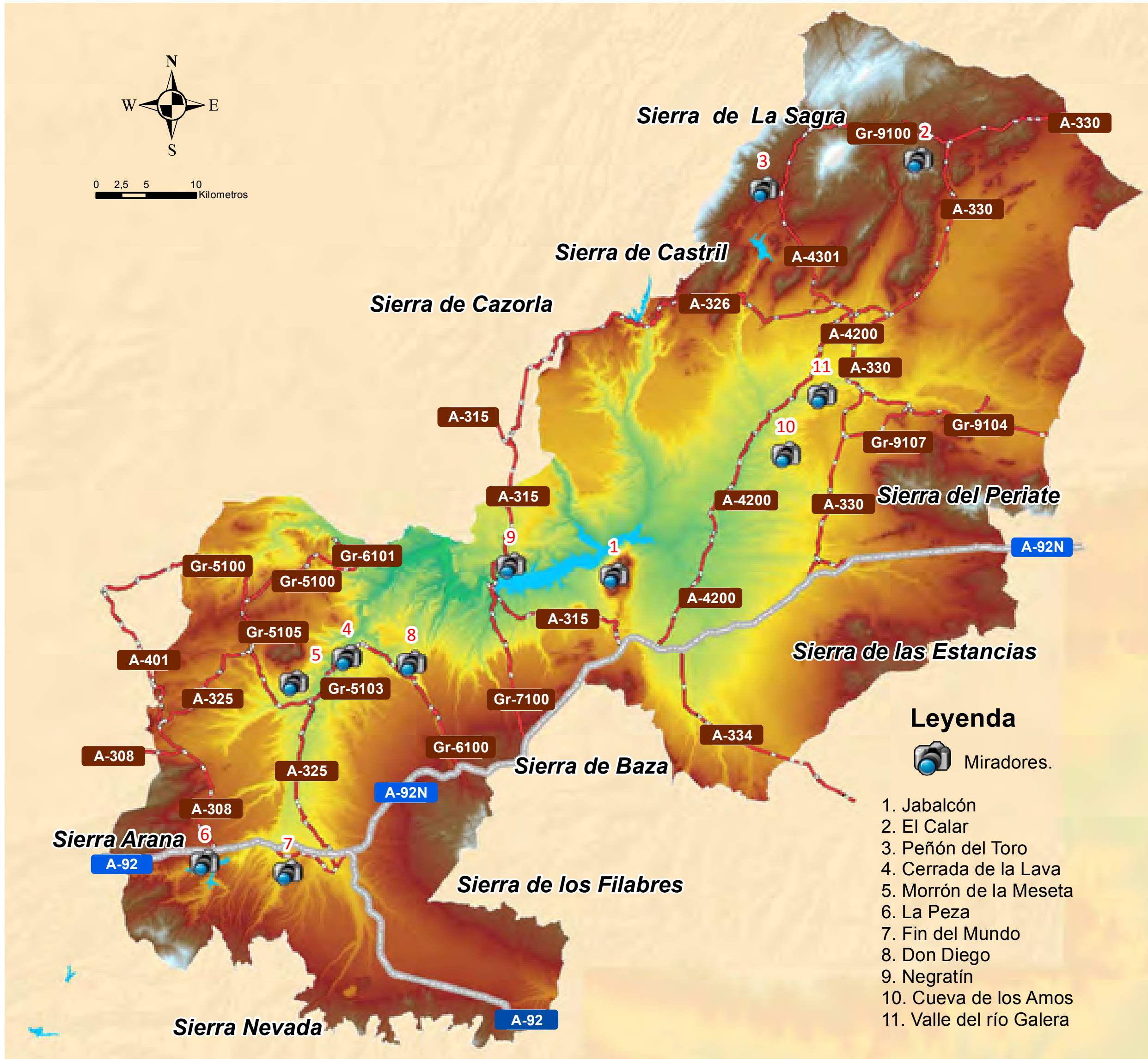


Figure 1. Location of the main viewpoints in the Granada Geopark.

Jabalcón Viewpoint

Zújar

View from the Jabalcón Viewpoint towards the valley of the Guadiana Menor and the Negratín Reservoir.

