Miocene to present-day tectonic control on the relief of the Duero and Ebro basins confluence (North Iberia)

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ABSTRACT
This article presents a morpho-structural map at 1:50,000 scale of the confluence area between three regional units: (1) the Burgalesa Platform (Mesozoic; Cantabrian Mountains), (2) the Duero Basin and (3) the Ebro Basin (Cenozoic foreland basins). The map covers an area of 527 km² in north Iberia. Additionally, structural lineaments such as joints are well preserved and documented in the Upper Cretaceous sediments of the Burgalesa Platform, represented by four main sets regarding their orientation. The foreland basins are incised in Miocene materials by rivers that have developed a complex drainage system controlling the deposition of the most recent alluvial sediments, following the four structural orientations. The map, together with the analysis of orthophotos and a Digital Terrain Model, and outcrop-scale observations, have led us to document the influence of the Miocene to present-day compression and strike-slip tectonic regime on the configuration of the drainage system and the geomorphological features.

1. Introduction

The central part of the northern Iberian Peninsula is characterized by the hydrographic basins of the Ebro River and the Duero River, both converging on the Burgalesa Platform, westward of the Pyrenees. The Pyrenean Orogen consists of a series of inverted Lower Cretaceous extensional basins, formed during the opening the Bay of Biscay and the North Atlantic realm from the Late Jurassic to Early Cretaceous (Roca et al., 2011). This extensional phase of evolution resulted in the development of intracontinental basins in the rift margins (Beaumont et al., 2000; Jammes et al., 2014; Roca et al., 2011). The convergence between the Eurasian and Iberian plates during Late Cretaceous-Cenozoic times triggered the inversion of the segmented rift system (Figure 1a). The Cantabrian Mountains are defined as the westernmost structural domain of the Pyrenean Orogen.

During the inversion tectonic phase, both basins were formed as foreland basins associated to the formation of the Pyrenean Orogen, the Cantabrian Mountains, the Catalan Coastal Ranges and the Central System (e.g. Moutheureau et al., 2014; Teixell, 1998; Vergés et al., 2002). The Ebro Basin developed by lithospheric flexure under the frontal thrust system of the Pyrenees, while the Duero Basin developed in front of the Cantabrian Mountains (Alonso et al., 1996; Pedreira et al., 2003). These continental sedimentary basins were filled by clastic alluvial and carbonate lacustrine sediments (López-Blanco et al., 2000; Pulgar et al., 1999). The westernmost extent of the Ebro Basin corresponds to the continental Bureba sub-basin (Figure 1b) (Pineda, 1997).

From the physiographic point of view, the Burgalesa Platform and its surroundings are located in the northern sub-plateau of the Iberian Peninsula (700–1300 m of altitude), sharing physic and geographic characteristics of the linking zone between the Duero and Ebro basins and its northern boundary (Cantabrian Mountains). To the east, the Folded Band (folded and faulted Mesozoic sediments producing a high topographic relief; Figure 1b and Main Map) disappears, leading to the connection between Ebro and Duero basins.

The southern part of the Cantabrian Mountains accommodated part of the contractional deformation, where thrust faults involving Variscan basement were reactivated, driving the Cantabrian Mountains to the south over the Duero Basin (e.g. Gallastegui, 2000; García-Senz et al., 2019; Martín-González & Heredia, 2011; Figure 1c). The southern frontal thrust is represented by a fault-propagation fold (Figure 1c). The hanging wall is represented by a regional anticline, while the footwall is represented by a major syncline in the Duero Basin (García-Senz et al., 2019).

The south-eastern extent of the Cantabrian Mountains corresponds to the Burgalesa Platform (Figure
1). The sedimentary record of the Burgalesa Platform is determined by deformed Triassic to Upper Cretaceous syn-extensional sedimentary succession, along with Miocene syn-compressional continental units of the Bureba sub-basin. The evolution of Burgalesa Platform was affected by compressional and transpressional structures during compression, such as the WNW-ESE Ubierna Fault System (UFS), a set of high angle right-lateral strike-slip faults rooting into the basement (Tavani et al., 2011; Figure 1b), located south of this tectonic domain. Other authors describe this structure as a fault system rooting into Triassic evaporitic facies, forming part of a low-angle thin-skinned tectonic model for the Burgalesa Platform (Carola et al., 2015; Herráiz 1994). To the southeast, the UFS changes the tectonic behaviour to a set of

Figure 1. (a) Location map of the study area in the southern portion of the Pyrenean Orogen, labelling major units and faults (modified from Tavani, 2012). UFS: Ubierna Fault System. (b) Geological map of the Burgalesa Platform mainly represented by carbonated Cretaceous sediments and bounded to the south by the Folded Band and the Ubierna Fault System (modified from Pérez-López et al., 2020). Dashed white line: location of Figure 5; red rectangle: study area and Main Map location; white polygons represent water masses. (c) Balanced cross-section across the Cantabrian Mountains, from the Duero Basin in the south to the Atlantic Ocean in the north (modified from García-Senz et al., 2019). NPFT: North Pyrenean Frontal Thrust.
thrusts with a NE-SW trend (Rojas Thrust), describing a noticeable cartographic bend (Figure 1b).

