Cent. Eur. J. Geosci. • 2(4) • 2010 • 420-432
DOI: 10.2478/v10085-010-0017-4

VERSITA

Central European Journal of **Geosciences**

The Upper Cenozoic evolution of the Duero and Ebro fluvial systems (N-Spain): Part I. Paleogeography; Part II. Geomorphology

Research Article

Daniel Mikeš*

Stellenbosch University,
Department of Earth Sciences, Private Bag X1,
Matieland 7602, South Africa

Received 14 April 2010; accepted 3 July 2010

Abstract: Lack of age dates in the terrigenous Cenozoic sediments of the Duero and the Ebro sedimentary basins has complicated tecto-stratic correlation across the two basins. We tentatively synthesize a range of existing studies and new data to construct a rough general paleogeography throughout Upper Cenozoic times.
The more extensive erosion of the Ebro has been previously attributed to the earlier moment of opening. We tentatively analyse lithostratic data to conclude that the lower knick-point and different lithologies have also contributed to the deeper erosion in the Ebro Basin.
We conclude from lithostratic data and field evidence that the W half of the Rioja was part of the Duero in earlier times and that the escarpment retreated westward through the Rioja in four subsequent episodes of erosion. The tilt of the NW Duero is a consequence of isostatic rebound to this erosion.

Keywords: Duero • Ebro • paleogeography • geomorphology • erosion • capture • escarpment

1. Introduction

The northern part of the Iberian Peninsula is composed of two major hydrographic basins, the Duero and the Ebro (Figure 1). In Miocene to Pliocene times both the Duero and the Ebro Basins opened to their respective repositories and erosion advanced through both basins. Erosion in the Duero Basin, however, was rather modest, whereas in the Ebro Basin it was severe. In this work we shall tentatively analyse the reasons for the difference in extent and style of erosion of both basins.

Published paleogeographic facies reconstructions [1, 2] are non-palinspastic and hence lack the spatial evolution of the basins' geometries. Since few age dates have and can be acquired in these sediments, tectonic reconstruction is mostly based on facies analysis, and the timing of major tectonic events is troublesome. In this work we shall tentatively synthesise previous paleogeographic studies and add some interpretations.

The main questions of this study are the following: (1) What was the paleogeographic evolutionary history of the Duero and the Ebro Basins? (2) What is the geomorphic evolution of the Bureba escarpment? To answer these questions we will use stratigraphic data [1, 2], digital

*E-mail: mikes@sun.ac.za

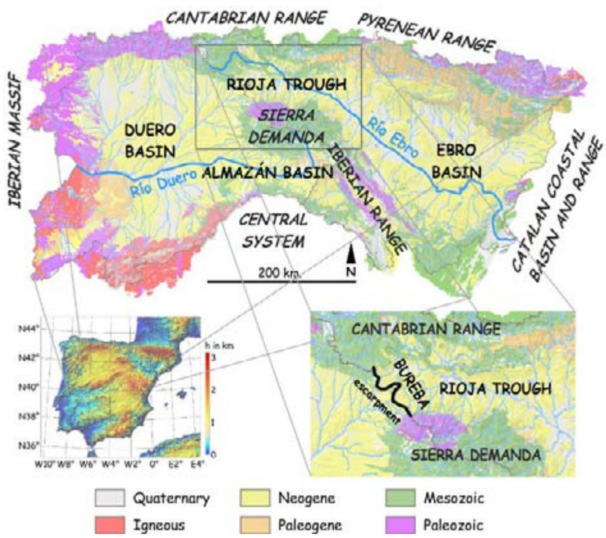

Figure 1. Duero and Ebro Basins and their major lithostratic units. The inset shows the topography of Spain and the Duero and Ebro Basins. The detail shows the Rioja Trough and the Bureba escarpment.

elevation models, geologic maps (ENRESA), large-scale cross-sections (ENRESA), small-scale (IGME) cross-sections and results from a modelling study [3].

Although most of this work is based on existing work and only in small part on personal fieldwork, it is to the author's knowledge the first attempt to synthesise all of these works into an analysis of both the Duero and the Ebro Basins in terms of paleogeographic evolution, sedimentary facies analysis and chronostratic correlation.

2. Regional setting

The Ebro and Duero Basins at present form two hydrographic basins, surrounded by mountains (Figure 1). However, in Upper Maastrichtian / Lower Paleocene times they formed one extended foreland basin, open to the Atlantic in the W and the Mediterranean in the E [4]. This basin was closed to the south by the Central and Iberian systems and to the north by the Pyrenees, the main thrust zone [5].

Geological cross-sections (Figure2) reveal most of the tectonic evolution of the Duero and Ebro Basins through the geometry of stratigraphic units. Both paleo-Duero and -Ebro Basins have their deepest basement and thickest sediment fill in the N, due to flexural loading of the main thrust system, the Cantabrian Range and the Pyrenees (ENRESA and IGME). Both have only minor subsidence in the S due to flexural loading of the Central System and Iberian Range, and in the W and the E through the subordinate thrust system, the Iberian Massif and Catalan Coastal Range. The N major thrust faults are steep and the basement and sediment form wide anticlines, whereas the S major thrust faults are gentle and fold neither basement nor sediment fill.