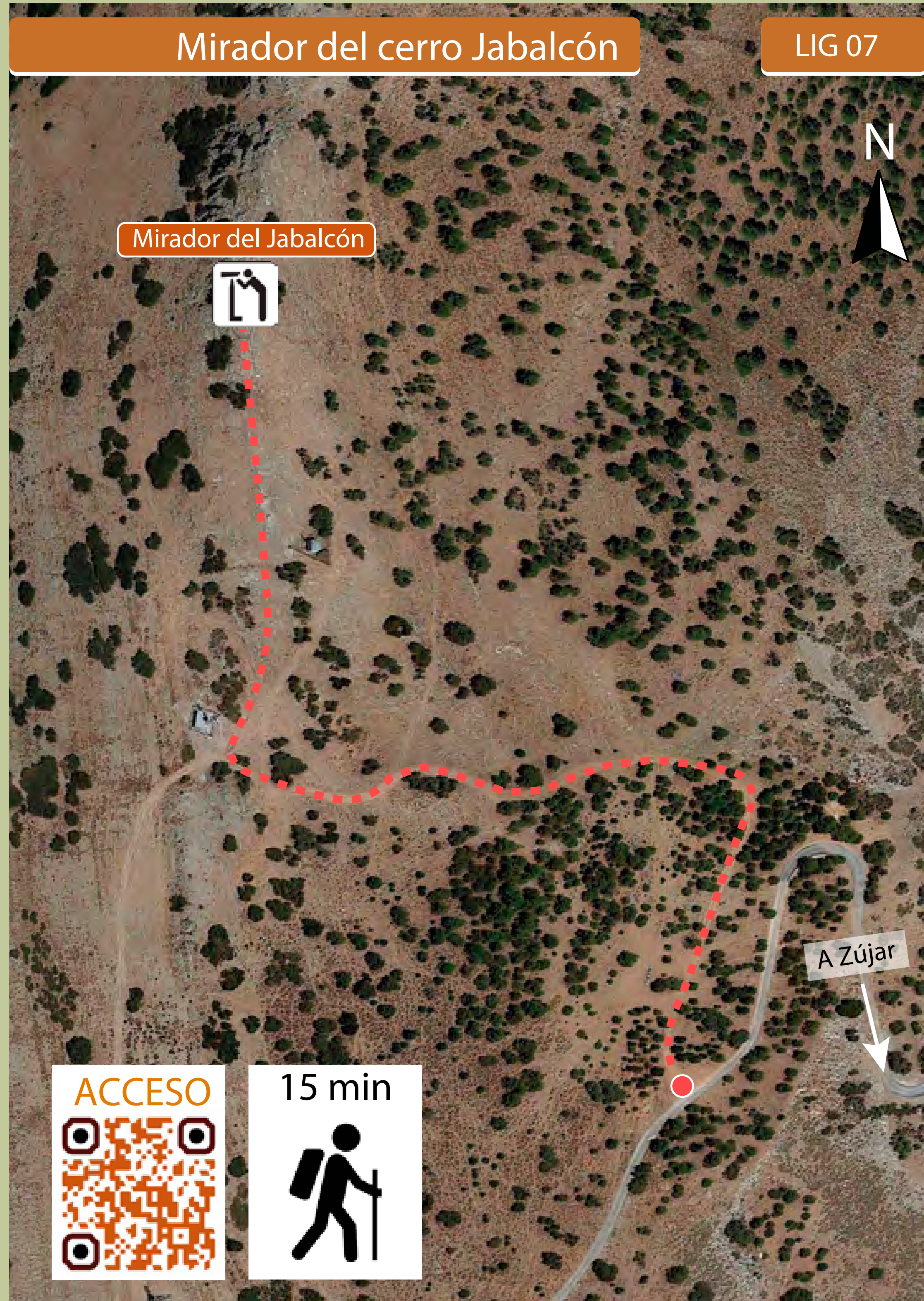
JABALCÓN VIEWPOINT
CENTRAL SECTOR, ZÚJAR, SGI 07

Access is from Zújar via an asphalt track that reaches the highest part of Jabalcón. This inselberg or island mountain, located in the centre of the Geopark, offers us an overview of the territory and its characteristic geology. It is the ideal place to explain how the Guadix-Baza Basin formed and evolved. From the top of Cerro Jabalcón you can understand the meaning of "**intramontane depression**", or *hoyas de Guadix y de Baza*, as it has traditionally been called in the region. The 360° panoramic view shows us how the mountains surround the Guadix-Baza Basin.

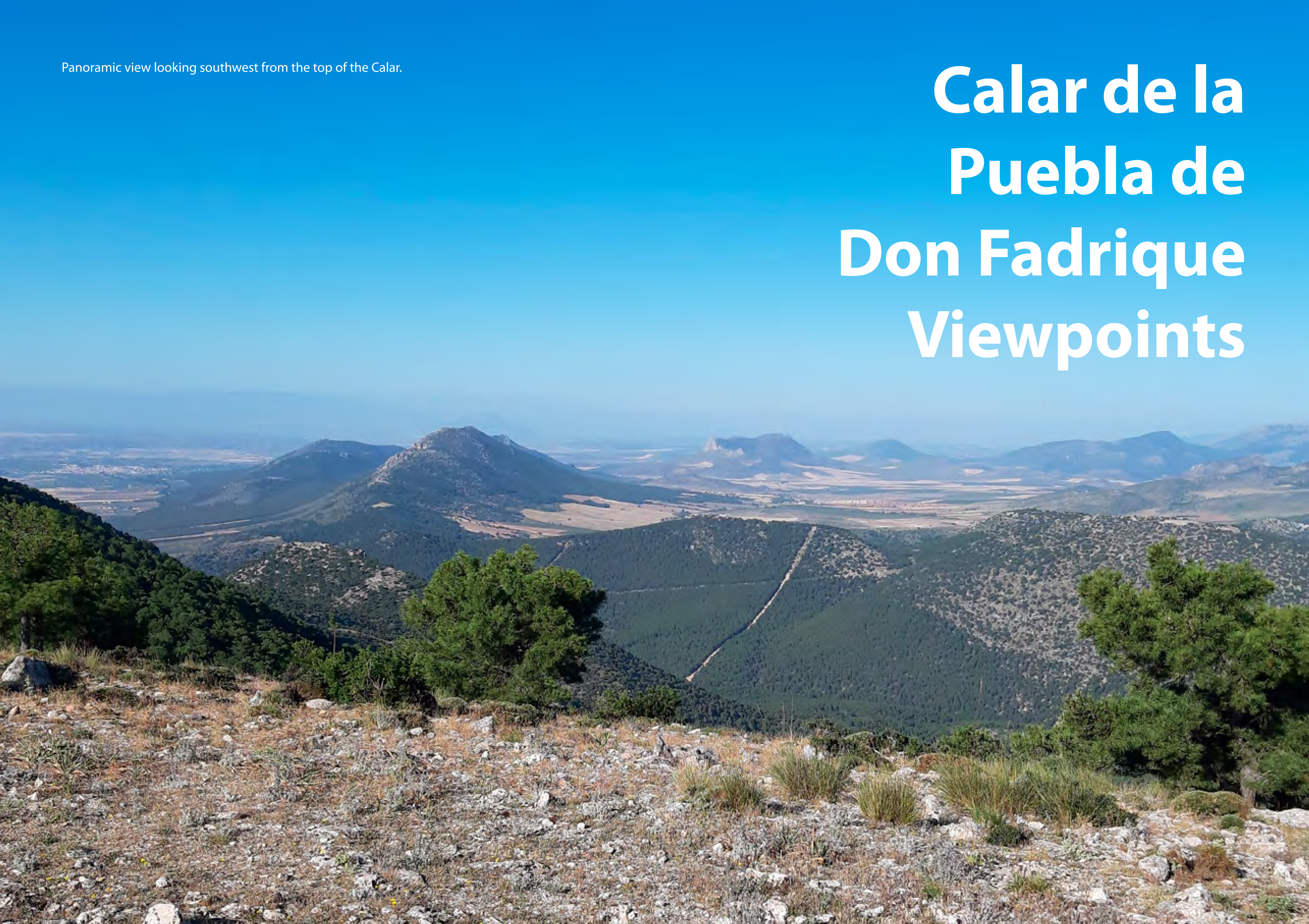
Within the intramontane depression are the other two important landscapes of the territory, the great plain or **glacis**, and below it, the valleys and ravines that shape the **badlands** landform.

This viewpoint is also the ideal place to appreciate another essential feature of the Geopark: its division into two major sectors, the western, with the Negratín Reservoir in the foreground, where there is a predominance of reddish tones from the sediments generated by rivers such as the palaeo-Fardes, and the eastern, with predominantly whitish colours, typical of the sediments deposited in the Baza palaeolake. In Chapter 2 of this guide you can find further information on Cerro Jabalcón.

Aerial view of the Jabalcón Viewpoint.