Up to now, several works have addressed studies dealing with the configuration and evolution of the drainage system in the area represented by three regional units: (1) the Burgalesa Platform, (2) the Duero Basin and (3) the Ebro Basin (Figure 1) (e.g. Pineda, 2006; Struth et al., 2019; Vacherat et al., 2018). However, these studies did not consider the role of the tectonism on the recent distribution of crests, valleys and the associated geomorphological features. This study presents a detailed morpho-structural map of this area integrating for first time the tectonic and geomorphological features of this portion of Iberia, with the aim to discuss the role of Miocene to present-day tectonism on the recent drainage systems of both basins and the related sedimentary deposits.

2. Material and methods

The geological map presented in this article covers most of the Burgalesa Platform, the northern part of the Duero Basin and the westernmost extent of the Ebro Basin (Bureba sub-basin), covering an area of approximately 527 km² (Figure 1 and Main Map). A Digital Terrain Model (DTM) with a resolution of 1 m / pixel, obtained from LiDAR data, provided by the Instituto Geográfico Nacional (IGN) of the Spanish Government (www.ign.es, last access October 2019), was overprinted in the geological map in order to represent the topography.

Several field campaigns were carried out during a year period (from mid 2018 to mid 2019) for collecting structural data (faults and joints, fold planes and sedimentary inverted and folded sequences) and mapping different sedimentary units. A total of 350 strike/dip and kinematic measurements were collected in the field. This kind of data was essential to determine newly undocumented tectonic features, such as faulting sets and folding related to syn-tectonic stages, determining the Mesozoic and Cenozoic sedimentary evolution of the Burgalesa Platform and Cenozoic basins. Moreover, we redefined and remapped some previously defined tectonic and sedimentological features by Mikeš (2010) and Pineda (1997). A large set of lithostratigraphic contacts and faults were redefined and mapped in the field at 1:5,000 scale, complementing field outcrops with previous geological maps and remote sensing data acquisition from aerial photographs (Vuelo Americano from 1957 provided by the Instituto Geográfico Militar), also considering recent orthophotos with 0.25 m pixel resolution for defining small-scale features. Fault symbols represented in the Main Map reflect the stratigraphical relationship of footwall to hanging wall of a fault (i.e. extensional fault: younger over older; thrust fault: older over younger).

Stratigraphical units of Miocene age presenting lithology from the two different foreland basins (Aquitanian-Burdigalian, Aquitanian, Burdigalian-Serravallian, Langhian-Serravallian and Serravallian-Tortonian units) were unified in order to simplify the stratigraphy of the area. The Main Map also includes new mapped geomorphological units (such as fluvial terraces, alluvial fans, along with colluvium and alluvium deposits) and an exhaustive re-editing of those mapped by Pineda (1997), taking advantage from the fieldwork and the orthophotos analysis. River traces are also provided by the IGN. All the data used and describe above were geo-referenced in an ArcGIS project.

The orientation analysis of the rivers and lineaments have been performed using the software RockWorks 15, rose diagram command in Linears analysis to plot the different rose diagrams, represented by measuring the star point/endpoint data of river traces and interpreted lineaments from orthophotos. Rock-Works plots two different rose diagrams: (1) Frequency diagram, counting the number of single segments, which are oriented in an interval of 15°, and (2) Length diagram, summing the total length of all segments oriented in a 15° interval, and calculating the frequency of the total length into the set data.

3. Stratigraphy of the Burgalesa Platform and the Cenozoic foreland basins

The stratigraphic record of the study area is associated with the different tectonic events that underwent this part of the margin from Triassic to present-day (Figure 2), consisting in several units described in this section. The Paleozoic basement consists of Ordovician phyllites and quartzites, Devonian sandstones, Carboniferous limestones and Permian claystones.

