



SCIENCE

Geology of the Cotiella thrust sheet, southern Pyrenees (Spain)

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ABSTRACT

This paper presents a geological map and cross-sections of the Cotiella thrust sheet at 1:25,000 and 1:50,000 scale, respectively. The map covers an area of 225 km² in the southern Pyrenees. The structure of the studied area is dominated by an upper Santonian – lower Miocene thrust system, which transported a middle Coniacian-lower Santonian extensional basin, the Cotiella Basin, 10 s of kilometres southwards during the Pyrenean orogeny. The map focuses on the internal structure of the Cotiella Basin, its partially inverted extensional faults and its up to 6.5 km of upper Albian – lower Santonian sediments that unconformably overlie Upper Triassic salts. The map and cross-sections, together with outcrop-scale observations, have led us to interpret the rising of passive diapirs in the area. This newly recognized salt tectonic event in the Cotiella Basin is important because of the insights it can provide for the paleogeographic reconstruction of the Upper Cretaceous paleomargin of the northern parts of the Iberian Peninsula.

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1. Introduction

The Pyrenean Orogen formed as the result of the collision between the Iberian and European tectonic plates from the end of the Upper Cretaceous to Miocene times (Muñoz, 1992). Its structural style and evolution was strongly controlled by the inversion of previous Upper Jurassic–Lower Cretaceous syn-rift extensional basins and by Upper Cretaceous post-rift basins that developed as a result of the opening of the central Atlantic and Bay of Biscay (Beaumont, Muñoz, Hamilton, & Fullsack, 2000; Derégnaucourt & Boillot, 1982; Malod & Mauffret, 1990; Roest & Srivastava, 1991). One of these basins is the middle Coniacian – lower Santonian Cotiella Basin.

The Cotiella Basin was tectonically inverted and incorporated into the Pyrenean Orogen during late Santonian – late Maastrichtian time to form the Cotiella – Bóixols thrust sheet. This was subsequently transported in a foreland-propagating sequence on top of the younger Montsec – Peña Montañesa and Gavarnie-Serres Marginals thrust sheets (emplaced during the early Eocene and the middle Eocene – Oligocene, respectively). Synchronously and afterwards, these thrust sheets were deformed and tilted towards the foreland (southwards) by underthrusting of an antiformal stack of basement-involved thrusts (referred to as the Axial Zone). As a result of this, the structure of the studied area is dominated by an upper Santonian – lower Miocene Pyrenean thrust system which uplifted for more than 3 km an Upper Cretaceous Atlantic post-rift basin.

The contractional structure has been widely discussed in the Pyrenean literature (Fernández, 2004; García-Senz & Ramírez, 1997; Garrido-Megías, 1973; Martínez-Peña & Casas-Sainz, 2003; Muñoz et al., 2013; Ríos-Aragües, Galera, & Baretino, 1997; Ríos-Aragües, Lanaja, & Frutos, 1982; Robador & Zamorano, 1999; Séguret, 1972; Souquet, 1967). The internal structure of the Cotiella Basin, however, has only been discussed in detail by García-Senz (2002) and McClay, Muñoz, and García-Senz (2004) prior to this study (and related papers, see below). This paper presents a detailed geological map of the Cotiella thrust sheet and six cross-sections, focussing on the structure of the Cotiella Basin.

2. Methods

The geological map of the Cotiella thrust sheet covers 225 km² (see Main Map). The map was constructed as part of a Ph.D. dissertation, following more than six months of fieldwork distributed over several years (Lopez-Mir, 2013). The cartographic basemap consists of 1:5000 topographic maps and orthophotographs (with 1 m pixel resolution) provided by the *Sistema de Información Territorial de Aragón (SITAR)* of the *Gobierno de Aragón*. Geological mapping was also performed at 1:5000 scale. Traces of the outcropping geological surfaces (mostly bedding and faults) were mapped in the field using the orthophotographs and up to 2000 dip data were collected using a compass-clinometer. The field data were geo-referenced and transferred into a digital environment, where more

traces of the outcropping geological surfaces were mapped. The younger Montsec – Peña Montañesa, Gavarnie-Serres Marginals and Axial Zone thrust sheets are also represented on the map, but they were mapped at less detail than the Cotiella thrust sheet. The mapping of those thrust sheets benefited from existing studies on the area (Fernández, 2004; García-Senz & Ramírez, 1997; Garrido-Megías, 1973; Ríos-Aragües, Galera, et al., 1997; Ríos-Aragües, Lanaja, et al., 1982; Robador & Zamorano, 1999; Souquet, 1967). Quaternary deposits have not been represented.