Calar de la Puebla de Don Fadrique Viewpoints

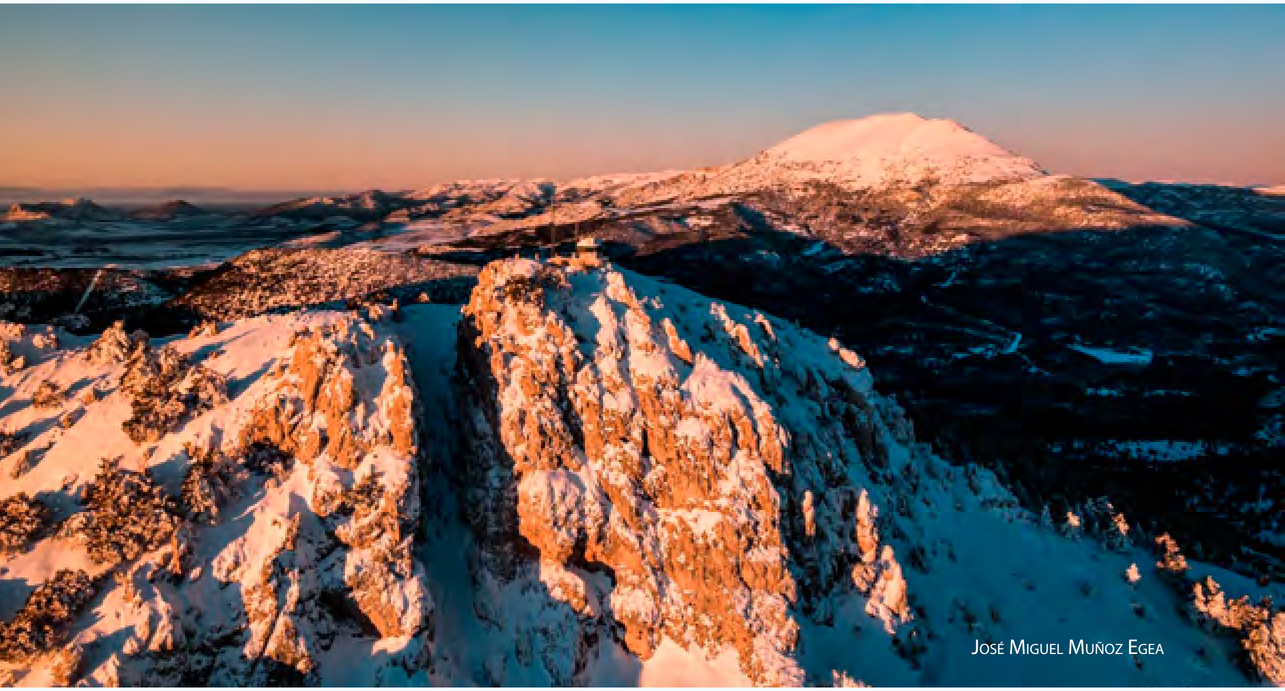


Panoramic view looking southwest from the top of the Calar.

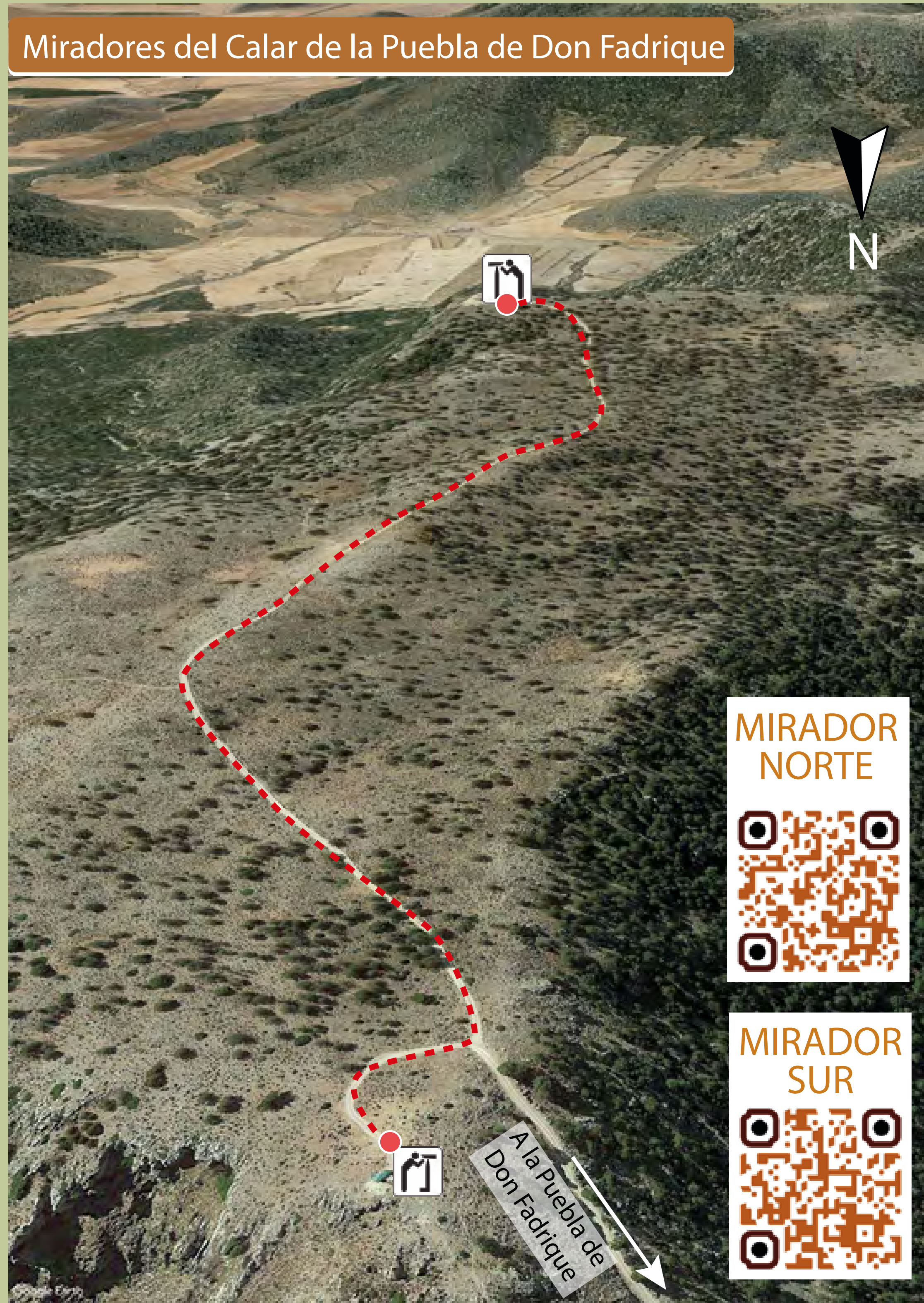
CALAR DE LA PUEBLA DE DON FADRIQUE VIEWPOINTS

These viewpoints can be reached from Puebla de Don Fadrique and from the Carretera de las Santas, in both cases along a forest track that climbs to the top of the Calar. The topography throughout the upper part is gentle and is known as Las Mesetas ("the plateaus"). There are several places at the top that are magnificent viewpoints, such as the area of the forest fire lookout post at the northern end and the area around the triangulation station, located at the southern end, just over 1 km from the previous point.