The Lower to Middle Triassic succession is represented by the Buntsandstein clastic facies and Muschelkalk carbonate facies, associated with the first Mesozoic extensional phase that recorded the margin, related to the Pangea break-up (e.g. Schettino & Turco, 2009; Figure 2). The Upper Triassic facies is represented by an evaporitic sequence with sub-volcanic intrusions (Figure 2), attested by the presence of salt diapirs in the study area (e.g. Poza de la Sal Diapir; Quintà & Tavani, 2012). A quiescence stage occurred during the Jurassic times, a period characterized by the development of a regional carbonate ramp (e.g. Quesada et al., 2005; Robles et al., 2004).

The main Mesozoic rifting event took place during the Late Jurassic to Early Cretaceous and is related to the opening of the North Atlantic and the Bay of Biscay. The stratigraphic record of the Burgalesa Platform during this tectonic phase is composed by fluvio-deltaic siliciclastic sandstones (Figure 2; e.g. Hernández et al., 1999; Pujalte et al., 2004). The margin
underwent thermal subsidence after the Early Cretaceous extension, allowing the deposition, from the Late Albian to the end of Late Cretaceous, of a succession made of clastic sediments at the base and carbonate sediments at the top (e.g. Ramírez del Pozo, 1971). The Cenozoic succession is mainly constituted by conglomerates, sandstones and claystones, deposited during the tectonic inversion of the Pyrenees (Figure 2). These sediments crop out in the Ebro and Duero foreland basins and the Villarcayo syncline, located northeast of the study area (e.g. Carola et al., 2015; Figure 1b). The Duero Basin is a wide Tertiary depression filled by sediments deposited in continental conditions and partially covered by Quaternary sediments (Pineda, 1997). The Bureba sub-basin is also filled by continental sediments, which are constituted by alluvial fans. In the study area, Pliocene and Quaternary deposits are represented by clastic sediments associated to colluvium deposits, alluvial fans, low and middle terraces (related to the drainage system of Ebro and Duero basins, the latter of which does not present middle terraces), along with Holocene sediments filling up the riverbeds and valley bottoms. From the stratigraphic and petrologic point of view, the Cenozoic deposits are rather similar between both basins.

4. Results

4.1. Structural lineaments

The Burgalesa Platform and the Bureba sub-basin are affected by four main lineament patterns according to their orientation: (1) ENE-WSW; (2) NW-SE; (c) NNW-SSE; (d) NE-SW (Figure 3 and Main Map). These lineaments are well preserved in the limestones of the marine Upper Cretaceous succession in the Burgalesa Platform (Figure 3).

To the north of the UFS, ENE-WSW structural lineaments emerge in Turonian deposits as the most penetrative set of fractures in the area, irregularly spaced between each other (Figure 3a). Most of these fractures are displaced by NNE-SSW to N-S faults, with different sense of movement. South of the UFS, the other three lineament sets coexist in a restricted area of 3 km² (see Figure 1b for location). The NW-SE fractures are parallel to the faults present in the surroundings (Main Map). The fracture orientation within these sediments is also parallel to the UFS, probably given by the influence of this regional structure (less than 1 km away), and therefore acting as minor-scale subsidiary faults affecting the N-S to NE-SW oriented fracture pattern. To the SW, another set of fractures are present in the Cretaceous limestones, with NNW-SSE orientation (Figure 3c). The orthophotos show the displacement of materials with different cohesion (soft vs. hard) through the fault set. These faults are preserved in an area affected by an E-W anticline, oblique to the hinge line of the fold. The NE-SW fractures do not present any remarkable displacement in map view (Figure 3d), therefore considered as joints. They are parallel to the main faults mapped nearby, while in some points are partially interrupted and displaced by NNW-SSE structural lineaments.

4.2. River network and the related sedimentological and geomorphological features of the Cenozoic basins

In the study area, both Duero and Ebro Cenozoic basins display a differentiated relief and fluvial network, which control the deposition of the main recent sediments and the geomorphological features. The Duero Basin is mostly characterized by a plateau and
tabular appearance. Most of the Miocene sediments filling the basin lie sub-horizontally (slightly dipping to the SSW), corresponding to marls, claystones, conglomerates and limestones (Main Map). The main drainage system flows from NNE to SSW, parallel to the Miocene sediment dip described above. It is represented by roughly rectilinear wide and low slope fluvial valleys (Main Map), and partially covered by colluvium deposits in some areas. In the most recent period, the northern margin of the Duero Basin seems to have a stable local base level. Thus, it presents valleys with gentle slopes, the incision of the network has been scarce, without higher and middle fluvial terraces, while addition valley bottoms and floodplains are flat with little migration of channels. This region was described by Pérez-González et al. (1994) as dominated by a well-characterized structural-type relief, while the local base level is controlled by lithology (Struth et al., 2019).