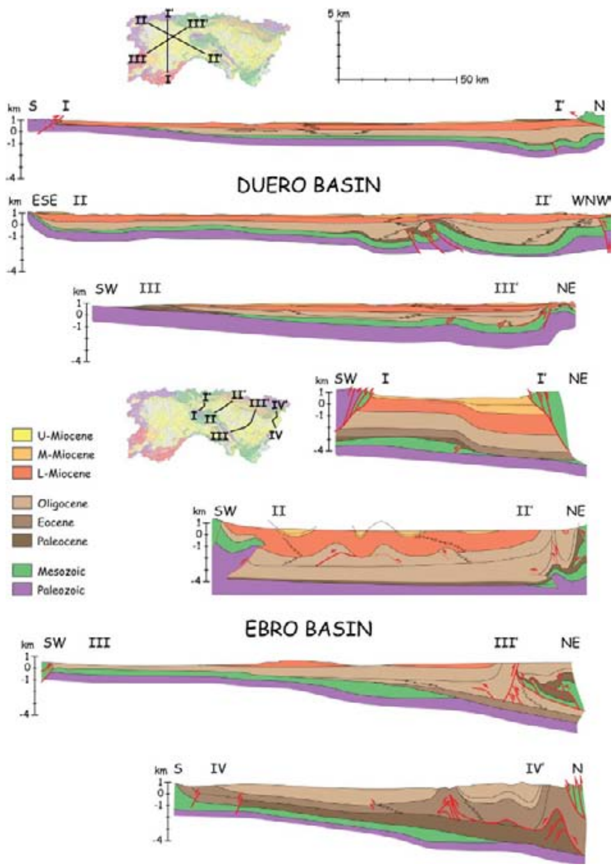

Figure 2. Geological cross-sections across the Duero and Ebro Basins (courtesy of ENRESA). The insets show their locations. Duero) Increased subsidence to N and steep bordering thrust faults from the N. Note the subsequent anticline and syncline to the NE and onlap to the S. Ebro). Increased subsidence to the N and gentler bordering thrust faults from the N. Note the internal thrusting of Paleogene.

The paleo-Central and -Iberian systems appear to have formed one range at first, and, due to the anticlockwise rotation of Iberia, an E-W compression against the Pyrenees bent its centre to the N, which ultimately broke, creating the Central and Iberian systems [4]. The Iberian System sheared along the Central System to the NW splitting it in two, hence creating the Ebro and Duero Basins and the Rioja Trough. Meanwhile, the Cantabrian Range closed the Duero Basin from the Atlantic and the Catalan Coastal Ranges closed the Ebro Basin from the Mediterranean. The Sierra Demanda caused additional subsidence in the

Rioja Trough through flexural loading [6].

The Neogene sediment fill (Figure 3) is indicative of the basin evolution as can be seen in a contour map of the Neogene sediment thickness [7]. Both basins have a Neogene sediment fill with zero thickness along the borders and several kilometres in the main depocentre, which, in both basins, is situated north of the geographic centre. The sediment fill of the Rioja, in contrast, has a rather constant thickness of several kilometres along the entire part with only a rapid decrease in thickness in the occidental part [7].

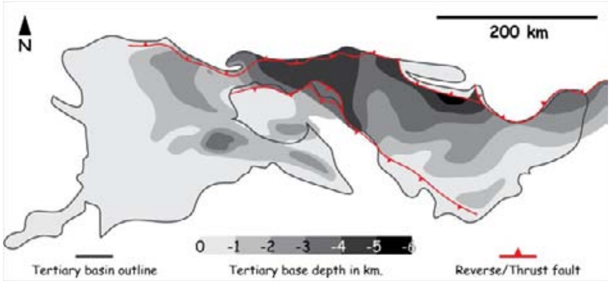

Figure 3. Thickness of Neogene sediment fill (after Lanaja, 1987). Highest thickness in both the Duero and the Ebro Basin is located in NE and NW of the basins, resp. Thickness in the Rioja Trough is rather constant, exhibiting only slight increase from W to E.

3. PART I: Paleogeography (Paleocene–present)

The interpretations in this section have been obtained in the following way: for paleogeography, by compiling several interpretations [1, 2, 8–17] and overlaying them with the lithostratic map from the ENRESA. The areal extension of stratigraphic units is used to interpret the nature and extent of sedimentary systems through facies analysis. These results are combined with existing structural and tectonic studies [15, 18] into a schematic overview of the timing of tecto-stratic events. Based on the above interpretation and the existing cross-sections (ENRESA and IGME) a chronostratic diagram is constructed through the Duero, the Rioja and the Ebro that indicates the facies distributions through time and space. It must be noted that all these interpretations are rather tentative in nature.