These viewpoints offer some of the best panoramic views of the **Sierra de La Sagra** (Chapter 5) and also of the **Sierra Guillimona**, both of which are the origin of some of the main rivers that make up the Guadiana Menor downstream. This is an exceptional place from which to observe the characteristic landscape created by the limestone mountains on the northern edge of the Guadix-Baza Basin. The panoramic view to the south from the triangulation station enables us to see another of the Granada Geopark's sites of geological interest in the distance: the **Bugéjar Endorheic Basin**, which has not yet been reached by any river to drain it into the Guadiana Menor (see Figure 4 in the previous chapter).



Panoramic view towards the Sierra de La Sagra, with the forest fire lookout post in the foreground, located on the peak known as *Piedra de la Rendija*.



Peñón del Toro Viewpoint

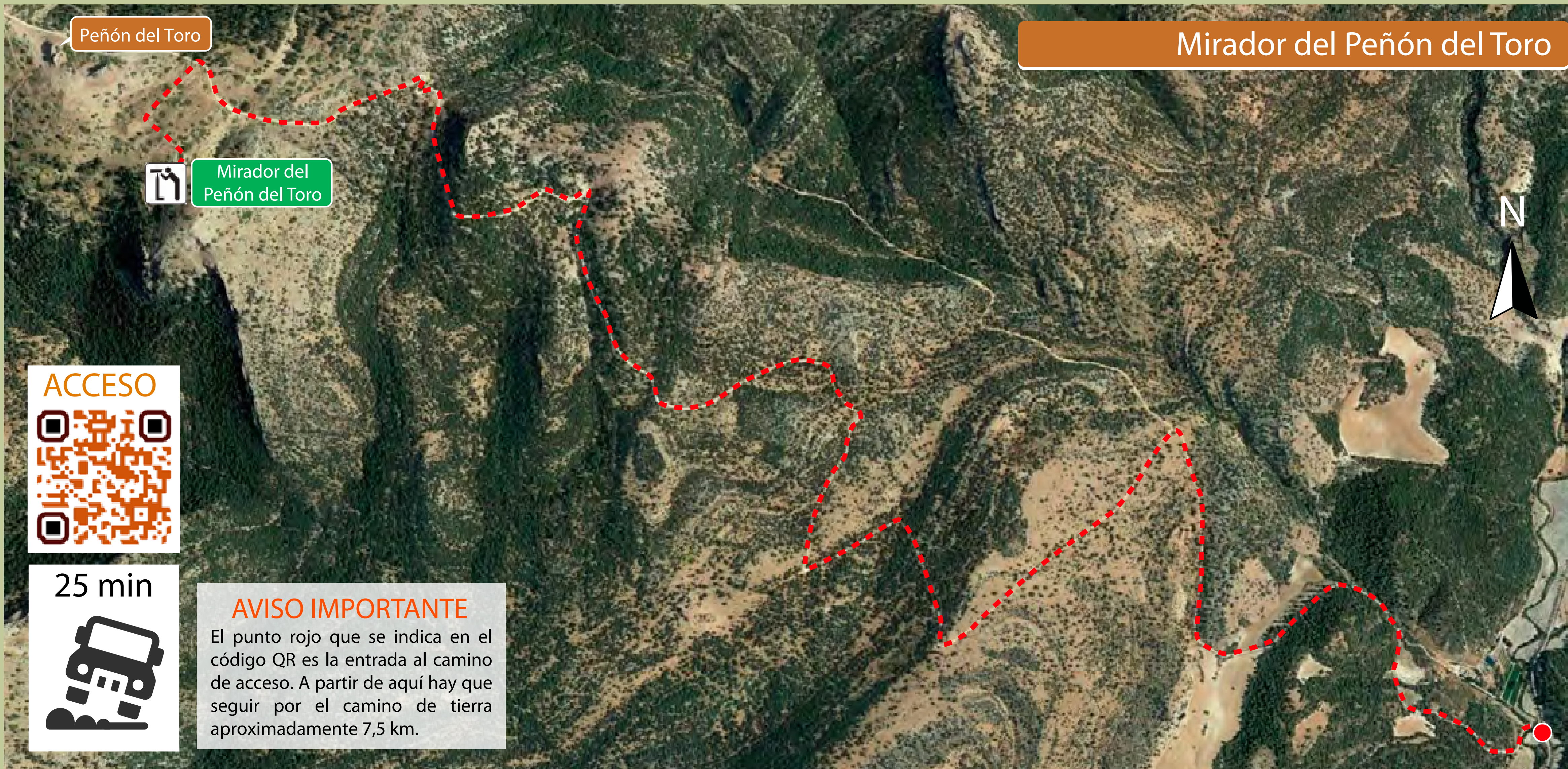
Sierra Seca (Huéscar)

On the right in the foreground, the Peñón del Toro; on the left, the north face of La Sagra.

Eloy Molina

PEÑÓN DEL TORO VIEWPOINT
SIERRA SECA (HUÉSCAR)

Access is via a forest track from the A-4301 road between kilometres 15 and 16 (Cortijo de la Noguera). It is essential to use a 4x4 vehicle. At the point where the dirt track begins you have to cross a riverbed that normally holds little water but may sometimes impede your ascent to the viewpoint after periods of heavy rainfall. In these circumstances it is advisable not to ford the river but to try when there is little or no flow. The viewpoint is signposted and has a car park and information panels. Together with the Calar de la Puebla viewpoints it is an ideal place to get to know the characteristic karst landscape that dominates the northernmost part of the Granada Geopark. From here we have magnificent views of the north face of La Sagra and much of the Sierra Seca, origin of the Guardal (see Chapter 7). In addition, the San Clemente Reservoir and some more distant mountain ranges such as the Sierra de María, Sierra del Periate, Sierra de Baza and even Sierra Nevada can be seen, tracing on the horizon the southern edge of the intramontane basin in which most of the Geopark lies. For those with some knowledge of geology it is also possible to recognize the eastern flank of the anticline that shapes this sector of the Sierra Seca (see the geological cross-section in the section on the River Guardal valley in the previous chapter). .



Cerrada de la Lava Viewpoint

Villanueva de las Torres

Triassic, Cretaceous and Palaeogene basement rocks of the Guadix-Baza Basin. View looking SW.

CERRADA DE LA LAVA VIEWPOINT

VILLANUEVA DE LAS TORRES

This viewpoint, in the River Fardes valley, is accessible by the Gr-5103 road. Here we can see a set of rocks of different ages that produce a striking multicoloured landscape. To draw a comparison with the famous Death Valley National Park in California, from this viewpoint we can contemplate the "artist's palette" of the Granada Geopark. Most of these rocks belong to the **basement** of the Guadix-Baza Basin (you can find what this means in Chapter 2). As well as some of the oldest rocks present in the Geopark, of Triassic age, some unusual greenish rocks on which vegetation does not grow can be seen from here. They are called ***bentonites*** (you can read more about them in Chapter 2). Other phenomena related to the formation of the valley can also be observed, such as the **river terraces** that occupy the lowest and flattest areas in the sector. In Chapter 2 we have a summary of the various geological and geomorphological features visible from this viewpoint.