To the NE, the Bureba sub-basin (Ebro Basin) is subdivided into two domains according to their topography (western and eastern). The western part presents a smooth relief (900–960 m altitude), and is shaped on Oligocene-Lower Miocene claystones and conglomerates (Main Map). The boundary with the eastern domain is represented by a striking erosive escarpment (Figure 4, Main Map), marking the Ebro-Duero divide. The westward migration of the
Ebro-Duero divide is attested by the fluvial captures from the Duero Basin to the Ebro Basin. The best example is located in the Bureba sub-basin, where the middle-high basin of the Ubierna river (Duero tributary) has been recently captured by the Homino river (Ebro tributary) (Figure 4c; Pineda, 1997; Struth et al., 2019), attested by the presence of Middle Pleistocene to Holocene fluvial deposits of the Ubierna river to the north (Figure 4c and Main Map). As a result, this fluvial capture produces an ongoing headward erosion of the Ebro against the Duero catchment (Struth et al., 2019). The Homino river and the tributaries preserve alluvial terraces due to the high river incision and the related erosion, which are more recent upstream, suggesting an intense retreat at the headwaters.

Other rivers such as de la Hoz and Rioseras rivers are incised through the Ubierna Mesozoic mountain range, forming gorges decapitated and captured by the Ebro drainage system to the north. Topographically, the eastern domain of the Bureba sub-basin is the lowest of the study area (800 m altitude average). The drainage system flows from SW to NE, pouring towards the Ebro Basin and describing dendriform patterns probably due to the low cohesion of the Tertiary sediments and a fractured Mesozoic substrate according to the structural context of the area. The largest rivers follow a NE-SW to NNE-SSW trend (Figure 5). Alluvial fans different in age are located in the outer parts of ravines from the main drainage system, most of them with small dimensions located in the Ebro Basin. Conglomeratic levels origin escarpments, under which few colluvium cones are formed locally. Generally, the Tertiary sediments lie sub-horizontally, except in the north and central parts where they are affected by monocline flexures verging towards the south and southeast (Main Map). The dynamic morphological tendency in the study area indicates a progressive incision of the drainage system.

5. Discussion

According to Quintà (2013), the final tectonic stage of the contractional deformation took place during the Miocene and is characterized by the formation of N-S and NNW-SSE oriented cleavage, WSW-ENE tension cracks and joints, NE-SW to NNE-SSW right-lateral strike-slip faults and WSW-ENE left-lateral strike-slip faults (reactivating previous faults; Figure 5b). These orientations are parallel to those described above (Figure 3). Therefore, Miocene compressive event is responsible for the formation and/or
reactivation of the four family structural lineaments (joints and faults) documented in the Upper Cretaceous units (Figure 3). The present-day transpressional stress field, defined by the maximum horizontal shortening with N-S trend (Carola et al., 2015; Her-raiz et al., 2000; Tavani et al., 2011, 2013), could have activated the previously mentioned structural features as thrust faults or strike-slip faults with NW-SE/NNW-SSE to NE-SW direction, with the UFS and the Rojas Thrust as the most representative (Figure 1). In this sense, the most frequent and largest structural lineaments follow a regional E-W trend (Figure 5b). However, those lineaments with a length lesser than 1 km and greater than 200 m are NE-SW oriented, roughly aligned with the main river trend in the study area (Figure 5), suggesting a tectonic control on the drainage configuration at local scale, and probably related to the inversion of Mesozoic transfer zones with the same trend (Tavani & Granado, 2015).
Several works have been published regarding the drainage system of both Ebro and Duero, documenting the fluvial captures in the Bureba sub-basin from the Ebro over the Duero (e.g. Mikeš, 2010; Pineda, 2006; Struth et al., 2019; Vacherat et al., 2018). In the eastern extent of the Main Map (Figure 4a, b), corresponding to the Bureba sub-basin, the crest and bottom valleys that form part of the complex drainage system follow the same four orientation as the above described lineament families (ENE–WSW, NW–SE, NNW–SSE and NE–SW; Figure 3). These lineaments are mostly documented in the Bureba sub-basin (Figure 4 and Main Map), where the rivers show major incision rates compared to the Duero Basin (Struth et al., 2019; Vacherat et al., 2018). The irregular space distribution and length that present the lineaments could be conditioned by the interaction between the tectonic and the lithology in the area. Joints, cracks and faults use to break up lithified sediments, which allow water circulation and erosion through them, eventually evolving to valleys that can harbour rivers at the bottom part. Therefore, we assume that the structural lineaments formed during the last stages of compression control the complex drainage system in the area, determining the parallelism between the structural and drainage lineaments (Figures 3–5). This tectonic stage coincides in time with the onset of opening from endorheic to exorheic conditions in the Ebro and Duero basins since the Miocene (e.g. Antón et al., 2012; García-Castellanos et al., 2003) and, inducing the headward advance of the erosion through both basins.

