Trabajo Fin de Máster

Máster en Geología: Técnicas y Aplicaciones

Estructura alpina y relaciones tectónica-sedimentación en el sector de Las Cuevas de Cañart (Cordillera Ibérica)

Alpine structure and tectono-sedimentary relationships in the Las Cuevas de Cañart sector (Iberian Chain)

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Table of Contents

Resumen

El sector de las Cuevas de Cañart es un sector complejo, en la zona de Enlace de la Cordillera Ibérica con las Cadenas Costeras Catalanas. Está caracterizado por la confluencia de tres direcciones estructurales distintas (NE-SW, N-S y E-W), con estructuras cuya formación se ha ido superponiendo a lo largo de la etapa compresiva que dio lugar al levantamiento de la cadena.

Para el estudio del sinclinal de las Cuevas de Cañart se han aplicado técnicas de cartografía geológica y geología estructural. Mediante la definición de una serie estratigráfica local, se ha realizado una cartografía geológica de detalle (escala 1:15.000), cortes geológicos perpendiculares a las principales estructuras y análisis estructural a la escala de afloramiento. Se destaca también la importancia dada al análisis de estructuras que afectan a las series sedimentarias sintectónicas, que permiten establecer una relación temporal entre los estadios de deformación con la sedimentación y datar de forma relativa las distintas estructuras.

Se propone una interpretación general para la formación de las estructuras, que se debe considerar preliminar, debido a la complejidad de la zona. A partir de las observaciones y teniendo en cuenta el contexto estructural de la Cordillera Ibérica, se puede inferir con cierta fiabilidad, una probable secuencia de direcciones de plegamiento (N-S, NE-SW, E-W), asociada a dos modelos de cuenca que probablemente se combinaron durante la etapa compresiva: Foreland/Piggy-back y transpresión (con una posible componente de pull-apart).

Abstract

The Las Cuevas de Cañart sector lies within the Linking zone of the Iberian Chain, in its confluence with the Catalonian Coastal Range. It is a complex sector characterized by the convergence of three different structural directions, NE-SW, N-S and E-W, that have overlapped over time, during the compressional stage that defined the structure of the range during the Cenozoic.

The study of the Las Cuevas de Cañart sector is based on geological mapping and structural geology techniques. For this, we have defined a local stratigraphical series, made a detailed geological map (1:15.000 scale), geological cross-sections perpendicular to the main structures, and a mesoscale structural analysis. The importance of the analysis of the syntectonic structures is also worth mentioning, given that they allow to set a chronological frame for the deformation and the sedimentation of the alluvial syntectonic units.

Because of its structural complexity, the interpretation of the results is not totally conclusive and some ambiguities remain. Nevertheless, taking into account the Iberian Chain context, it allows us to infer, up to a certain certainty degree, a probable folding chronology (N-S, NE-SW, E-W), associated with two end-member complex basin models that probably combined during basin formation:Foreland/Piggy-back and Transpression/Pull-apart.

1. Introduction

The Iberian chain has been subject of many structural geology, sedimentology and tectonosedimentary studies. However, its tectonic evolution is still a matter of debate, particularly when it comes to the interference patterns between different folding directions and their relationships with the Iberian context.

In this work, we try to increase the knowledge in this line of studies, with the study of the Las Cuevas de Cañart syncline, a structure that has not been extensively analysed from the structural point of view, mentioned only in a handful of published works.

This sector is particularly interesting, because there are three structural directions out cropping (N-S, NE-SW and E-W), some of which (E-W) are not commonly found in the Iberian chain. Because of this, and alongside with its size, geographical location and easy accessibility, the Las Cuevas de Cañart sector is an extraordinary location, presenting itself as a singular opportunity to study the different compressional stress-fields that were active during the Cenozoic period.

2. Objectives

This master thesis aims to characterize the contractive alpine structure in a sector that belongs to the Iberian chain, through structural geology and geological mapping techniques. This structure is located in the Las Cuevas de Cañart sector, in the linking zone of two mountain ranges, the Iberian Chain and the Catalan Coastal Ranges, characterized by the existence of different structural trends (NE-SW, NW-SE and E-W).

To achieve the above-mentioned main objective, the following specific objetives were considered:

- To develop a detailed geological map of the Las Cuevas the Cañart syncline, allowing to characterize in detail the geological structure of the area, according to the definition of the stratigraphic series.

- To define the geometry of the the different unconformitites within the Mesozoic, and especially, the Cenozoic sequences as markers of the deformational structures.

- To define and interpret structures resulting from fold interference and their relationships with mesostructures observed at the outcrop scale.

- To build an evolution model of the Las Cuevas de Cañart syncline, considering the different deformation stages chronologically ordered and their tectonic context, through the analysis of the kinematics of folding.

- To reach a first approach to the different stress fields that the units have experienced through time and their relationships with macrostructures.

3. Methodology

In order to achieve the previously mentioned objectives, different techniques were applied. They can be organised into three different groups, each one connected to a different stage of the project.

The objective of the planning stage is to have an overview of the previous works in the sector and to plan how to tackle the different obstacles that may come up.

The first step of the work is to get a first approach to geological mapping through aerial photography analysis with a stereoscop, and satellite images analysis through qGIS and Google Earth pro. This provides a first approach for determining how many geological units have to be distinguished, and possible sets of of structures (faults and folds), according to their direction. Observations obtained from this first approach were compared with previous works such as Canérot *et al.*, (1979) and González *et al.*, (1989). This also gives a perspective of the validity of previous authors' assumptions in relation to the objectives of our work. This stage is directly connected to the two subsequent tasks, not only because the bibliographical research conducted here affects them directly, but also because the next stages are planned upon this first approach, i.e. the field campaigns that are programmed for the second stage of the work and how to tackle the data analysis that happens on the third one.

The second stage consists of field campaigns that summed up to 16 full days of field work distributed throughout the year. These were both organised in campaigns of 4 days, as a way to optimize the usage of the financial and time resources, and single day campaigns, as a last resource. The objective for the aforementioned campaigns is to both verify the analysis of the aerial photography and satellite images and to collect as many field data (orientation of bedding, foliation, fault planes, fold hinges, angular unconformities and lithological limits verification, among others) as possible. For this, tools such as a geological compass, GPS and satellite images were used, to measure the data when need be, and to geographically reference the measurement site, alongside with field pictures taken in order to illustrate, throughout the final report, different noteworthy situations.

All these data were analysed and interpreted during the third and final stage. For that, the programs Google Earth pro, Adobe Illustrator and qGIS were used to map, delineate, vectorize and georeferentiate the different geological units and structures mapped during the previous stages. The orientation of structures was represented in detail through the program Stereonet, and the main structure through geological cross sections. All these analyses were compared to previous works connected to the same sector or the surrounding areas.

4. Previous works

The Las Cuevas de Cañart sector lies within the linking zone of two thouroughly researched mountain ranges, the Catalan Coastal Range and the Iberian Chain. Even though the linking zone itself has been at the centre of many research papers, PhDs and other published works in the past, this particular sector has been neglected, with around 6 published works referencing it – Canérot *et al.*, (1979), Simón, (1979), Guimerà, (1988), González *et al.*, (1989), Canérot *et al.*, (1982) and Margarit, (2019) – none of which is fully capable of describing the structural complexity that characterizes this sector.

Both Canérot *et al.*, (1979) and González *et al.*, (1989), were able to map the mentioned sector up to a certain point, reaching however different structural interpretations of the main structure that complement each other. In Canérot *et al.*, (1979), the authors mention a basin consisting of a syncline whose hinge line plunges towards the SW, emerging again over the thrust fault of the Ejulve High, with three sets of structures, SW-NE, WSW-ENE and SE-NW. According to the same authors, the area is bounded to the North by an important thrust, the Castellote-Herbers thrust, that has a SE vergence, and to the south by the *Ladruñan* Anticline with an opposite vergence.

While the main structure remains a syncline for González *et al.* (1989), they propose that this structure has a fault at its core. Their work is, however, more focused in the Cenozoic units that fill its core, identifying up to four tectonosedimentary units (see below). They have been compared with other Iberian basins by Guimerà, (1988) Finally, Simón,. (1979) admits that the fold interference in this sector can be interpreted in different ways, such as a small example of a dome and basin structure.

5. Geographical context

The studied area is a 15 km^2 sector named after the Las Cuevas de Cañart village that is located at its center. It is located South to the municipality of Molinos, in the northern zone of Maestrazgo district, Teruel province, Aragón, Spain.

This sector is encapsulated by the Garrocha mountains from the South, and by the district of Bajo Aragón by the North, (sheet 519-I Molinos of the national topographic maps at a 1:25.000 scale). The topographic features here variate between 1200 m, at Fuente de San Juan, and 700 m in El Estrecho, where we can find the Barranco del Estrecho gully.

6. Geological context

The Las cuevas de Cañart sector is located in the linking zone between the Iberian and the Catalan Coastal Chains (Fig.1 a, b), specifically in the Morella subbasin, within the Maestrazgo basin. The sector is represented in the sheet 519 (Aguaviva) of the IGME's geological maps in a 1:50.000 scale (Fig. 1 c).

6.1 Iberian Mountain Range

The Iberian Chain is an intraplate mountain range with an approximate NW-SE direction, and a moderate deformation rate. It was developed by a positive inversion of the extensional Mesozoic Iberian basin, caused by compression both normal (NNE to NE) and parallel (SE to SSE) to its boundaries (Liesa *et al.*, 2018). The normal compression occurred during the Middle Eocene to Late Oligocene, and was responsible for the main folds and thrusts. The parallel compression took place during the Early Miocene, when the effects of the convergence between the Iberian and African plates were transferred from the Pyrenean to the Betic margin of Iberia.