Triassic, Cretaceous and Palaeogene basement rocks of the Guadix-Baza Basin. View looking NW.

Panoramic view looking east from the viewpoint. The Mesa de Bacaire (SGI 16) can be recognized near the horizon in the central part.

Morrón de la Meseta Viewpoint

Pedro Martínez

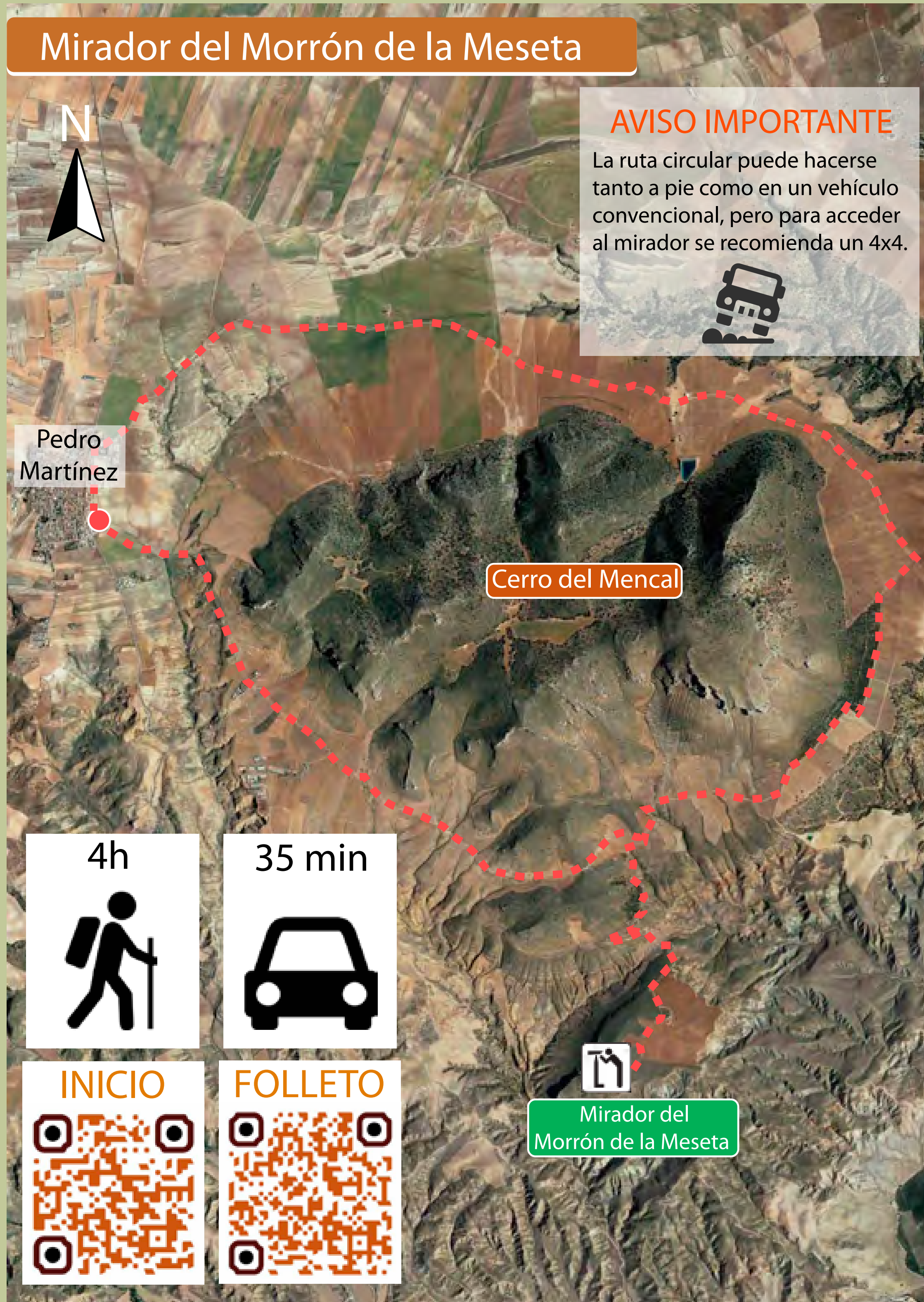
MORRÓN DE LA MESETA VIEWPOINT

PEDRO MARTÍNEZ

This can be reached via a forest track that starts from Pedro Martínez and forms part of the Mencal geological route: *https://issuu.com/ayto.pedro-martinez/docs/ruta_del_mencal*

As well as the multicoloured rocks belonging to the basement of the Guadix-Baza Basin, which can be seen at the previous viewpoint, this one gives us magnificent views of some of the most iconic mountains in the Geopark, such as Mencal and Jabalcón, with La Sagra on the more distant horizon. This viewpoint is an outstanding place to observe the glacis in the westernmost part of the Geopark and also the badlands landform, which in this sector has developed especially in the soft basement rocks. It is a prime location for understanding the relationship between the basement, the continental sedimentary infill, the glacis and the current erosion. Just opposite the viewpoint we have one of the Geopark's Sites of Geological Interest, the Mesa de Bacaire, where part of the glacis has remained like an inselberg or mesa surrounded by ravines that are downcut below the glacis.

Panoramic view of Morrón de la Meseta and Mencal from the Mesa de Bacaire.



La Peza Viewpoints

Panoramic view towards the Sierra Nevada from the upper viewpoint.

LA PEZA VIEWPOINT

This is really two viewpoints, accessible by an old asphalted road. Both are located on the north shore of the Francisco Abellán Reservoir. The higher of the two offers us magnificent views of the Sierra Nevada, and the lower, as well as the beauty of the reservoir, shows us the most outstanding geological feature of the sector: the Late Miocene marine rocks downcut by the River Fardes valley. You can see a detailed description of them in Chapter 3. From these viewpoints, once again, the three main landscapes that characterize the territory can be observed: **mountains** such as the Sierra Nevada, **river valleys** and the **glacis** surface that links the lower slopes of the mountains with the valleys.

View of the Late Miocene marine rocks from the lower viewpoint.

Marchal and Beas de Guadix Viewpoints

"End of the World Viewpoints"

Vista aérea de los miradores, donde se aprecia el glacis y los badlands.