The drainage river system of the Bureba sub-basin is mainly represented by four main orientations, playing a key role on the distribution, orientation and geometry of the more recent sediments in map view, mainly composed by Quaternary alluvial deposits (Figure 4c, d and Main Map). This indicates that the present-day topography of the Bureba sub-basin (Struth et al., 2019; Vacherat et al., 2018) and the Quaternary sedimentary deposition are controlled by the recent tectonic field, reactivating the structures and affecting the Miocene sedimentary cover of the basin. However, the extension of these deposits is rather variable depending on their orientation (Figure 4c, d). The study area shows three main Quaternary (Holocene) alluvium deposits aligned NNE–SSW in the Bureba sub-basin, separated 4 km from each other (Figure 4 and Main Map), in which the Ubierna, Homino and La Molina rivers, and the Fuente Monte stream are incised. The western and most striking Quaternary deposit is disposed just to the west of the erosive escarpment that splits the Bureba sub-basin in two sub-domains (Figure 4a). According to Struth et al. (2019) and references therein, the Ubierna river (Duero Basin), responsible for the development of this deposit, is later captured by the Homino river (Ebro Basin) in Holocene times, attested by the underdeveloped alluvial sediments in the capturing point, where the Homino river changes its orientation from N–S to WSW–ENE (Figure 4c). Additionally, the roughly NW–SE oriented tributaries that feed this deposit are concentrated on its western side, suggesting that the main sedimentary source area was located to the NW. All these observations are in agreement with the presence of the Hontomin Thrust, a ENE–WSW Mesozoic extensional fault inverted during the right-lateral transpressive stage of the UFS, interpreted from seismic data and tectonic stress analysis (Tavani et al., 2011, 2013). Verging towards the ESE, the inverted fault is interpreted to uplift and elevate the hanging wall (Upper Cretaceous present in the Burgalesa Platform plateau) and thus, inducing the erosion and transport of these sediments towards the same direction. The current direction is favoured by the presence of structural lineaments related to the thrust tectonic activity that controlled their orientation and flow direction (Figure 4c, d). The uplift of the hanging wall of this major structure and the orientation of the structural lineaments favoured the development of NNW–SSE Quaternary deposits disposed west of the main fluvial fan, NNE–SSW oriented (shared by the Homino and Ubierna rivers; Figure 4). Furthermore, the orientation and location of Quaternary deposits that fill the valley bottom of the La Molina river and the Fuente Monte stream to the east (Figure 4c, d), could be controlled by contractional structures related to the Hontomin Thrust, overlain by the Miocene sediments of the Bureba sub-basin.

Overall, the tectonic compression determined the distribution of uplifted and subsided areas in the sedimentary basins, conditioning the location and the NNE–SSW to NE–SW orientation of the main river currents active at present-day. This trend is also recognizable in the south-eastern exposure of Cretaceous sequences from the Burgalesa Platform, affected by the NE–SW Rojas Thrust, a Mesozoic extensional structure also reactivated as a reverse fault during the Cenozoic, forming part of the horsetail termination of the UFS (Tavani, 2012; Figure 1b). Nevertheless, east of the erosive escarpment (the orientation of which could be conditioned by the Hontomin Thrust), the Homino river is oriented ENE–WSW (Figure 4c), parallel and aligned with the Quintanilla anticline (Quintà, 2013), located in the southern extent of the Cretaceous carbonates in the central part of the Main Map (Figure 1b). This fold is probably related to a north-verging thrust close to the Ubierna Fault.

As evidenced in the Main Map, the drainage system of the two main basins (Duero to the SW and Ebro to the NE) differs in terms of geometry and distribution of the main tributaries. The equilibrium in the erosion of the Duero drainage (Struth et al., 2019), along with the regional steep base level, induced a rectilinear geometry for the drainage network of the Duero with gentle
slopes and flat valleys bottom. This drainage network also indicates the relative tectonic quiescence that has undergone the headwaters of the Duero Basin in recent times. The Ebro Basin on the contrary, more specifically the Bureba sub-basin, experienced a lowering of the base level possibly due to a combination of Cenozoic compressional tectonics and dropping of the sea level. Under this context, the expected drainage network would be formed by rectilinear streams and rivers. However the fracturing of the Burgalesa Platform favoured the development of the dendriform drainage network and the V-shaped fluvial valleys of the Bureba sub-basin.