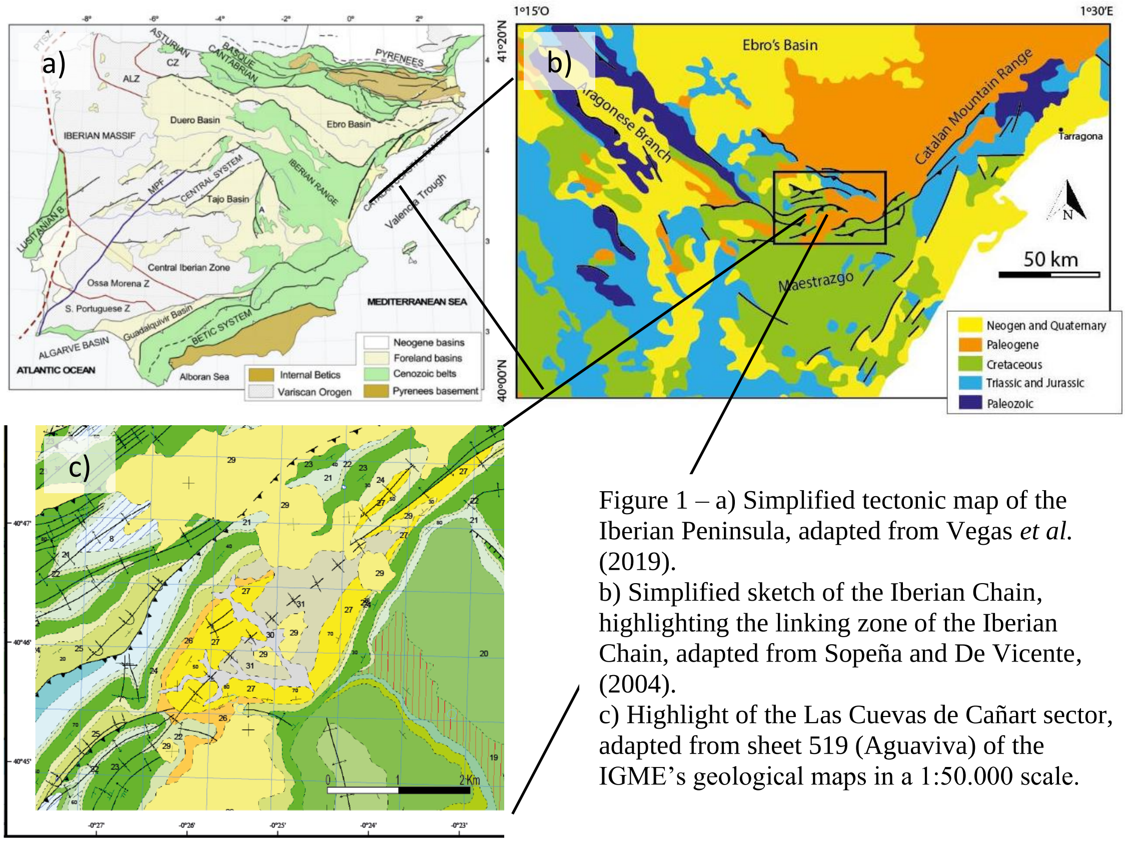

Figure 1 – a) Simplified tectonic map of the Iberian Peninsula, adapted from Vegas *et al.* (2019).
b) Simplified sketch of the Iberian Chain, highlighting the linking zone of the Iberian Chain, adapted from Sopeña and De Vicente, (2004).
c) Highlight of the Las Cuevas de Cañart sector, adapted from sheet 519 (Aguaviva) of the IGME's geological maps in a 1:50.000 scale.

The Iberian Chain can be divided into five main sectors, the Cameros unit and the Aragonese and Castillian Branches, the Linking Zone and the Levante sector.

According to some authors, there are three main tectonic episodes that helped to shape the Iberian Chain – the Mesozoic rift, the Alpine compression and the Neogene extension. The first one is associated with the propagation of the Northern Atlantic rift (Salas *et al.*, 2001) and is responsible for some of the extensional complex basins that are found within the Iberian plate. These basins were formed by high angle normal faults, with a NW-SE direction (Álvaro *et al.*, 1979), that belong to the Iberian rift system. The second episode is dominated by the Alpine compression, dating from the Oligocene. It produces the main structures found in this chain such as folds and thrust faults with a NW-SE direction that are later overlapped by another series of WSW-ENE and E-W folds (Álvaro *et al.*, 1979; Salas and Casas, 1993; Liesa, 2011; Liesa *et al.*, 2018). The final stage mentioned above is associated with the opening of the Gulf of Valencia during the Neogene-Quaternary, that originated multiple basins oblique to the Iberian chain compressive structure (Capote *et al.*, 2002).

6.2 Catalan Coastal Ranges

The Catalan Coastal Ranges constitute a NE trending fold-and-thrust belt, covered with Mesozoic (mainly) carbonated deposits (Salas *et al.*, 2001). Its deformation dates from the Eocene up to Late Oligocene, (Anadón *et al.*, 1985), and it happened through a sinistral transpressional motion along NE faults. These faults were later responsible for the NW verging reverse faults that directly affected the thrusting of the basement and Mesozoic cover, over the Paleogene deposits of the Ebro Basin (Salas *et al.*, 2001).

To some extent, both the evolution of the Mesozoic basins and the Cenozoic tectonic inversion that followed, are quite similar for the Iberian and Catalonian Coastal ranges, up to a point where some authors (Guimerà, 2004) consider the second to be a part of the first.

6.3 Linking zone

This is the area where structures normally associated with the Iberian chain, NW-SE, converge with others associated with the Catalan Coastal chain, NE-SW. Aside from this, it is also possible to find structures with an intermediate direction, approximately E-W, namely thrust fault structures (Salas *et al.*, 2001). This area is the result of the Cenozoic tectonic inversion of the Maestrazgo Basin (Guimerà and Salas, 1996). Some seismic profiles and boreholes that were made in the southern area, indicate that some of these thrust fault structures reach the Variscan basement (Salas et al., 2001).

The northern part of the linkage zone is characterized by a low-angle thrust belt, detached at the “middle Muschelkalk” evaporitic facies (Vegas et al., 2019).

6.4 The Maestrazgo basin and the Morella subbasin

The Maestrazgo basin is one of the Mesozoic extensional basins found in the Iberian Mountain Range. These basins, according to Martín-Chivelet *et al.* (2002), were formed during the rifting and postrifting stages of the Iberian Rift system.

The first stage, which consists of a rifting that dates to the Permian and the Triassic, coincides with the first stage of the formation of the Iberian Chain previously described. This stage is followed by a postrift stage, during the Early Jurassic time, where there was a generalized subsidence of the Iberian basin that, together with some eustatic fluctuations, was responsible for a marine transgression (Álvaro *et al.*, 1979 and Salas, 1987). This transgression influenced the deposition and filling of the basins until the Middle Jurassic. During the third stage, Late Jurassic and up to the Early Cretaceous, there was an extensional stage that is normally associated with the opening of the Bay of Biscay (Álvaro et al., 1979). During this third stage, the Maestrazgo basin was divided into different subbasins - Oliete, Galve, Salzadella, Penyagolosa, Las Parras, El Perelló and Morella (Salas *et al.*, 2001). The fourth stage corresponds to the Late Cretaceous thermal subsidence throughout eastern Iberia.

The subbasin of Morella lies within the NW sector of the Maestrazgo Basin. This sector is controlled by listric faults that dip towards the South with an ESE-WNW direction, like the Herbers and Utrillas thrusts (Guimerà and Salas, 1996; Antolín-Tomas *et al.*, 2007; Nebot and Guimerà, 2016). Because of the collision between the African and European plates, this basin, like many others, underwent a tectonic inversion during the Late Eocene-Early Miocene, with several compression directions of the stress fields: NE-SW, NNE-SSW and SE-NW (Liesa and Simón, 2007; 2009).

6.5 Lithological units

The outcropping rocks in this sector vary between Jurassic or Cretaceous carbonates and Cenozoic siliciclastic rocks, such as conglomerates, clays and sandstones (Canérot *et al.*, 1979) (Fig. 2). According to the same authors, there are several different units that crop within the Las Cuevas de Cañart sector:

- Dolostones, dolomitic breccias, and grey limestones (Rhaetian-Hettangian)
- Limestones and marlstones (Lower Jurasic – Kimmerdgian)

- Limestone, breccias with dark clasts and dark grey limestones (Valanginian)
- Red and grey marlstones with sandstones and limestone levels (Hauterivian)
- Bioclastic limestones and marlstones (Barremian – Lower Aptian)
- Marlstones (Lower Aptian)
- Bioclastic limestones and marlstones (Upper Aptian)
- Sandstones with carbonaceous layers and limestone beds (Upper Aptian– Albian)
- White to violet sands with ferruginous concretions (Albian)
- Bioclastic limestones and marlstones (Albian – Cenomanian)
- Crystalline limestones and Dolomites (Cenomanian – Senoniam)
- Intercalations of limestones, argillaceous limestones and marlstones, and variegated marlstones (Senonian)
- Granular white limestones (Senonian)
- Red clays, marlstones, sandstones and conglomerates (Paleocene)
- Conglomerates, clays and sandstones (Oligocene)

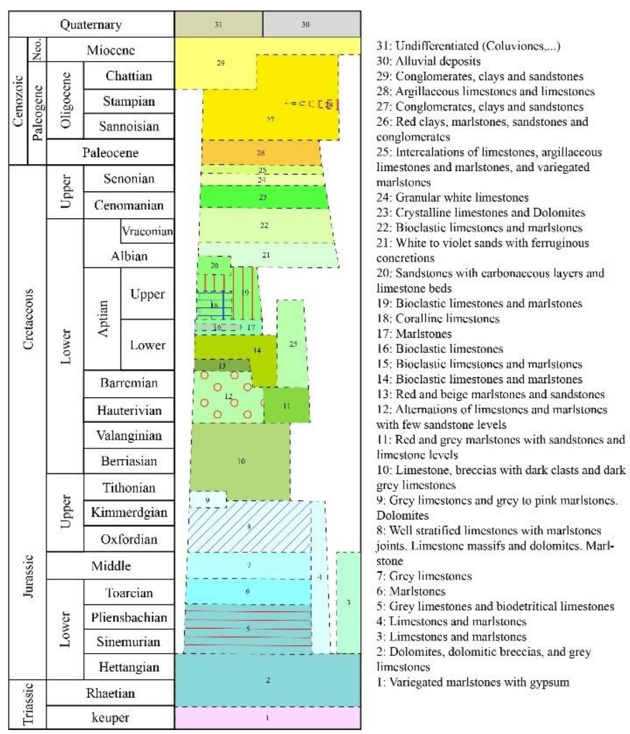

Figure 2 – Stratigraphical column, adapted from Canérot *et al.* (1979).

- Conglomerates, clays and sandstones (Oligocene-Neogene)

- Alluvial deposits (Quaternary)

- Undifferentiated (Collivial and alluvial deposits, …) (Quaternary)

González *et al.,* (1989) studied the Cenozoic filling of the basin and divided them into four tectono-sedimentary units (Fig. 3):

- First unit – Succession of grey conglomerates with carbonated and conglomeratic clasts, red clays and pink to beige limestones. Paleocurrents indicate sedimentary contributions sourced in the E.