ALBERTO TAUSTE

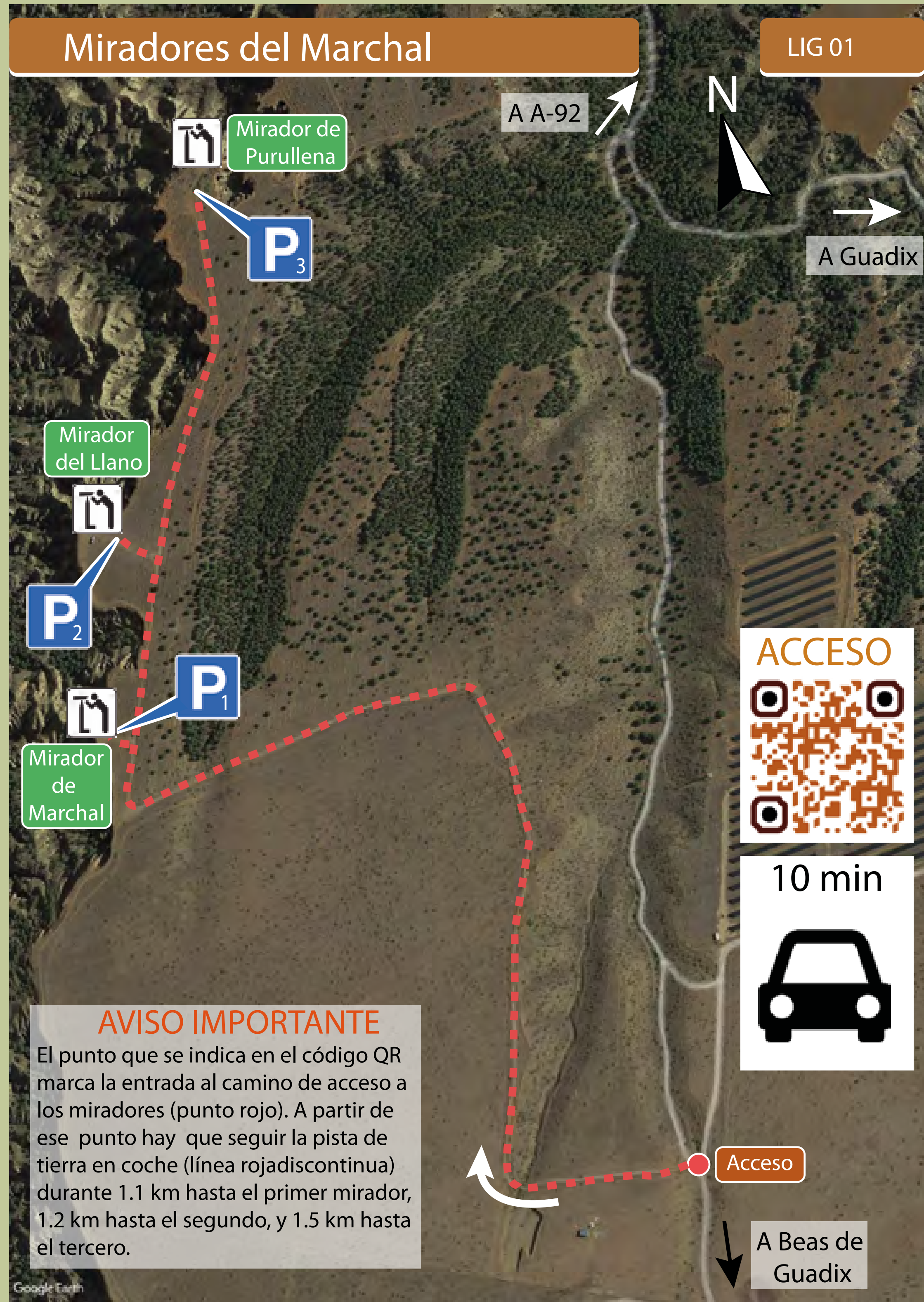
MARCHAL AND BEAS DE GUADIX VIEWPOINTS

"END OF THE WORLD VIEWPOINTS"

Access to the Marchal Viewpoints is by a forest track. With care, albeit with some difficulty, they can be reached by car. They are a group of viewpoints located on the surface of the glacis (see Chapter 7), just on the edge of large escarpments created by the downcutting of the river network that shaped the badlands landscape. All of them are within the municipal limits of Marchal, although the northernmost one is also known as the Purullena Viewpoint, referring to the town that can be seen from it. Some 2 km to the south of this group of viewpoints is the Beas de Guadix Viewpoint, which is accessed by a road that starts from this village, or also from the Paulenca district. This road is not directly connected to the previous viewpoints.

All these viewpoints are good places for understanding the relationship between the three major landscapes: the mountains that delimit the depression, the glacis surface, that is, the last vestige of the endorheic stage of the basin, and the valleys and ravines formed after its capture. They provide a very good view of the great thickness of sediments that the rivers flowing from the Sierra Nevada accumulated during the endorheic stage. As for the current exorheic stage, from these viewpoints we can observe a characteristic landform known as *piping* or *tunnel erosion*, described in Chapter 7.

Detail of the *tunnel erosion* or *piping* characteristic of this sector.



Panoramic view of Beas de Guadix from the viewpoint. Sierra Arana can be recognized in the background.

View of the Sierra Nevada from the Beas de Guadix viewpoint.

Don Diego Viewpoint

Gorafe

Panoramic view of the Gorafe badlands towards Mencal.

DON DIEGO VIEWPOINT
GORAFE, SGI 04

Access is by a dirt track that is passable, with care, for any car. The Don Diego Viewpoint, located in the centre of the western part of the Geopark, is undoubtedly one of its most spectacular in terms of landscape, and also one of the most complete from a didactic point of view in relation to the geology of the Geopark. From this viewpoint, located once again at the boundary between the glacis and the badlands, you can observe almost all the geological and geomorphological elements described in the course of this guide, as if you were zooming in on the western sector of the Geopark from the top of Jabalcón. Mountains such as the Sierra Nevada, Sierra de Baza, Sierra Arana, or the Pozo and Castril ranges, together with Jabalcón, trace the Hoya de Guadix, that is, the western part of this great intramontane depression, on the horizon and in a 360° panoramic view. Whitish sediments towards the north, in places where the glacis surface has disappeared, show us the vestiges of the marine stage of the territory. Multicoloured rocks and fluvial sediments, with a predominance of brown and reddish tones, indicate different origins of the rivers during the endorheic stage (see Chapter 4) and mark the entrance to the Desierto de los Coloraos ("Red Desert").

To the east, the Negratín Reservoir shows us the position towards which the palaeo-Fardes flowed when the rivers had no outlet from this intramontane depression. The glacis surface we are standing on, extending for miles, enables us to imagine what the landscape was like throughout the whole territory, including the sectors now occupied by the badlands. Ravines of various shapes, with tunnel erosion processes or sharp ridges between them, offer us a spectacular landscape.

Panoramic view of the Gorafe and Bácor-Olivar badlands looking towards Cuevas del Campo.

Negratín Viewpoint

Cuevas del Campo

Negratín badlands.

“Fairy chimneys” or “hoodoos” can be seen in the foreground.