The fault symbols depicted on the **Main Map** reflect the stratigraphical relationship of hangingwall to footwall (i.e. thrust: older over younger; normal: younger over older) in order to avoid confusion derived from the complex tectonic evolution of the area. Map-scale complexities are both related to tectonic inversion (which might generate thrust geometries with young-over-old relationships) and to the deformation of the thrust system by underthrusting (which tilted the thrust system southwards). As a result of underthrusting, the current thrusts present an apparent normal sense of movement (with their current hangingwall moving downwards relative to the footwall) despite having contractional characteristics, as can be observed on the enclosed cross-sections. These complexities have historically led to relevant interpretation discrepancies on the fault kinematics of the thrust system so that the fault symbols depicted on the map represent the stratigraphical relationship of hangingwall to footwall instead of interpreting the fault sense of movement.

The **Main Map** is accompanied by six cross-sections at 1:50,000 scale. The cross-section lines were chosen in order to depict the main structural features of the eastern central and western portions of the Cotiella Basin (cross-sections B-B', D-D' and F-F', respectively) as well as the internal structure of the northern Armeña, Mediodía and Seira sub-basins (cross-sections C-C' and E-E'). The cross-section location was chosen according to the availability of dip data and the orientation of the structures in each area. A longitudinal cross-section (A-A') to depict the structural changes along-strike is also presented.

The structure in depth depicted in the cross-sections was constrained by 3D reconstructions of the Gavarnie and Montsec – Peña Montañesa thrusts constructed by Fernández, Muñoz, Arbués, Falivene, and Marzo (2004) and by Muñoz et al. (2000), where structural interpretations were constrained with the available subsurface data from the Tremp-Graus basin. In the Cotiella Basin, the general structural and stratigraphic features were extracted as vertical slices from a surface-data-based 3D reconstruction of the Cotiella Basin presented by López-Mir, Muñoz, and García-Senz (2016). This was fundamental to constraining the lateral projection of data in structures that present

complex variations along-strike, including abrupt changes in the stratigraphic polarity. Additional dip data and outcrop observations were afterwards implemented in these vertical slices in order to increase the degree of detail. Dip data were projected into the cross-section lines using projection vectors calculated by the definition of cylindrical dip-domains. Interpolation and extrapolation of data were performed using Move software, assuming parallel folding. The geometry of the faults was interpreted from the geometry of the strata, and vice versa. Our interpretations were validated and improved by constructing sequential restorations of the salt related extensional structure (Lopez-Mir, Muñoz, & García-Senz, 2014).

3. Stratigraphic units

The stratigraphic units depicted on the map are grouped into four main groups of rocks, according to the tectonic events that controlled their deposition (Figure 1).

The pre-rift succession is subdivided into four main cartographic units, two of which are located underneath the main detachment and are therefore considered mechanical basement. The basement units are only exposed in the Axial Zone and consist of Paleozoic meta-sedimentary rocks and Upper Permian – Triassic red beds (the Buntsandstein facies). The main detachment consists of Middle to Upper Triassic carbonates and evaporites (Muschelchalk and Keuper facies,