- Second unit – Represents a complex cyclical evolution, asymmetrical towards the top, being the upper hemicycle more developed. It consists of grey conglomerates with carbonated clasts, intercalated by red clays and, towards its top, yellow sandstones. There is one important layer of multicoloured limestones intercalated by red clays and grey conglomerates. It is possible to observe stream flood and braided stream facies.

- Third unit – Also composed by a succession of grey conglomerates, with carbonated clasts, intercalated by red clays. Its lower limit forms an angular unconformity with the previously mentioned unit, and its upper limit forms a syntectonic unconformity with the fourth unit.

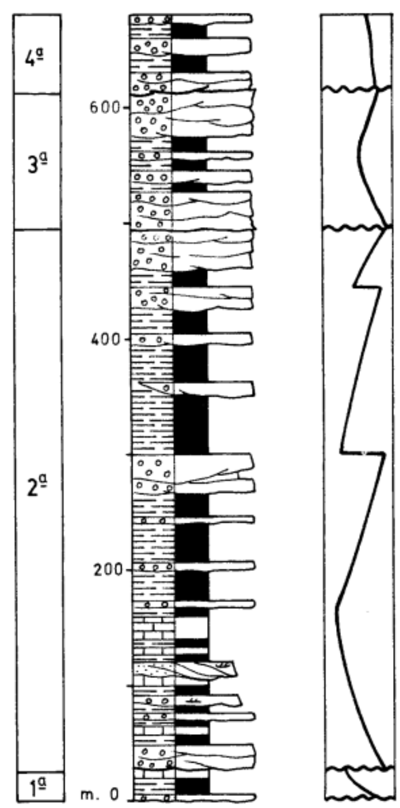

Figure 3 – Lithological column for the Cenozoic units, adapted from González *et al.* (1989).

- Fourth unit – The strata that compose this unit, which consists of a succession of grey conglomerates, with occasional intercalations of red clays, are horizontal. Paleocurrents indicate sedimentary contributions from the SE.

7. Results

The results presented in this chapter are divided into four main groups:

- Stratigraphical results, which consist in a proposal for the local lithological series, modifying the existing divisions and units

- Analysis of the main structure at the map scale

- Tectono-sedimentary relationships

- Analysis of specific mesostructures

7.1 Stratigraphy

The proposed series (Fig. 4) aims to, in a simplified way, characterize the different units found in the Las Cuevas de Cañart sector. For this, the units described in the previous chapter, as well as field observations, were taken under consideration. The final division follows the classic stratigraphical units defined for the Cretaceous and Jurassic of the Iberian Basin (Gómez and Goy, 1979; Canérot *et al.*, 1982). For the Cenozoic units, this series is based on the division proposed by González *et al.* (1989) verified through field observations.

Keuper facies

Although this unit does not crop out within the Las Cuevas de Cañart sector, it is exposed nearby. It dates to the Late Triassic, and it consists of clays and green to red shales. It contains gypsum that belongs to the original sediments, which subsequently recrystallized as veins that cut across clays (Gómez and Goy, 1979).

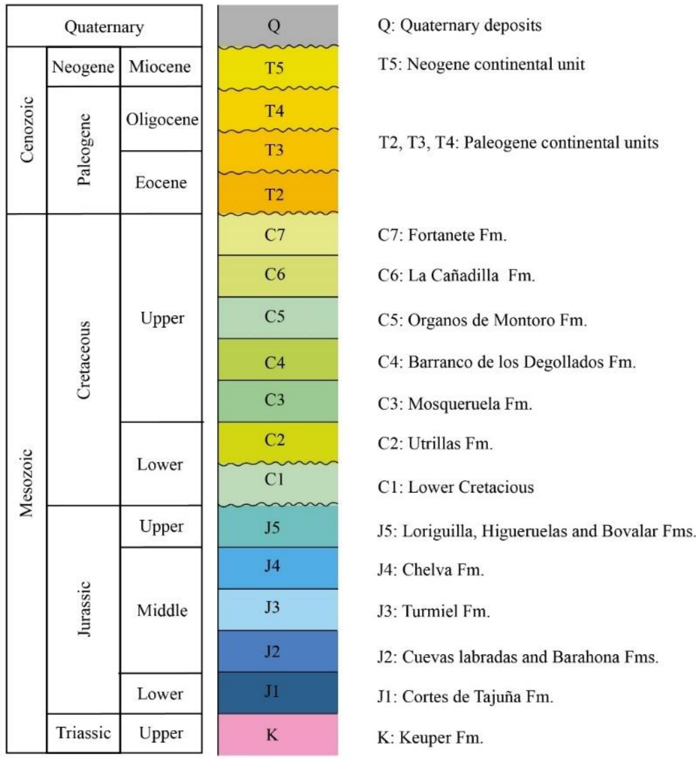

Figure 4 – Synthetic stratigraphic column with the proposed series.

Cortes de Tajuña Formation

The Cortes de Tajuña Formation consists of brecciated dolomites with a pink to grey colour and a massive appearance, dating of the Late Triassic-Early Jurassic. (Gómez and Goy, 1979).

This unit may reach around 100 m of thickness and crops out just outside the sector, over the northern limb of the Las Cuevas de Cañart syncline.

Cuevas Labradas and Barahona Formations

The Cuevas Labradas Formation consists of micritic limestones forming well-defined layers and dolomites. The upper layers of this unit present bioclastic levels with fragments of crinoids, brachiopods and molluscs. The Barahona Formation consists of grey bioclastic and bioturbated limestones, with fragments of brachiopods, belemnites and echinoderms. Both formations date to the Middle Jurassic. (Gómez and Goy, 1979; Gómez *et al.*, 2003*)*

These two formations were grouped in the map and cross-sections because the second one has a very low thickness; together, they have an approximate thickness of 75 m within this sector.

Turmiel Formation

The Turmiel Formation, dating to the Middle Jurassic, consists of white to yellow marls with ammonite and brachiopod remains, alternating with limestones (Gómez and Goy, 1979; Gómez *et al., 2003)*.

Within the sector, the unit reaches around 100 m of thickness in the northern limb of the Las Cuevas de Cañart syncline.

Chelva Formation

The Chelva Formation, dating of the Middle Jurassic, is composed of limestones and dolomites with chert nodules, and bioclastic limestones with ostreidae, echinoidea and brachiopod remains (Gómez and Goy, 1979; Gómez *et al.*, 2003). Within this sector, it reaches a maximum thickness of 170 m.

Loriguilla and Higueruelas Formations

The Loriguilla Formation consists of a well-bedded rhythmic alternation of silty mudstones and marls, while the Higueruelas Formation is made of massive white to grey grain-supported, peloidal and oncolite limestones (Aurell *et al.*, 2019).

These two Upper Jurassic formations, together, reach about 150 m in thickness within the sector.

Lower Cretaceous

Whitin this map unit, we group the La Pleta, Ladruñán, Herbers, Cantaperdius, Artoles, Morella, Chert, Forcall, Villarroya de los Pinares and Escucha formations (Canérot *et al.,* 1982; Margarit, 2019). Both the upper and lower limits of this unit are angular unconformities, and its upper limit crops out in the southern limb of the Las Cuevas de Cañart syncline. The whole unit approximately reaches 800 m in thickness.

Utrillas Formation

The Utrillas Formation, an Early Cretaceous unit (Albian in age in this sector), consists of layers of multicoloured, poorly compacted sand and sandstones (from white and yellow to red and brown), alternating with multicoloured clay levels. Locally, it is possible to find ferruginous nodules (Canérot *et al.*, 1982).

The base of this unit represents an erosive surface onto the underlying Lower Cretaceous units. The average thickness is about 200 m, which decreases towards the South, locally disappearing under the Mosqueruela Formation.

Mosqueruela Formation

The Mosqueruela Formation is the first of the Upper Cretaceous units and consists of an alternation of limestones and marls with ostreideae, orbitoline and rudist remains in its lower half. The upper half of this unit is formed by a succession of well-bedded white limestones (Canérot *et al.*, 1982).

In the Las Cuevas de Cañart sector, this unit reaches a maximum thickness of approximately 75 m and crops out in both limbs of the main structure, decreasing its thickness towards the S.

Barranco de los Degollados Formation

The Barranco de los Degollados Formation, formed during the Late Cretaceous, consists of dolomitic limestones and white, crystalline massive dolomites (Canérot *et al.*, 1982).

This formation has an average thickness of 75 m, locally decreasing towards the S in the studied sector.

Órganos de Montoro Formation

The Órganos de Montoro Formation dates to the Late Cretaceous. It is characterized by thin, well-bedded, brecciated grey to white limestone layers, easily identifiable by the presence of darker clasts. Its upper part consists of small binary sequences of limestones and marls with rudists (Canérot *et al.*, 1982).

In the studied sector, this unit reaches a maximum thickness of 125 m, decreasing towards the southern limb of the Las Cuevas de Cañart syncline.

La Cañadilla Formation

The La Cañadilla Formation consists of alternating white marls and limestones with a predominance of limestone at its base and marls at its top, with important rudist levels (Canérot *et al.*, 1982).

In the Las Cuevas de Cañart sector, this unit has a maximum thickness of 250 m, also decreasing towards the South.

Fortanete Formation

The Fortanete Formation represents the last of the Cretaceous units. It consists of heavily brecciated dark continental limestones, at its base, alternating with thick grey marlstone levels towards its top (Canérot *et al.*, 1982).

In this sector, this unit is mainly represented by the previously mentioned thick beige to grey marls. It reaches a maximum thickness of 70 m, decreasing towards the S, and is bounded by an angular unconformity at its top, where it is overlain by the Cenozoic units (Canérot *et al.*, 1982).

In the Las Cuevas de Cañart sector, this unit has a maximum thickness of 250 m, also decreasing towards the South.

Cenozoic tecto-sedimentary units T1, T2, T3, T4 and T5

These units consist of alternating grey conglomerates, sandstones, and mudstones/clays (González, 1989).

The T1 unit would possibly correspond, according to the same authors, to a thin layer of red clays that crop out only at the northern limb of the main structure. Because of its low thickness we have not considered it in maps and cross-sections.

Lying onto T1 is the T2 unit that dates to the Early Eocene. This unit crops out at the southern and northern limbs of the syncline structure, reaching a maximum of 25 m in thickness. Its conglomeratic base represents a sedimentary rupture onto the marl deposits of the Fortanete Formation and T1 unit.

The T3 unit lies onto the T2 unit, and partially on the Fortanete and La Cañadilla Formations through an angular unconformity, while it has an onlap geometry towards the E. It was sedimented during the Late Eocene-Early Oligocene, reaching a maximum thickness of 470 m in the Las Cuevas de Cañart sector. It crops out at the centre of the syncline, occupying its core.