NEGRATÍN VIEWPOINT

Cuevas del Campo, SGI 05

This can be reached by an asphalt track from the vicinity of Cuevas del Campo. Again it is close to the boundary between the glacis and the badlands. From a geomorphological point of view, we have another magnificent panoramic view of the badlands from this viewpoint. Moreover, we can contemplate the scale of the valley created by the Guadiana Menor, occupied here by the Negratín Reservoir, whose blue waters enhance the strength and beauty of the landscape. Just below the viewpoint, between the ravines that make up the badlands of this part of the territory, we also find formations known as fairy chimneys or hoodoos. Other highlights are the panoramic views of the Sierra de Baza to the south, the west face of Jabalcón and the glacis on the horizon.

Panoramic view towards Cerro Jabalcón.

Cueva de los Amos Viewpoint

Castilléjar

Badlands of the eastern sector. View towards Castilléjar and La Sagra.

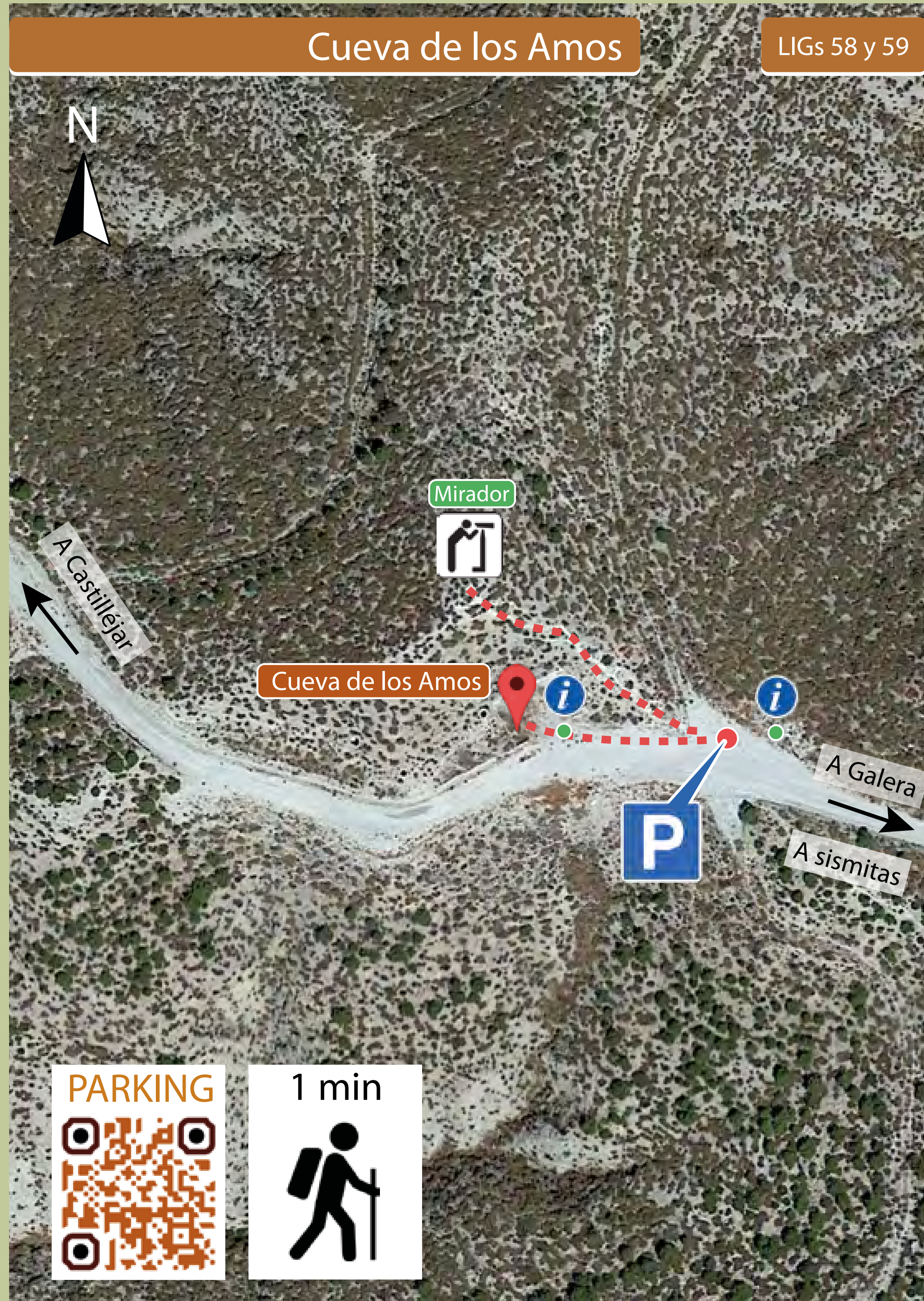
In the foreground is the Cueva de los Amos.

CUEVA DE LOS AMOS VIEWPOINT

Access is by a dirt track starting from Castilléjar, right at the confluence of the Rivers Guardal and Galera. The Cueva de los Amos Viewpoint is located at the top of the hill where the cave is excavated. This spot offers us a magnificent panoramic view of the Baza Depression, in which Jabalcón disconnects us visually from the Guadix Depression, not forgetting that both are really part of the same intramontane depression in which the Granada Geopark is located. This is one of the best places to view the badlands of the eastern sector, which developed on whitish-coloured lacustrine sediments with bright sparkles produced by the gypsum crystals known as espejuelos or "little mirrors". The colour of this part of the Geopark is very variable depending on the time of day and the time of the year, which makes it essential to visit it at different times to enjoy the landscape in its entirety. If the Don Diego Viewpoint was the perfect place to understand the meaning of the Guadix Depression, the Cueva de los Amos Viewpoint is the perfect place to visualize the Baza Depression, surrounded by the Sierra de Castril, Sierra Seca, Sierra de La Sagra, Sierra del Periate, Cúllar and Jabalcón.

If we continue along the track that brought us to the Cueva de los Amos, we will reach the next viewpoint, that of the River Galera Valley, completing a spectacular tour through the badlands of the "Desierto de los Espejuelos". On this tour we will cross the Gypsum Trail, the Castilléjar Badlands and the Galera Seismite Trail.

Interior of the Cueva de los Amos.