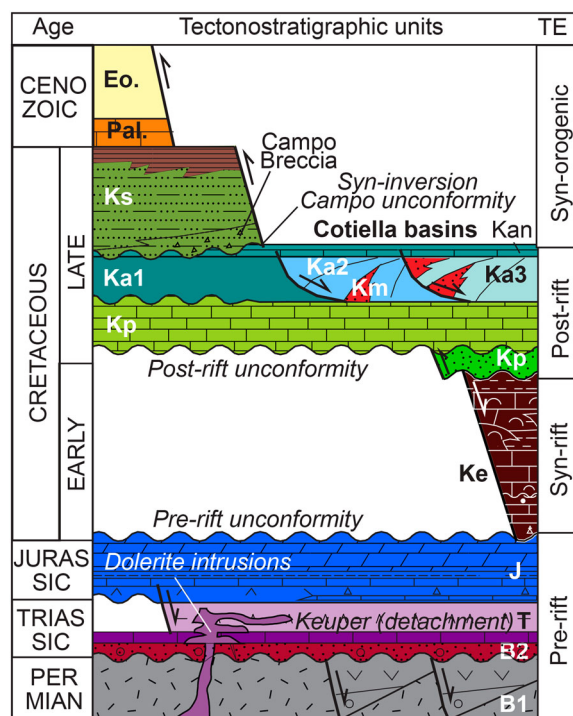


Figure 1. Chronostratigraphic diagram of the South-Pyrenean thrust system showing the stratigraphic units and related tectonic events. Modified from García-Senz (2002). See **Main Map** for abbreviation list.

respectively). The Buntsandstein and Muschelchalk facies have an average thickness of 150 m in the study area (e.g. [Souquet, 1967](#)), whereas the Keuper facies present variable thicknesses due to salt mobility. Above, the Jurassic succession consists of Lower Jurassic carbonates, breccias and marls; and of Middle Jurassic dolomites ([Garrido-Megías, 1973](#)). They thin towards the south-west from up to 400 m in the Bóixols thrust sheet to 0 m in the Cotiella and Gavarnie thrust sheets.

The Lower Jurassic – Upper Cretaceous syn-rift succession does not crop out in most of the study area. Only condensed series of less than 25 m of Lower Cretaceous carbonates outcrop in the Sin Chuan, Montaña de Gavás and Sierra de Chía mountains in the northeast ([García-Senz, 2002](#)). This is relevant as the Cotiella Basin was only developed in areas where the post-rift carbonates were directly overlaying the Keuper evaporites.

The post-rift succession is subdivided into two main groups of rocks. (1) The upper Albian – lower Coniacian section consists of carbonate platforms which have been subdivided into five cartographic units (the Turbón Sandstone, Santa Fe Limestone, Pardina Limestone, Congost Formation and a unit of undifferentiated limestones; [Caus, Gómez-Garrido, Simó, & Soriano, 1993](#); [Souquet, 1967](#)). The post-rift strata are 100 to 700 m thick and, in the study area, they unconformably overlie Keuper evaporites. (2) The middle Coniacian – lower Santonian succession has been subdivided into six units of sandstones (Angón and Maciños) and carbonates (Aguasalenz, Gallinés, Armeña and Seira), and two formations of limestones and marly limestones (Ventamillo and Anserola, respectively), ([Lopez-Mir, 2013](#); [Lopez-Mir, Muñoz, & García-Senz, 2015](#); and references therein). These intervals are up to 5.9 km thick in the Cotiella Basin; whereas in the Montsec and Bóixols thrust sheets (the footwall of the Cotiella Basin) they are only 300 m thick. In the Gavarnie thrust sheet, the upper Albian to lower Santonian sequences are combined, with their thickness ranging from up to 400 m in Congosto de Ventamillo to less than 100 m in the south.

The syn-orogenic succession consists of two main groups of rocks: upper Santonian – Maastrichtian and Palaeocene – Eocene. The first group has been subdivided into five main cartographic units made up of breccias (Campo Breccia Member), marls and turbidites (Mascarell and Barbaruens formations), quartz sandstones (Areny sandstone) and an undifferentiated sandy limestone unit ([Souquet, 1967](#)). These units increase in thickness to the north and display growth stratal geometries related to the inversion of the extensional basins. They are up to 2500 m thick in the Bóixols thrust sheet, 1500–2500 m thick in the Montsec thrust sheet and up to 690 m thick in the Gavarnie thrust sheet. The Cenozoic succession involves three

main cartographic units made up of: lower to middle Palaeocene limestones, upper Palaeocene to lower Eocene limestones; and Eocene marls and turbidites. The limestone unit's thickness ranges from 300 to 400 m in the Gavarnie thrust sheet and 350 to 400 m in the Montsec thrust sheet. The marls and turbidites show significant thickness variations up to 2500 m, as they were deposited during the emplacement of the Montsec and Gavarnie thrust sheets.