The T4 unit lies onto the T3 unit, as well as on several of the Cretaceous ones and it dates to the Oligocene. It crops out at the centre of the syncline and reaches an approximate thickness of 120 m. Both its lower and upper limits are angular unconformities and, locally, the upper limit consists of a syn-tectonic unconformity.

The T5 unit, formed during the Early Miocene, is the most recent out of this group. It crops out attached both to the northern and southern limbs of the main syncline forming an angular unconformity with the previous units. Its maximum thickness within the sector is approximately 70 m.

Quaternary deposits

The Quaternary deposits include detrital alluvial and colluvial deposits, a small piedmont on the northern limb of the Las Cuevas de Cañart syncline, as well as an important tuff system. These deposits cover the previously described formations, originating another angular unconformity.

7.2 Analysis of the main structure at the map scale

To better understand the structure of the Las Cuevas the Cañart sector, and to improve the existing geological map, the sector was mapped in detail at a 1:15.000 scale (Fig. 5). For a more detailed analysis of the Cenozoic units, see Annex 1.

To analyse the main structure, and the multiple structures found within, three cross-sections were drawn (Fig. 6):

- The A-A' cross-section (Fig 6 b) intends to represent the main structure, as well as the main thrust on the North and the Cenozoic deformation of the T3 and T4 units.

- The B-B'-B'' (Fig 6 c) aims to provide a picture of the double thrust system, as well as the E-W folds that affect the Cretaceous units.

- The C-C'-C'' (Fig 6 d) depicts both the main structure and the N-S structures on the West, that affect both Cretaceous and Jurassic units.

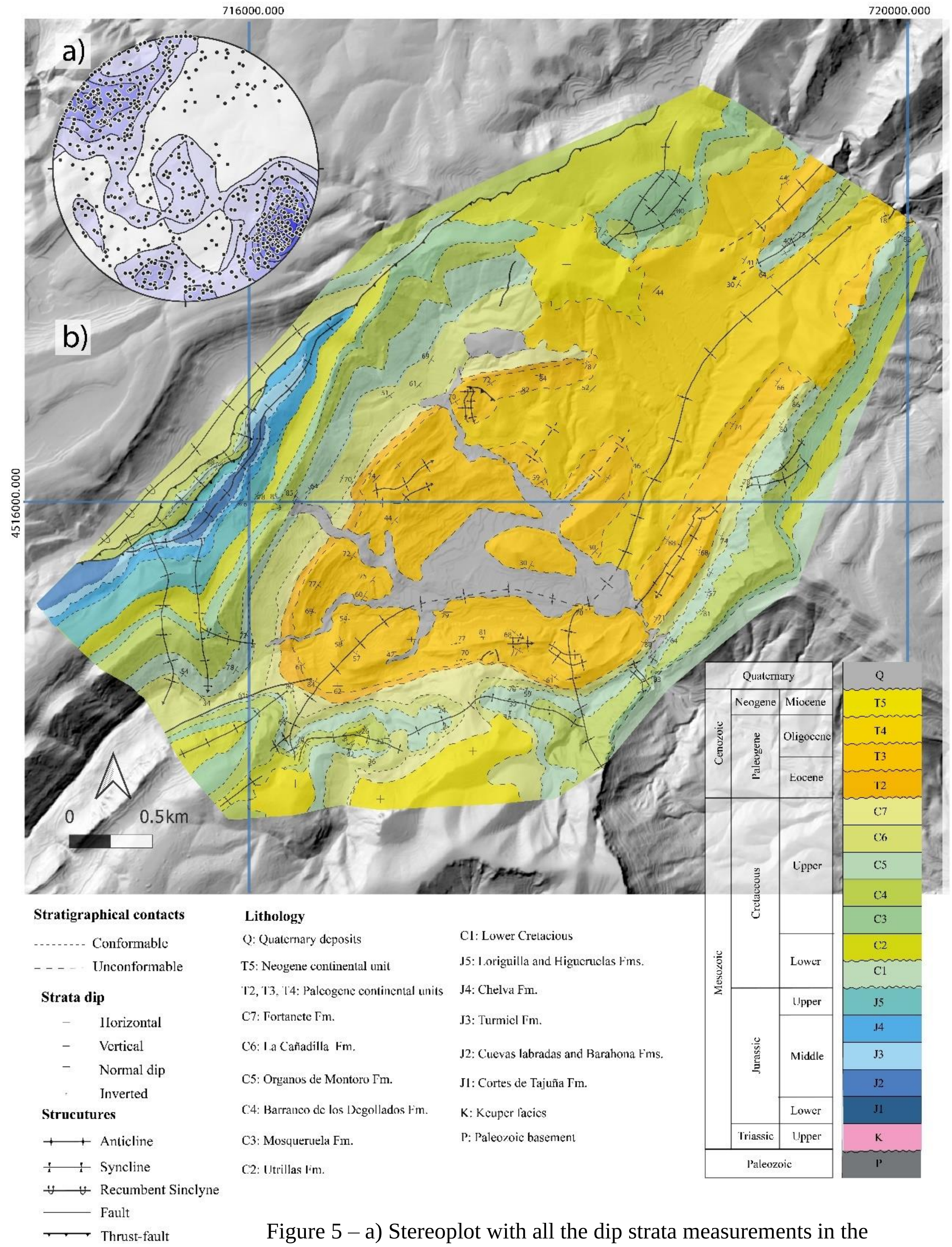

Figure 5 – a) Stereoplot with all the dip strata measurements in the sector.
b) Detailed geological map, at a 1:15.000 scale, of the Las Cuevas de Cañart sector and respective legend. Colour scale according to figure 4. (For a more detailed analysis of the Cenozoic units, see Annex 1).

To draw these cross sections, both the Jurassic limestones and the carbonate Cretaceous units are considered to be parallel and to have a constant thickness when possible. For the remaining units (Fortanete Fm. and the Cenozoic units), containing a significant proportion of mudstones, increases in thickness at the hinge of anticlines are allowed. This means that their thickness variation throughout the sections is partially linked to deformation, particularly in the hinges of the folds, and partially connected to their formation, particularly the thinning towards the borders of the basin at the time of their formation.

The main structure represented in figure 5 is the Las Cuevas de Cañart syncline. It is a braquisyncline, with a SW-NE direction and NW vergence, with Cretaceous and Jurassic units at its borders and Cenozoic units at its core. It has an approximate amplitude of 1200 m and an approximate wavelength of 6000 m.

In its northern limb, the structure is controlled by a double thrust system. The upper thrust affects both the Cretaceous and Jurassic units and has approximately 400 m of displacement. Its footwall is characterized by a very tight, symmetric syncline, with the Órganos de Montoro Formation at its core and two sub-vertical limbs. The lower thrust affects the same units with an approximate displacement of 100 m. Its footwall is characterized by an asymmetric syncline, with the La Cañadilla Formation at its core and a NW vergence, which can be locally described as a recumbent fold. In this limb, an angular unconformity, with the Mosqueruela Formation directly on top of different Jurassic units (Chelva, Loriguilla and Higueruelas Formations), is also visible. This means that this unconformity represents an erosive surface since the entire Lower Cretaceous unit is missing.

To the South, the Las Cuevas de Cañart syncline is bounded by the Ladruñán Anticline the Estrecho Anticline (Margarit, 2019) and another Cenozoic structure (Canérot *et al.*, 1979). The Ladruñán Anticline affects both Upper Jurassic and Cretaceous units and has an overall N-S direction, slightly curving towards its northern and southern tips. It is an asymmetric anticline with strata dipping between 15-30ºW (Lower Cretaceous units in its western limb), 45ºW (Upper Cretaceous units in the western limb) and 5-10ºE (Upper Cretaceous units in the eastern limb). The structure also presents a periclinal border to the

North, and a graben structure at its hinge, composed of NW-SE faults, dipping towards NE and SW. It is also evident a post-rift unconformity, with the Utrillas Formation lying directly on top of the Cantaperdius, Artoles, Morella, Chert, Forcal, Villarroya de los Pinares, and Escucha Formations (Margarit, 2019).

The Estrecho Anticline has an ENE-WSW direction and affects the Ladruñán and Herbers Formations. It is an asymmetric fold with an axial plane dipping 70º towards the South and a 2º plunge towards the East. The southern limb has a maximum dip of 34ºS whilst the northern limb dips 56ºN (Margarit, 2019).

In the southern limb of the Las Cuevas de Cañart syncline, the Mosqueruela Formation lies directly on top of the Lower Cretaceous unit. This means that the Utrilllas Formation either did not deposit here or was eroded, thus forming an angular unconformity. There is also a general decrease in the thickness of units compared with the other limb, which may be a result of tectonic movements at the time of their formation.

The overall structure, as previously stated, is an asymmetric syncline verging towards the NW and plunging towards the SW, faulted at its core (Fig. 6). The thrust fault system depicted in figures 6a and 6b shows a ramp geometry in both walls and is responsible for the two footwall synclines and the hanging wall anticline, depicted in the same figure. It uses the Keuper facies as a detachment surface and reaches the basal décollement at a 2.5 to 3 km depth, where it tends to become horizontal. This interpretation considers the existence of an irregular basement with a low zone in the middle, consistent with a graben structure. However, there are other interpretations that could be considered, such as a flat basement top with a thickening of the detachment level towards the margins of the main structure.

Based on these cross-sections, it is possible to infer that the upper thrust was the first one to be formed, originally as a normal fault that was subsequently reactivated as a reverse fault, originating the hangingwall anticline and a footwall syncline. The lower thrust, formed during a subsequent deformation stage (in normal–footwall sequence), cutting across the footwall syncline. After this, the deformation continued, developing the above-mentioned structures, tightening the folds, which also resulted in steepening of thrusts up to a close-to-vertical position.

To the South, there is a blind fault involving the basement, probably responsible for some of the thickness variations of the Lower Cretaceous units during the extensional stage.

The Cenozoic pocket reaches approximately 1 km in thickness and is faulted at its core by a (Paleogene-Neogene) reverse fault (Fig. 6a).

The angular unconformities (Upper Jurassic-Lower Cretaceous, Lower Cretaceous-Utrillas Formation, Utrillas Formation-Mosqueruela Formation, Fortanete Formation-T2, T2-T3, T3-T4, T4-T5), are also observable in the cross-sections.