6. Conclusions

This work introduces a geological map at 1:50,000 scale of Mesozoic to Cenozoic and Quaternary deposits of the Burgalesa Platform and the surroundings. The sedimentary deposits and the main structural features, represented in the Main Map, recorded the tectonic events that configured the Burgalesa Platform and its surroundings: (1) break-up of Pangea and thermal subsidence during the Triassic times and deposition of carbonate and evaporitic sequences respectively; (2) ongoing thermal subsidence during the Early-Middle Jurassic allowed the deposition of stable carbonate ramps; (3) clastic sediments associated to the main rifting event from Late Jurassic to Early Cretaceous; (4) thermal subsidence recorded by Upper Cretaceous carbonate sediments; (5) tectonic inversion during the Cenozoic leading to the uplift of the mountain range and the formation of foreland basins, erosion and deposition of Oligocene and Miocene sediments, the configuration of the Quaternary deposits according to the activity of the main faults and the elevated incision rates of the tributaries.

Furthermore, in this map we show the relationship between the recent tectonics and the Quaternary alluvial deposits embedded in Miocene sediments, with special emphasis on the present-day drainage system configuration in the south-eastern termination of the Burgalesa Platform. The presence of four different fracture/fault families (ENE-WSW, NW-SE, NNW-SSE and NE-SW oriented) have been confirmed by the analysis of DTM and by a detailed mapping of these discontinuities mostly present in the Miocene sediments of the Bureba sub-basin. The association between topography and structural lineaments, allows us to confirm that the Miocene to present-day tectonic compression and strike-slip regime strongly controls most of the tributaries fluvial channels and the related alluvial sediments.

The main rivers and streams and related alluvial deposits present in the Bureba sub-basin show a NNE-SSW orientation, related with the emplacement of the frontal thrust of the Cantabrian Mountains and the inversion of the NNE-SSW Hontomin Mesozoic extensional fault, active during the Miocene up to present-day.

Software

The Main Map was produced using ArcGIS software from Esri, used to include the digital terrain models and the orthophotographs, allowing us to digitalize and georeference the lithostratigraphic contacts and the faults/fractures mapped in the field and using the stereograph. Final editing and PDF building were made through CorelDraw. We have used the software RockWorks 15, rose diagram command in Linears analysis to plot the different rose diagrams of the manuscript.

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Disclosure statement

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References

Alonso, J. L., Pulgar, J. A., Garcia-Ramos, J. C., & Barba, P. (1996). Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain). In P. F. Friend & C. J. Dabrio (Eds.), Tertiary basins of Spain: The stratigraphic record of crustal kinematics, V. Chapter W5 (pp. 214–227). Cambridge University Press.
Antón, L., Rodés, A., De Vicente, G., Pallás, R., Garcia-Castellanos, D., Stuart, F. M., Braucher, R., & Bourles, D. (2012). Quantification of fluvial incision in the Duero Basin (NW Iberia) from longitudinal profile analysis and terrestrial cosmogenic nuclide concentrations.