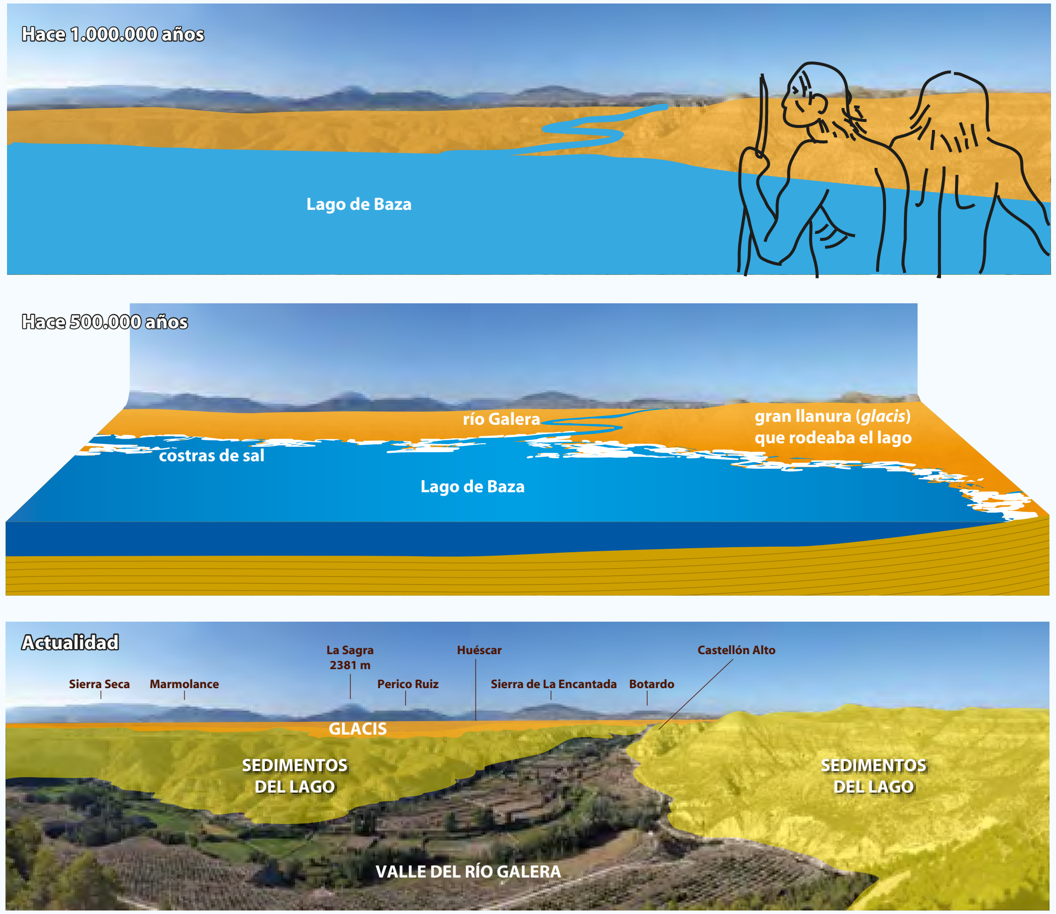
River Galera Valley Viewpoint

Panoramic view towards the Sierra Seca.

RIVER GALERA VALLEY VIEWPOINT

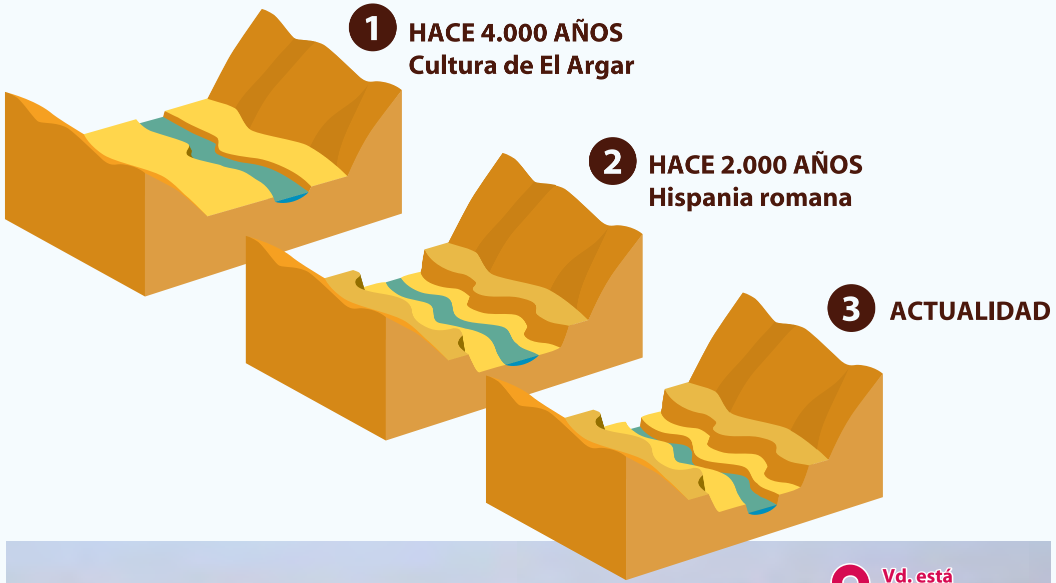
This viewpoint is accessible from the town of Galera by the same track that leads to the Argaric site of Castellón Alto. It can also be reached from the old national road. In both cases there is a section that requires some experience of driving on dirt tracks. As described in the previous viewpoint, there is a third option for access to this one, by continuing along the dirt track that led us to the Cueva de la Amos. Access is the same as for the Galera Seismites Trail. This viewpoint is a magnificent place to observe the sediments and rocks that accumulated in the Baza palaeolake as well as to imagine the extent of that great lake, which covered the territory from Jabalcón to the vicinity of Huéscar and Orce. From the River Galera Valley Viewpoint, as well as questions concerning the great lake that existed during the endorheic stage, we can observe issues related to the formation of the valleys in the Geopark, such as the river terraces, perfectly developed and preserved in this section of the River Galera. It is also an outstanding place for understanding the relationship between geomorphology, vegas (fertile plains) and prehistoric settlements, such as Castellón Alto, perfectly recognizable from the viewpoint.

Gálvez plain. Terrace and meanders of the River Galera.



From this viewpoint you can see the three major landscapes of the Granada Geopark: its mountains, the great plain (for which the geological name is a glacis) on which the town of Huéscar stands, and the valleys of our rivers, such as the River Galera valley. However, this landscape is very recent from a geological point of view, since the valley we see now began to form half a million years ago, when the territory had already been inhabited by humans (as the nearby Orce sites testify) for nearly a million years more. So those first inhabitants of this territory would only have recognized the mountain ranges we can see from here, which at that stage bordered the great Baza lake. The sediments that accumulated in that lake now form the hills such as this one we are standing on.

Today, thanks to the erosion of the River Galera and its small tributaries, we can see and touch the sediments of the ancient lake and the landscape of ravines, hills and fertile plains that reaches our panoramic gaze.



The valley of the River Galera contains one of the oldest fertile plains in Europe, already cultivated nearly 4000 years ago by the inhabitants of the settlements located along the valley.

In this panoramic view the terrace known as the "Gálvez Plain", which represents the position of the River Galera some 4000 years ago, can be recognized. This was the surface cultivated by the inhabitants of the castellones, settlements located on the left bank of the River Galera. The lower river terraces are more recent and have been cultivated from Roman times to the present day.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