Throughout the Las Cuevas de Cañart syncline, both the Mesozoic and Cenozoic units are affected by three sets of structures: SW-NE, N-S and E-W (Fig. 7). These different sets will be described, separately, in the next subsections.

SW-NE structures

The SW-NE set of structures has, out of all three, the clearer expression (Fig. 7 a). The Las Cuevas de Cañart syncline belongs to this set. In both limbs, it is possible to find both Cenozoic and Mesozoic overturned layers. Its hinge plunges 61º towards the NE, and its limbs dip between 50 and 70º (see stereoplot 6 of Fig. 7b).

On the southern limb of the Las Cuevas de Cañart syncline, affecting the T3 unit, there is a syncline-anticline structure (Fig. 7b stereoplot 2). This structure is plunging 23º towards the S and verging towards the E. On the northern limb, there is also a syncline-anticline structure (Fig. 7b, stereoplot 8). This structure plunges 36º towards the NW, it is asymmetric, and it verges towards the N.

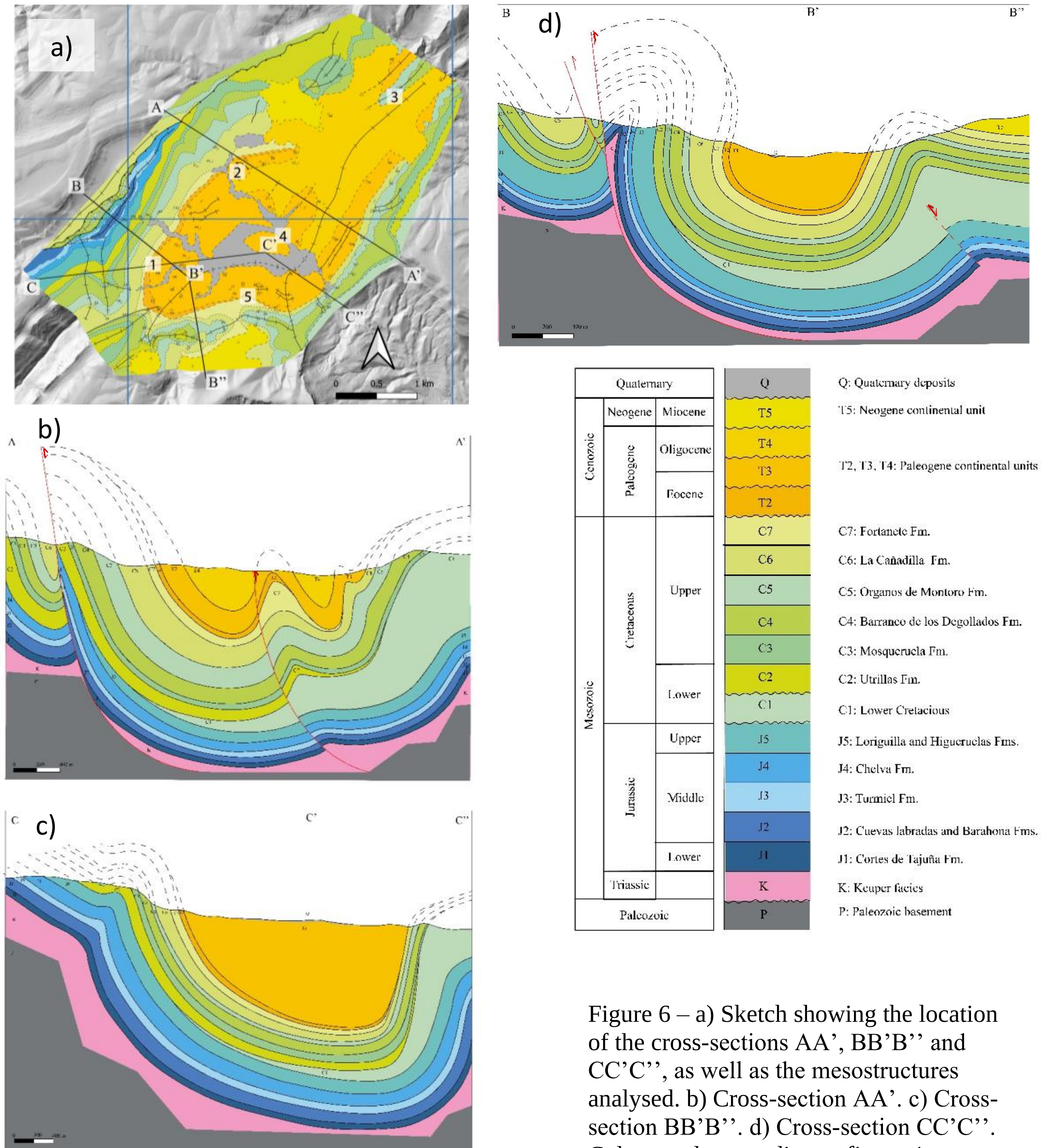

Figure 6 – a) Sketch showing the location of the cross-sections AA', BB'B'' and CC'C'', as well as the mesostructures analysed. b) Cross-section AA'. c) Cross-section BB'B''. d) Cross-section CC'C''. Colour scale according to figure 4.

N-S structures

The N-S set affects most of the units as well, but it is not so well represented as the first one (Fig. 7b, stereoplots 7 and 9).

the first stereoplot (Fig. 7b, stereoplot 7) refers to the N-S anticline that crops out in the western corner of the studied sector. It is a box fold that affects both Cretaceous and Jurassic units, with an eastern limb dipping 54ºW, a southern limb dipping 78ºS and a western limb dipping 77ºS.

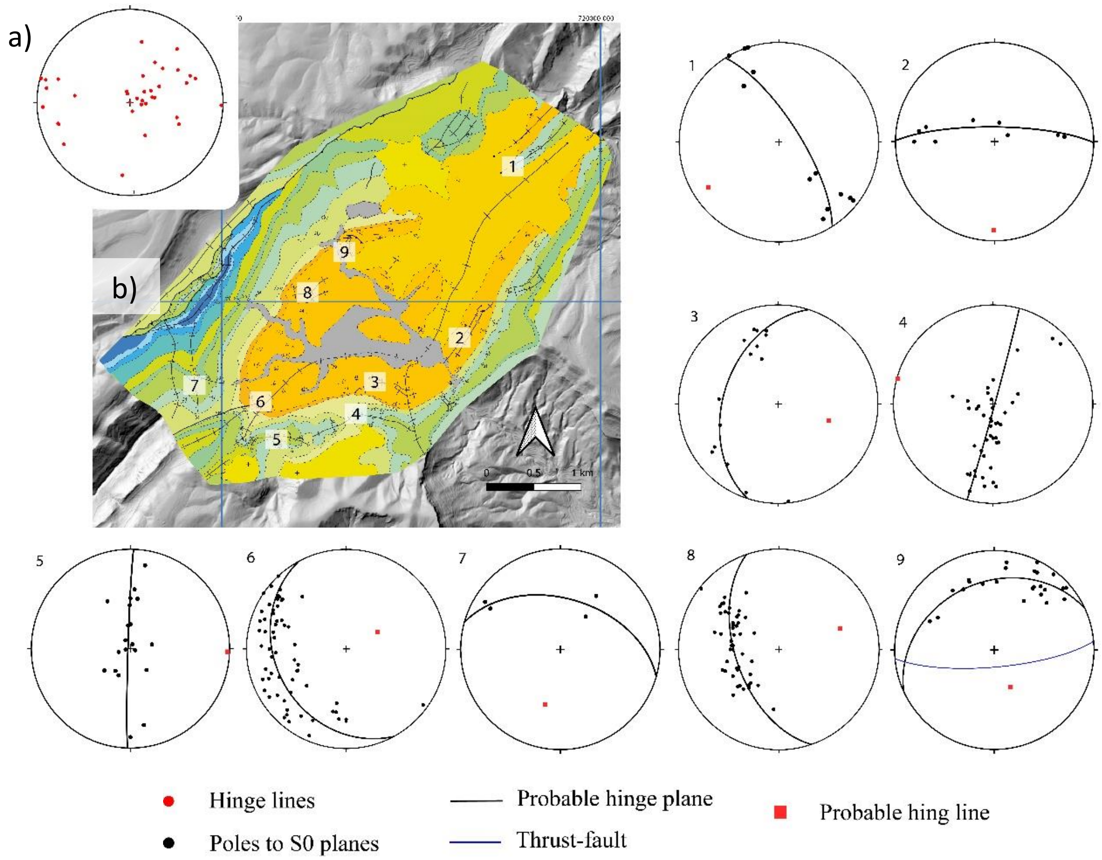

Figure 7 – a) General stereoplot with all the measured and determined fold hinges within the Las Cuevas de Cañart sector, evidencing a clear dominance of the NE-SW structures.
b) Situational map highlighting the locations of the different studied structures and corresponding stereoplots.

The second set of structures with a N-S orientation (Fig. 7b, stereoplot 9) affects the T3 unit and is covered by the T4 unit. It consists of an asymmetric anticline-syncline structure, verging towards the NE and plunging 60º towards the SE. It is associated with a NW-SE thrust.

E-W structures

The third set of structures crops out mostly in the southern limb of the Las Cuevas de Cañart syncline (Fig. 7b, stereoplots 3, 4 and 5).

The first structure (Fig. 7b, stereoplot 3) affects the T3 unit and consists of a symmetric anticline-syncline structure that plunges 46ºSE.

Two of these folds affect the Cretaceous units on the southern limb of the Las Cuevas de Cañart syncline (Fig. 7b, stereoplots 4 and 5). Both show horizontal axes, with a nearly horizontal southern limb and a northern limb that dips 80ºN.

7.3 Tectono-sedimentary relationships

In order to make a tectono-sedimentary analysis, it is important to look at the structures located at the basin margins. In this sector, these margins have been partially eroded, leaving just a few of these structures behind.

The first structure is the syntectonic unconformity between the T4 and T5 units at the northern limb of the Las Cuevas de Cañart syncline (Fig. 8). In this case, the bed dip variates between 50º and the horizontal, when reaching the T5 unit.

Since the T5 unit remains horizontal, it means that the deformation that took place during the deposition of the T4, progressively stopped until the T5 deposition. This unit, however, may also have been affected by brittle deformation.

Another significant geometrical relationship is the onlap of the T2 and T3 units onto the Cretaceous units, in both the southern and northern limbs of the main syncline, visible in figure 5. This indicates that the elevation of both limbs, and so the first deformation stages, are prior to their deposition.

Given these two aspects, we infer that the main syncline formation began at the same time as the T2 unit, or at least the T2-T3 limit, and continued its development until the T4-T5 limit. This means that its formation began in the Early Eocene and continued, up to the Late Oligocene.