JOURNAL OF MAPS
Herraiz, P. P. (1994). La Falla de Ubierna (margen SO de la
García-Castellanos, D., Vergés, J., Gaspar-Escribano, J., &
García-Senz, J., Pedrera, A., Ayala, C., Ruiz-Constán, A.,
Mike Gallastegui, J. (2000). Estructura cortical de la cordillera y
Barnolas, A., & Pujalte, V. (2004). La Cordillera Pirenaica.
Beaumont, C., Muñoz, J. A., Hamilton, J., & Fullsack, P. (2000). Factors controlling the Alpine evolution of the
central Pyrenees inferred from a comparison of observa-
tions and geodynamical models. Journal of Geophysical Research: Solid Earth, 105(B4), 8121–8145. https://doi.org/10.1029/1999JB00390
Carola, E., Muñoz, J. A., & Roca, E. (2015). The transition from thick-skinned to thin-skinned tectonics in the
Basque-Cantabrian Pyrenees: The Burgalesa Platform and
surroundings. International Journal of Earth Sciences, 104(8), 2215–2239. https://doi.org/10.1007/s00531-015-1177-z
Gallastegui, J. (2000). Estructura cortical de la cordillera y
margen continental cantábricos: perfiles ESCI-N. Trabajos de geología, 22, 9–234.
García-Senz, J., Pedrera, A., Ayala, C., Ruiz-Constán, A.,
Robador, A., & Rodríguez-Fernández, L. R. (2019). The role of exhumed mantle indentation during conti-
ental collision. Geological Society, London, Special Publications, SP490–2019–2112. https://doi.org/10.1144/SP490-2019-112
García-Castellanos, D., Vergés, J., Gaspar-EScribano, J., &
Cloetingh, S. (2003). Interplay between tectonics, climate, and
fluvial transport during the Cenozoic evolution of the
Ebro Basin (NE Iberia): TECTONICS, CLIMATE, AND DRAINAGE. Journal of Geophysical Research: Solid Earth, 108(B7). https://doi.org/10.1029/2002JB002073
Hernández, J. M., Pujalte, V., Robles, S., & Martín-Clossas, C. (1999). División estratigráfica genética del grupo Campóo
(Malm-Cretácico Inferior, SW Cuenca Vasconcantábrica).
Revista de la Sociedad Geológica de España, 12, 377–396.
Herraz, P. P. (1994). La Falla de Ubierna (margen SO de la
cuenca Cantábrica). Geococatá, 16, 39–42.
Herraz, M., De Vicente, G., Lindo-Naupari, R., Giner, J.,
Simón, J. L., González-Casado, J. M., Vadillo, O.,
Rodríguez-Pascua, M. A., Cucéndez, J. I., Casas, A.,
Cabañas, L., Rincón, P., Cortés, A. L., Ramírez, M.,
Lucini, M. (2000). The recent (upper Miocene to
Quaternary) and present tectonic stress distributions in the
Iberian Peninsula. Tectonics, 19(4), 762–786. https://
doi.org/10.1029/2000TC900006
Jammes, S., Huismans, R. S., & Muñoz, J. A. (2014). Lateral
variation in structural style of mountain building: Controls of rheological and rift inheritance. Terra Nova,
26(3), 201–207. https://doi.org/10.1111/ter.12087
López-Blanco, M., Marzo, M., Burbank, D. W., Vergés, J.,
Roca, E., Anadón, P., & Piña, J. (2000). Tectonic and cli-
matic controls on the development of foreland fan deltas: Montserrat and Sant Llorenç del Munt systems (Middle
Eocene, Ebro Basin, NE Spain). Sedimentary Geology, 138 (1), 17–39. https://doi.org/10.1016/S0037-0738(00)00142-1
Martín-González, F., & Heredia, N. (2011). Complex tec-
tonic and tectonostratigraphic evolution of an Alpine
foreland basin: The western Duroo Basin and the related
Tertiary depressions of the NW Iberian Peninsula. Tectonophysics, 502(1–2), 75–89. https://doi.org/10.1016/j.tecto.2010.03.002
Mikes, D. (2010). The upper cenozoic evolution of the Duero
and Ebro fluvial systems (N-Spain); part I. paleogeography;
part II. geomorphology. Open Geosciences, 2(3). https://doi.
org/10.2478/v10085-010-0017-4
Mouthereau, F., Filleaudeau, P.-Y., Vacherat, A., Pik, R.,
Lacombe, O., Fellin, M. G., Castelltort, S., Christophoul,
F., & Masini, E. (2014). Placing limits to shortening evolu-
tion in the Pyrenees: Role of margin architecture and
implications for the Iberia/ Europe convergence. Tectonics, 33(12), 2283–2314. https://doi.org/10.1002/2014TC003663
Pedreira, D., Pulgar, J. A., Gallart, J., & Díaz, J. (2003). Seismic evidence of Alpine crustal thickening and wed-
ging from the western Pyrenees to the Cantabrian Mountains (north Iberia): CRUSTAL THICKENING AND WEDGING IN NORTH IBERIA. Journal of Geophysical Research: Solid Earth, 108(B4). https://doi.org/10.1029/2001JB001667
Pérez-González, A., Martín-Serrano, A., & Pol Méndez, C. (1994). Depresión del Duero. In M. Gutiérrez Elorza
(Ed.), Geomorfología de España (pp. 351–383). Rueda.
Pérez-López, R., Mediato, J. F., Rodríguez-Pascua, M. A.,
Giner-Robles, J. L., Ramos, A., Martín-Velázquez, S.,
Martínez-Orío, R., & Fernández-Canteli, P. (2020). An active tectonic field for CO2 storage management: The
Hontomin onshore case study (Spain). Solid Earth, 11 (2), 719–739. https://doi.org/10.5194/se-11-719-2020
Pineda, A. (1997). Mapa Geológico de la Hoja nº 167
(Montorio) del Mapa Geológico Nacional (MAGNA) a escala 1/50.000. IGME.
Pineda, A. (2006). El Ebro captura al Duero en el norte de
Burgos. Guía de una excursión geológica. Tierra y
tecnología: revista de investigación geológica, 30, 47–53.
Pujalte, V., Robles, S., García-Ramos, J. C., & Hernández, J. M. (2004). El Malm-Barremiense no marinos de la
Cordillera Cantábrica. In J. A. Vera (Ed.), Geología de España (pp. 288–291). SGE-IGME.
Pulgar, J. A., Alonso, J. L., & Espina, R. G. (1999). La
deposición alpina en el basamento varisco de la Zona
Cantábrica. Trabajos de geología, 21, 283–294.
Quesada, S., Robles, S., & Rosales, I. (2005). Depositional
architecture and transgressive–regressive cycles within
Liassic backstepping carbonate ramps in the Basque–
Cantabrian basin, northern Spain. Journal of the
Geological Society, 162(3), 531–548. https://doi.org/10.1144/0016-764903-041
Quintá, A. (2013). El patrón de fracturación alpina en el sec-
tor suroccidental de los Pirineos Vascos [PhD Thesis].
Universitat de Barcelona, 170 pp.
Quintá, A., & Tavani, S. (2012). The foreland deformation in
the south-western Basque– Cantabrian Belt (Spain).
Tectonophysics, 576–577, 4–19. https://doi.org/10.1016/j.
tecto.2012.02.015
Ramírez del Pozo, J. (1971). Bioestratigrafía y Microfacies
del Jurásico y Cretácico del Norte de España (Región
Cantábrica). Memorias Instituto Geológico y Minero de
España, 78, 1–357.
Robles, S., Quesada, S., Rosales, I., Aurell, M., & García-
Ramos, J. C. (2004). El Jurásico marino de la Cordillera
Cantábrica. In J. A. Vera (Ed.), Geología de España (pp.
279–285). SGE IGME.
Roca, E., Muñoz, J. A., Ferrer, O., & Ellouz, N. (2011). The role
of the Bay of Biscay Mesozoic extensional structure in the
configuration of the Pyrenean orogen: Constraints from the
MARCONI deep seismic reflection survey. Tectonics, 30(2). https://doi.org/10.1029/2010TC002735
Schettino, A., & Turco, E. (2009). Breakup of Pangea and plate kinematics of the central Atlantic and Asia regions. Geophysical Journal International, 178(2), 1078–1097. https://doi.org/10.1111/j.1365-246X.2009.04186.x
Struth, L., Garcia-Castellanos, D., Viaplana-Muzas, M., & Vergés, J. (2019). Drainage network dynamics and knickpoint evolution in the Ebro and Duero basins: From endorheism to exorheism. *Geomorphology*, 327, 554–571. https://doi.org/10.1016/j.geomorph.2018.11.033