4. Results

The Cotiella thrust sheet exposes a 5.9 km thick succession of middle Coniacian-lower Santonian carbonates and sandstones which fan towards the main Cotiella fault in the southern portion of the basin and are disrupted by smaller sub-basins in the north (Armeña, Mediodía and Seira). [García-Senz \(2002\)](#) and [McClay et al. \(2004\)](#) interpreted that these sediments were deposited as a result of the gravitational collapse of the upper Albian to lower Coniacian post-rift carbonate platforms above Upper Triassic salts. However, the calcarenitic wedges mapped in the northern Armeña, Mediodía and Seira sub-basins depart from classical models of listric extensional fault systems in that, first, there are shallower-water facies in the thickest parts of the wedges ([Figure 2](#)) and, second, the strata contain clasts derived from the Keuper salts. Moreover, their geometric relationships to Keuper exposures (e.g. between the Armeña and Mediodía sub-basins) documents the presence of halokinetic sequences ([Giles & Lawton, 2002](#); [Giles & Rowan, 2012](#)) during passive diapirism during their deposition ([Lopez-Mir et al., 2015](#)). These observations together with sequential restoration of the current extensional structures ([Lopez-Mir et al., 2014](#)) led to a re-interpretation of the structural evolution of the area. This is characterized by five main stages of development:

- (1) Development of post-rift carbonate platforms above salt.
- (2) Gravitational collapse of the post-rift platforms and formation of rollovers in the hangingwalls of extensional faults.
- (3) Rising of passive diapirs from the salt rollers in the footwalls of the early listric faults.
- (4) End of passive diapirism and formation of primary salt welds.
- (5) Tectonic inversion and squeezing of the diapirs.

5. Conclusions

This work presents a new detailed geological map of the Cotiella thrust sheet that has facilitated the construction of cross-sections and sequential restoration that illustrate our re-interpretation of the tectonic evolution of the area. Structural features and particularly

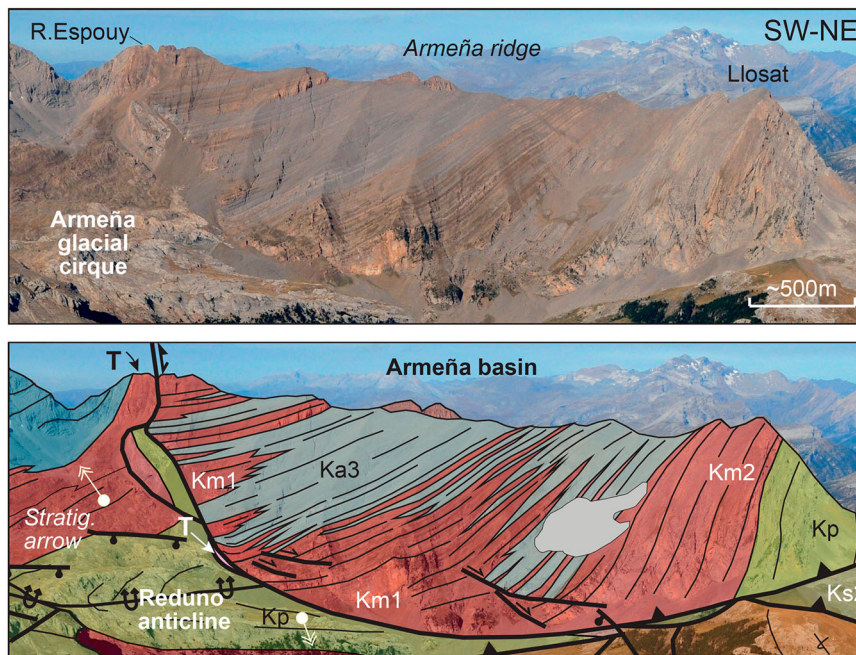


Figure 2. Photograph and interpretation of the Armeña ridge showing calcarenitic wedges fanning towards the Armeña fault. Modified from Lopez-Mir et al. (2015).

the mapped facies distribution of the syn-extensional deposits support the hypothesis that the Cotiella extensional faults were synchronous to the rising of passive diapirs. This had not been previously identified and is important because of the insights it can provide for paleogeographic reconstructions of the upper Cretaceous paleomargin of the northern Iberian Peninsula.

Software

The **Main Map** was produced using Microstation (Bentley Systems) software which was used to assemble the 1:5000 topographic maps and orthophotographs and to digitize the lithological contacts and the main structures mapped in the field. The cross-sections were constructed and restored using Move (Midland Valley). Final editing and PDF construction was made using CorelDraw.

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Disclosure statement

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