Figure 8 – T4-T5 contact, located on the northern limb of the Las Cuevas de Cañart syncline, originating a sintectonic unconformity structure on the left. On the right, an angular unconformity between the Cretaceous and Cenozoic units.

On the NE corner of the sector, in the road that leads to Dos Torres de Mercader, TE-8101, there is a visible angular unconformity between the T4 and the La Cañadilla and Órganos de Montoro Cretaceous units (Fig. 9 a).

The Cenozoic unit is dipping approximately 20ºN, whilst the underlying Cretaceous units are overturned and dip approximately 82ºS. The contact between them acts like a reverse fault (Fig. 9 b).

On the NE border of the sector, the T4 presents an onlap geometry over the T3 unit, La cañadilla, Órganos de Montoro and the Barranco de los Degollados Formations, all with a close to vertical disposition, thus, forming an angular unconformity. Locally, this unconformity behaves as a reverse fault, diping 30ºW and with clear movement direction markers.

By the northern border, this same angular unconformity, between the T4 units and the underlying units is also quite evident. Here, the T4 unit has a 52ºS dip, whilst the T3 is overturned, dipping 78ºN.

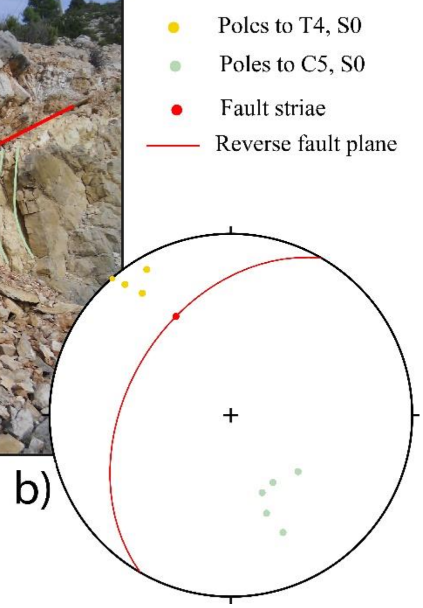

Figure 9 – a) Angular unconformity between the T4 unit and the Órganos de Montoro Formation (C5). The erosive surface was later reactivated as a reverse fault that produced a hangingwall syncline in C5 limestones.
b) Stereoplot representing the T4 and C5 bedding, as well as the reverse fault.

7.4 Analysis of specific meso-structures

This section is dedicated to the analysis of specific structures at the meso-scale within the Las Cuevas de Cañart sector. These structures are located according to figure 6.

1. Subvertical folds

Throughout the northern limb, close to the main syncline hinge, the T3 unit consists of intercalations of sandstones and limestones that laterally grade into conglomerates. On the limestone layers, it is possible to identify a series of nearly vertical folds, that are represented in figure 10. The closer one gets to the hinge of main structure, the more vertical are these smaller folds, reaching a subvertical position.

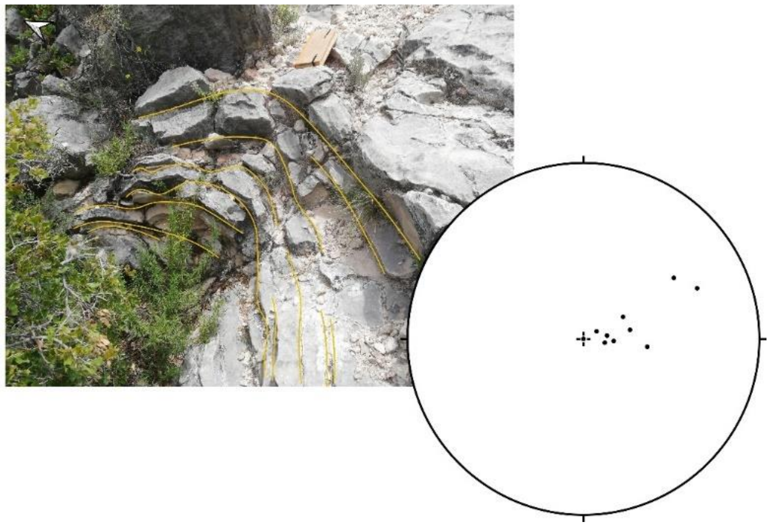

Figure 10 – a) Example of a subvertical fold outcropping on the northern limb of the Las Cuevas de Canãrt sector, affecting the T3 unit. b) Stereoplot with the described folds' hinges projection.

2. NW-SE thrust

This singular structure is a steeply-dipping fault showing a NW-SE direction. However, the fact that it duplicates a stratigraphic unit, with a spectacular fold associated to one of the fault walls, allows to interpret it as a folded thrust (Fig. 11). In fact, it is the only thrust with a NW-SE direction (after restoring bedding to the pre-folding, post-thrusting position), typically associated with the tectonics of the Iberian Chain. Though small, it separates two portions of the T3 unit, one deformed by N-S folds and the other not affected by this deformation stage.No indicators of the direction of movement were found *in situ.*

Figure 11 – Highlight of the N-S folds and its associated NE-SW thrust that affect the T3 unit. This structure outcrops on the northern limb of the Las Cuevas de Cañart Syncline.

3. Reverse faults on the NE corner of the sector

In this site we measured six reverse faults with clear movement direction markers. Using the Right Dihedra method (Angelier and Mechler, 1977), it is possible to approach the local paleostress axes, using Allmendinger's, (2016) software FaultKin 8. Figure 12 is the representation of the obtained results, through a stereoplot in which the numbers represent the total amount of faults that are kinematically compatible with a compression direction. This means that the T4 unit, where these faults were measured, was under a NW-SE stress field at some point in time.

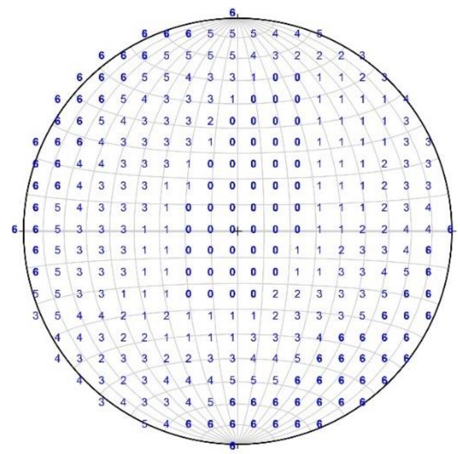

Figure 12 – Results of the PT Dihedra method, where each number represents the total amount of faults that are kinematically compatible with a specific compression direction.

4. Pressure-solution lineations in conglomeratic clasts

Based on the collection of over 50 different measurements of solution lineations in conglomeratic clasts (Fig. 13), it is possible to determine that three main compressional stress directions (WNW-ESE, SW-NE and N-S) co-existed, or sequentially developed in this sector since the T3 unit was formed. Given the overlapping of different lineations, it was possible to locally define a chronological order between the WNW-ESE (earlier) and SW-NE (younger) compressional stress fields. However, there were not enough data to define the order of all three, leaving the N-S field undetermined in time.

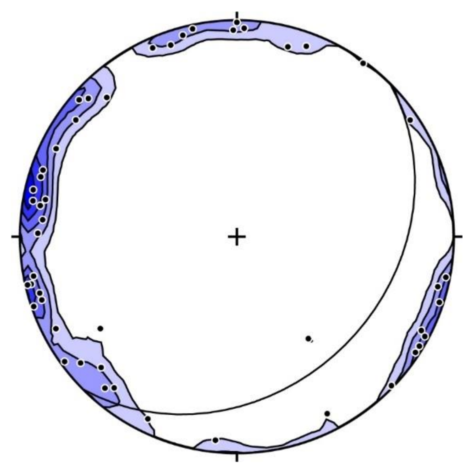

Figure 13 – Projection of the pressure-solution lineation measurements, highlighting three different compressional stress directions (WNW-ESE, SW-NE and N-S).

5. Shear zone

A shear zone (Fig 13) has been surveyed at the southern limb of the main structure, affecting the T3 unit. It consists of both left-lateral and right-lateral transversal faults, with associated rough solution foliation (Fig 14 a). There is also one thrust (Fig 14 b) with movement direction markers.

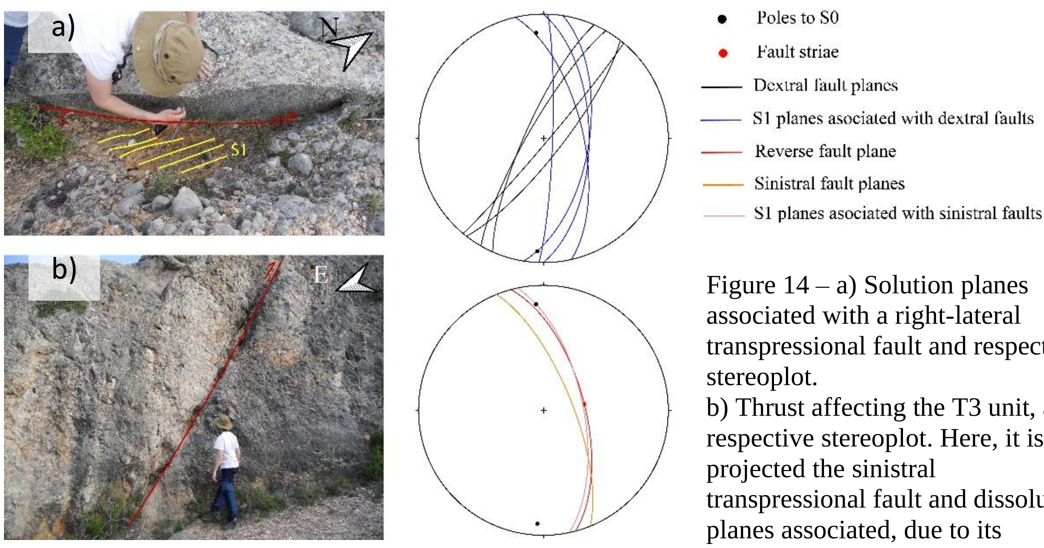

Figure 14 – a) Solution planes associated with a right-lateral transpressional fault and respective stereoplot.
b) Thrust affecting the T3 unit, and respective stereoplot. Here, it is also projected the sinistral transpressional fault and dissolution planes associated, due to its similarity.