Tavani, S. (2012). Plate kinematics in the Cantabrian domain of the Pyrenean orogen. *Solid Earth*, 3(2), 265–292. https://doi.org/10.5194/se-3-265-2012

Tavani, S., Carola, E., Granado, P., Quintà, A., & Muñoz, J. A. (2013). Transpressive inversion of a Mesozoic extensional forced fold system with an intermediate décollement level in the Basque-Cantabrian Basin (Spain). *Tectonics*, 32(2), 146–158. https://doi.org/10.1002/tect.20019

Tavani, S., & Granado, P. (2015). Along-strike evolution of folding, stretching and breaching of supra-salt strata in the Plataforma Burgalesa extensional forced fold system (northern Spain). *Basin Research*, 27(4), 573–585. https://doi.org/10.1111/bre.12089

Tavani, S., Quintà, A., & Granado, P. (2011). Cenozoic right-lateral wrench tectonics in the Western Pyrenees (Spain): The Ubierna Fault System. *Tectonophysics*, 509(3–4), 238–253. https://doi.org/10.1016/j.tecto.2011.06.013

Teixell, A. (1998). Crustal structure and orogenic material budget in the west central Pyrenees. *Tectonics*, 17(3), 395–406. https://doi.org/10.1029/98TC00561

Vacherat, A., Bonnet, S., & Mouthereau, F. (2018). Drainage reorganization and divide migration induced by the excavation of the Ebro basin (NE Spain). *Earth Surface Dynamics*, 6(2), 369–387. https://doi.org/10.5194/esurf-6-369-2018

Vergés, J., Fernández, M., & Martínez, A. (2002). The Pyrenean orogen: Pre-, syn-, and post-collisional evolution. *Journal of the Virtual Explorer*, 8, 55–74. https://doi.org/10.3809/jvirtex.2002.00058