8. Interpretation and discussion

The Las Cuevas de Cañart sector is a complex and intriguing area in the Linking Zone of the Iberian Chain. So complex in fact, that it is hard to adopt a unique model for explaining its structural features. For this reason, in this chapter we present multiple possible interpretations with their arguments and counter arguments, while trying to reach the most probable hypothesis. It is often difficult to relate structures with a particular compressional stress direction, especially when dealing with folds. We have considered that the most probable situation, is that structures form, or reactivate, more easily when the compression direction is nearly perpendicular to them, but this is not always necessarily the case.

8.1 Chronology of structures

The key factor to understand how the studied structure was formed is to chronologically order the three sets of compressional structures and, try to correlate them within the Iberian Range context, for which we have based ourselves in the model presented by Liesa, (2000) and Liesa and Simón, (2009). However, this has proven to be very complicated, and therefore we propose two possible relative chronologies.

E-W –> N-S –> NE-SW

At a map scale, it is quite visible that the E-W fold axial traces are somewhat irregular, almost zigzagging on the southern border. This is commonly seen in first stage folds that were subsequently folded in a different direction, in this case N-S (Gosh and Ramberg, 1968). In the southern border of the sector, in some of the inflections along the traces, there is also a shift in dip directions of strata associated, which supports this idea. In the T3 unit, to the South, there is a superposition pattern between a N-S syncline and an E-W syncline-anticline structure; it is however, just one. Besides the E-W folds in the southern border, there is also one singular E-W structure in the northern limb of the Las Cuevas De Cañart structure, when the Fortanete, T2 and T3 units take an E-W direction. This could possibly indicate an underlying E-W structure preceding the N-S and NE-SW deformations.

None of the above mentioned sets of structures are found in the T4 unit, and therefore, there is a possibility for them to predate the T4 sedimentation during the Late Oligocene.

The compression field that originated the NE-SW set of structures was active throughout the entire formation of the basin (Early Eocene-Early Miocene) up until, and including, the deposition of the T4 unit. This is supported by the onlap geometry of the T2 and T3 units at the southern limb of the Las Cuevas de Cañart syncline, the onlap geometry of the T4 unit in the southern and northern limbs of main structure and, the synsedimentary structure at the limit of the T4-T5 units in the northern limb. The first argument, indicates that the uplift of the Cretaceous units in that area is previous to the sedimentation of the T2 unit. The onlap geometry of the T4 unit, indicates that the Cretaceous units, at least locally, were already very deformed by the Late Oligocene, when the T4 unit started to form and, simultaneously, to be folded with a NE-SW direction according to the synsedimentary structure at the limit of the T4-T5 unit. The last argument also indicates that throughout the deposition of T4, a compression stress field was active until the formation of T5, after which it decreases its activity to a minimum since this unit is no longer folded.

In order for this chronology to be possible, however, the first folds would have to be connected to an approximate N-S compressive stress field, which according to Liesa and Simón, (2009), has not been obtained from paleostress analysis in Eocene units within the Iberian Chain.

The first stress field that could potentially form E-W structures, according to the same authors, would happen during the Late Oligocene to Early Miocene, with the Pyrenean compression, assuming that it would have to approach a perpendicular to the E-W direction. Such compression, with a N-S direction, is commonly associated with the Neogene period, when the Pyrenean and Betic overlapping compressive stress fields have either a NNE-SSW or NNW-SSE direction.

The NW-SE structures would likely be formed synchronously since the Oligocene, in periods characterized by a stronger expression of the Betic compression (Liesa and Simón, 2009). This does not, however, comply with the collected field data.

N-S –> NE-SW –> E-W

The main difference between the above-described chronology and this one is that the latter considers the E-W set as postdating all the other events, given that these structures are mostly restricted to the southern border of the structure, separating the Las Cuevas de Cañart basin from the southern Cenozoic sector. For this reason, the above arguments that stated that the N-S structures were formed synchronously to the NE-SW set, are also valid for this proposal.

According to Liesa and Simón (2009), the Early Betic compressional direction was close to WNW-ESE during the Eocene. This direction of compression could possibly be behind some of the N-S structures that crop out in the Las Cuevas de Cañart. If the structure is conditioned by inherited structures, such as E-W basement faults, it is also possible for, during this period in time, the Iberian-Pyrenean compressive direction to affect these faults giving them a transpressional component, which would possibly originate the N-S structures.

The NE-SW structures, given the onlap geometry of the Cenozoic units, have probably started to form during the Eocene. During this period, the Iberian chain was probably under the influence of the Betic NW-SE compressional stress field, as stated by the same authors, up until the Late Oligocene-Early Miocene, which is when the T4 unit started to be deposited. This compressive direction is coherent with the NE-SW structures.

Finally, the E-W structures that affect the entire structure, particularly the southern border, could possibly be associated with the N-S Pyrenean stress field, active since the Late Oligocene (Liesa and Simón, 2009). The concentration of this these structures in the southern border, could be explained by the existence of underlying structures, such as the blind fault in the southern limb of the Las Cuevas de Cañart syncline (Margarit 2019), that possibly reactivated and controlled the following deformation stage.

This chronology is supported by the pressure-solution lineations measurements described in the previous chapter and, if the N-S syncline found in this limb is prior to the E-W structures, the single superposition pattern found could also exist and, therefore, does not contradict it.

8.2 Definition of a basin model

Trying to define a basin model for this sector also proved to be an intricate task, with two different possibilities – piggyback/foreland or pull-apart basins.

The first proposal, a piggyback basin associated with a previously formed foreland basin (Fig. 15), is connected to the geological context within the Iberian Chain. Several NE-SW thrusts in the area dip towards the S and are constantly verging towards the NW (Canérot *et al.*, 1982). One of these bounds the sector by the N and could be the thrust that controls the basin. There is also an inferred blind fault at the southern limb of the syncline, stated by Margarit, (2019), and the Estrecho anticline to the SE. These structures could represent the positive inversion of a previous extensional fault responsible for the angular unconformity between the Lower Cretaceous and the Utrillas formation, as well as the thickness variations in the same units. The main direction of these structures (NE-SW), is parallel to the directions of thrusts, which is a strong argument for this model, since these were coeval with the Cenozoic units.

According to González *et al.*, (1989), there are paleocurrents measurements that indicate sediment transport from the E in T2, from the N in T3 and from the SE in T5. This indicates a higher erosion of the northern anticline during the first stages of compression, and the southern anticline during the later ones, which is coherent with a piggy-back basin model.

This model, however, does not fully justify either the separation of the Las Cuevas de Cañart sector from the Cenozoic sector found to the S, why this limit is so straight and abrupt, neither the N-S structures.

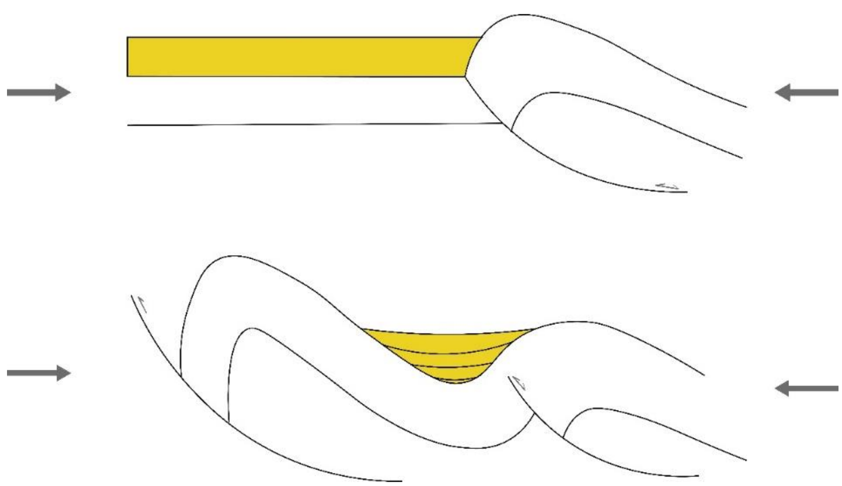

Figure 15 – a) Cross-section diagram representing the formation of a Foreland basin, with the sedimentary deposits represented in yellow.
b) Cross-section diagram representing the formation of piggy-back basin basin, after continuous compression, with the sedimentary deposits represented in yellow.

The second option, a pull-apart basin (Fig 16 a), seems to be the most obvious one at a map scale, because of the rhomboidal geometry of the basin. This has a particular interest because the southern limb has an impressively straight geometry and is responsible for the separation between the Las Cuevas de Cañart sector and, another Cenozoic structure completely covered by the T5 unit by the S. For the pull-apart model to work, we need to find two subparallel faults, by the northern and southern limbs of the basin, in this case, the thrust fault system and the inferred fault mentioned above. These would need to have been subjected to a strike-slip movement at some point in time, in order to create this depression. The Betic compressive stress field (ESE-WSW, Liesa and Simón, 2009) would possibly affect the previously mentioned faults during the late Eocene, with a dextral transpressional movement, originating the rhomboidal depression. This structure would be subsequently reactivated under the Pyrenean compression (thus defining a compressional relay zone), activating the underlying structures at the southern border and thus creating the E-W folds described in the previous chapter (Fig. 16 b).

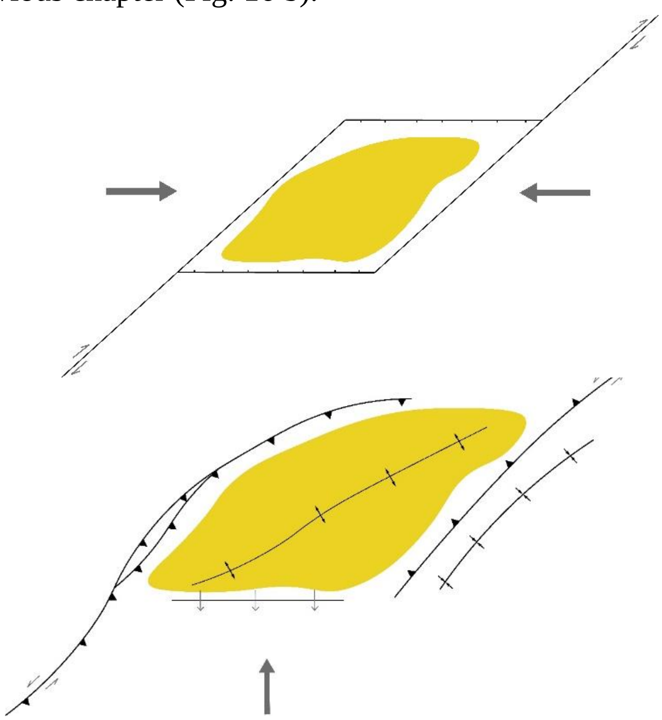

Figure 16 – a) Schematical representation of the formation of a pull-apart basin, through dextral transpression, with the sedimentary deposits represented in yellow.
b) Schematical representation of the formation of the results of posterior deformation of a pull apart basin, originating a piggy-back basin, with the sedimentary deposits represented in yellow.

8.3 Geological context

To discuss the feasibility of these different hypotheses, both the folding chronology, and the possible basin model, we must bear in mind the geological context the sector is in. For that reason, it is necessary to compare the Las Cuevas de Cañart basin with some close and well-studied basins, such as the Aliaga and Montalbán ones.

The Aliaga basin is located in the Maestrazgo sector of the Iberian Chain. It is a piggy-back basin associated with the North-verging Utrillas thrust. During the Oligocene, its displacement was approximately 5-8 km (González and Guimerà, 1993; Casas *et al.,* 2000) in successive NNE and NNW transport directions (Liesa, 2000). The basin is a complex syncline whose septentrional limit is bounded by a footwall accommodation monocline, and its meridional limit is defined by a set of WSW-ENE structures associated with the Cobatillas thrust fault (Simón, 2006).

The vast majority of the Aliaga basin structures are connected to the Alpine compression, originating two sets of structures, the first with a N-S to NW-SE direction and the second with an ENE-WSW direction. These two sets produced some spectacular superposition structures (Simón, 2004; 2005) that indicate that the ENE-WSW folds followed the NW-SE to N-S set. Some of these structures are connected to the reactivation of Cretaceous faults with a reverse or transpressional (?) component, such as the Miravete fault (Soria, 1997). The filling of the basin is essentially Cenozoic and consists of conglomerates, sandstones and siltstones, that can be divided into 6 tectono-sedimentary units (González, 1989). According to Simón (2006), this basin went through four main stress fields:

- NNE-SSW, affecting all of the units
- SSE-NNW, affecting the T2, T3 and T4 units
- ENE-WSW affecting the T2, T3 and T4 units
- ESE-WNW affecting the T2 and T3 units.

Which represent, respectively, the Pyrenean, Guadarrama, Iberian and Betic directions. The same author proposes that the most logical chronological sequence would be from the earliest to the latest, Betic, Iberian and Guadarrama followed by the Pyrenean stress field, compatible with the model proposed by Liesa (2000). This means that there are three different evolutionary stages.

The first one occurred up until the Early Oligocene and is characterized by a ESE-WNW direction (Early Betic). It could be responsible for the N-S folds after a positive, probably oblique inversion (transpression) of underlying Cretaceous faults.

The second stage occurred until the Late Oligocene, with a Pyrenean-Iberian direction, and was probably responsible for some of the NW-SE and N-S structures.

The third and last stage is connected to the Late Betic stress field (SSE-NNO), followed by the Late Pyrenean stress field (NNE-SSW), between the Late Oligocene and Early Miocene. Thus originating the E-W structures set that overlap the previous ones. These two stress field directions tend to overlap throughout the Iberian Chain (Arlegui *et al.*, 2005; Ezquerro and Simón, 2017).

The Montalbán basin is located within the Aragonese branch of the Iberian Chain, in the SE sector of the Calatayud Basin. It is bounded to the North by the Montalbán anticline, and to the South by the Utrillas thrust. Its core is occupied by six tectono-sedimentary units that together have over 2000 m in thickness (Pérez *et al.*, 1983; Pérez, 1989; Casas *et al.*, 2000). This allows a direct correlation with the Aliaga units (Pardo *et al.*, 1989), also because both basins are associated with the deformation connected to the Utrillas thrust. However, whilst Aliaga is a piggy-back basin this is a foreland basin in relation to this structure. According to Simón, (2019), the Montalbán basin went through the exact same evolutionary stages as the Aliaga basin, described above, originating structures with the same approximate directions: NW-SE, E-W and NE-SW.

With this in mind, given the geographical distance between the Las Cuevas de Cañart sector to these two basins (Fig. 17), and that the tectono-sedimentary units in the sector are directly correlated with the Aliaga and Montalbán ones (González *et al.*, 1989), it is possible to establish a probable, yet not definitive, comparison between them.

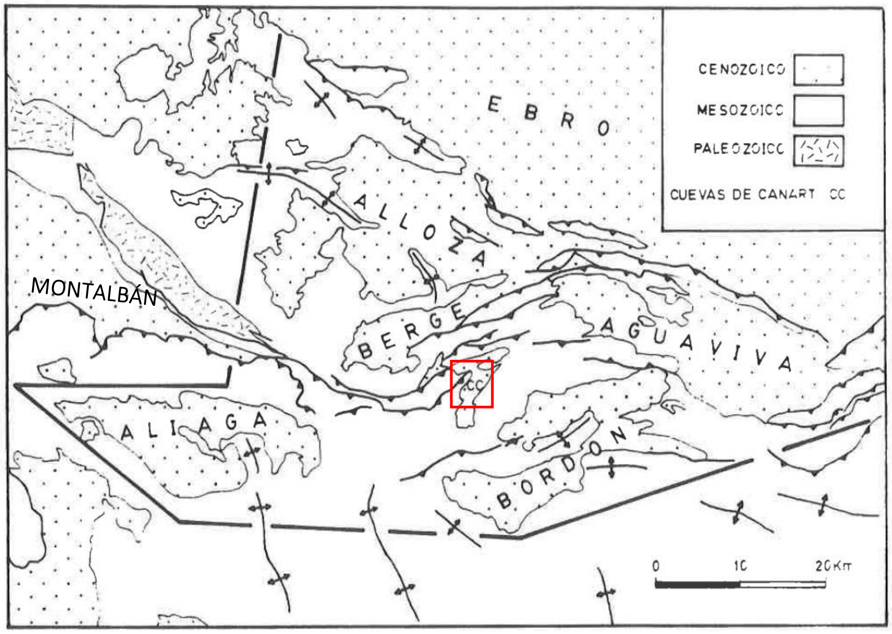

Figure Fig. 17 – Geographical location, and structural contextualization of the Aliaga and Montalbán basins and the Las Cuevas de Cañart sector, highlighted. Adapted from González, (1989).

The most probable chronology for the sets of structures in the Las Cuevas de Cañart sector, is the second proposal (N-S –> NE-SW –> E-W), because it would follow the same model as the Aliaga and Montalbán basins. However, the distance between them is enough to allow changes in the chronology of the stress fields, and for that reason is not definitive. Considering this as the most probable chronology, it is easier to understand that the basin model could not simply be one of the previously mentioned, but something more complex. For example, it could have started as a pull-apart basin, during the Eocene, reactivating NE-SW Cretaceous faults with reverse or transpressional kinematics, that would be responsible for the N-S structures, and some underlining E-W structures. These E-W structures would be the ones responsible for the separation of the two Cenozoic sectors. However, after a stress field shifting during the Oligocene, these same Cretaceous faults could have followed a thrust fault kinematics, which would be responsible for the quick burial of the depocenter of the sector and the NE-SW structures. During the Late Oligocene, the overlapping of the Late Betic and Late Pyrenean stress fields, possibly reactivated the underlining E-W structures, deforming them and originating the E-W anticlines found in the southern limb of the Las Cuevas de Cañart syncline. All these structures were subsequently covered by the T5 unit, eroded, and, lately, covered by Quaternary deposits.

9. Conclusions

Through the development of a detailed geological map, at a 1:15.000 scale, the newly defined stratigraphic series, elaboration of cross-sections and the detailed analysis of the three sets of structures and their correlation with the Cenozoic units, we were able to characterize the alpine structure that constitutes the Las Cuevas de Cañart sector.

The aforementioned sector is complex. It is, in a simplified way, an asymmetrical braquisyncline, verging towards the NW, faulted at its core. It is controlled by a double thrust system by the N, and 2 anticlines by the S (Ladruñan and Estrecho). The sector is affected by three sets of structures (NE-SW, N-S and E-W), overlapping each other, without forming any important interference structures, however clearly controlling the formation and deformation of the Las Cuevas de Cañart basin, and the units at its core.

Due to its complexity, we were unable to reach a unique model to explain its structural features. When comparing all the analysed data with well-known and deeply studied basins at its surrounding (Aliaga and Montalbán), it is possible to reach a probable, yet not definitive, hypothesis. The most probable chronology for the three sets of compressional structures starts with the N-S structures during the Eocene, followed by the NE-SW set during the Eocene-Oligocene and finally, E-W set during the Early Miocene. These are associated with, at least, the Early Betic (WNW-ESE), and Pyrenean (N-S) compression stress fields. The Iberian (NE-SW compression) has been recorded by solution lineations in conglomerate pebbles of the T3 unit, but its control on macrostructures remains unknown.

If the structure is controlled by underlying structures, such as basement faults, this may not be the case. For example, for the stress field associated with the N-S structures, instead of the Betic compression, these could be associated with the Iberian-Pyrenean compressional direction (NE-SW), through the reactivation of such faults with a dextral transpressional movement. Through a couple of field data sets, we know for sure that at least locally, the NW-SE and an approximately E-W compression directions were active in this sector.

The origin of the main structure is also somewhat ambiguous. We admit that to achieve such a structure, we might need to base our theory in more than one classic compressive basin model, given its complex geological context. With this in mind, there are two most likely scenarios.

The first one is a pull-apart basin, formed by the dextral transpression of the double thrust system by the N, and an underlying structure by the S during the Eocene. This structure was subsequently compressed, through an oblique compression direction, gaining a reverse component within these faults and forming a piggy-back basin.

The second is a foreland basin, associated with the Estrecho anticline that was later compressed, reactivating underlying normal Cretaceous faults with a reverse component and forming a piggy-back basin.

10. Future works

In order to clear up the questions that were left unanswered, there are several options that we can take:

- Prepare a geophysical campaign, in which we would collect both gravimetric data and refractions seismic data. This would help us to define the contacts between the Cenozoic and Cretaceous units, to define the basement depth, and the thickness of the different units, including the detachment level. This would also check the possibility for any possible diapiric activity that could potentially be connected to the structure formation.

- Make a high resolution 3D model of the sector, in order to locate possible interference structures that were not identified and analyse in depth the intra-cretaceous unconformities and thickness variations within these units.

- Detailed geological mapping of surrounding sectors, to try and find more examples of interference structures, that could help us detail the evolution model of the sector.

- Try to find more mesostructures within the sector, as well as intra Cenozoic unconformities that could offer more information about the tectono-sedimentary relationships, and thus, offer a stronger base to possible basin models for this structure.

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Annex 1

Detailed geological map of the Las Cuevas de Cañart sector, highlighting the Cenozoic layers and its structures.