The paleogeographic reconstructions in this work are pseudo-palinspastic. We estimate the ancient basin geometry through geometric analysis of the strata deposited in each epoch. Absolute age dates of facies in these basins are rare and even correlation from the Duero to the Ebro Basin is prone to discussion. Hence the character and timing of these tectonic events is yet uncertain. We are aware of this, but believe that this approach contributes to an appreciation of some vital aspects of these basins.

Subordinate questions of this part are the following: (1) How do the Duero and Ebro strata correlate? (2) When do major tecto-stratic events occur? (3) Why are the Duero and Ebro erosional expressions different?

The results in this section are based on a variety of data, i.e. previous interpretations of tectonics, stratigraphy, and paleogeography, on the one hand, and digital data of geomorphology, cross-sections, lithology, and stratigraphy, on the other. We propose a paleogeographic reconstruction in Figure 4 and a tecto-sedimentary and chronostratic correlation in Figure 5.

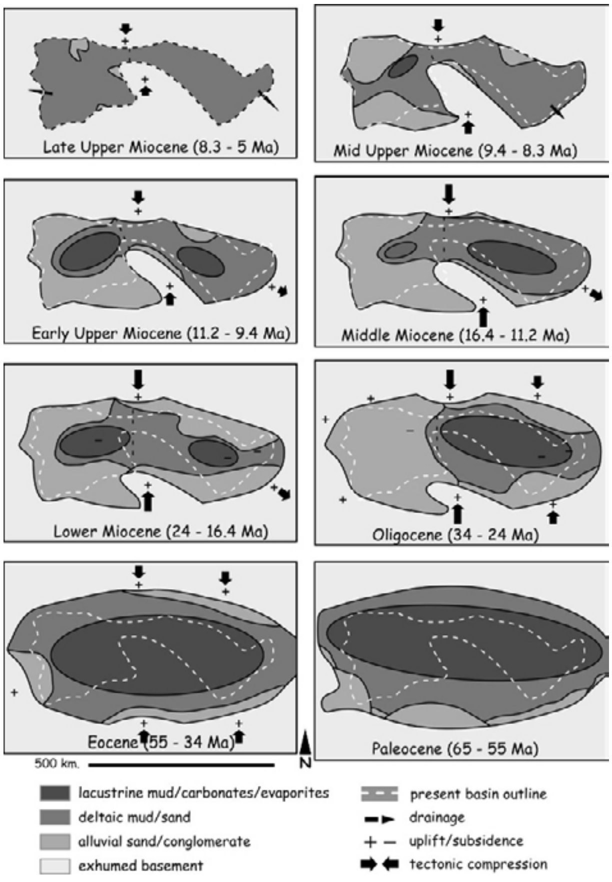

Figure 4. Tentative paleogeography of the Duero/Ebro Basins from Paleocene to Miocene (75–5 Ma). The broken white line denotes present outline of outcropping Tertiary sediments. In part, information has been used from Mediavilla 1996, Pineda-Velasco 1996.

The following section gives an overview of the epochs from Paleocene to Present in terms of tectonic events, depositional systems and paleogeographic setting. From the above mentioned results and analysis we arrive at the following tentative synthesis.

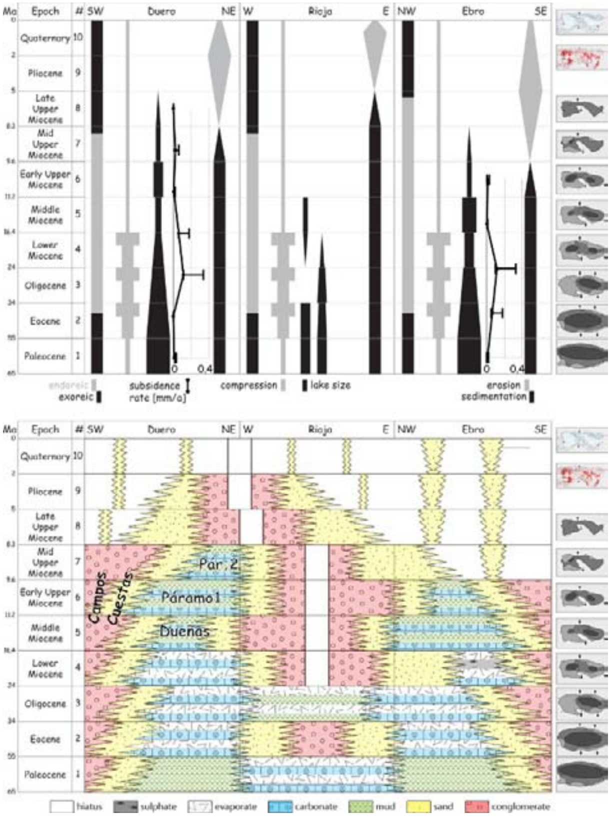

Figure 5. Tentative tecto-stratic diagram of the Duero/Ebro Basin. Tectonics) Features of the Duero Basin, Ebro Basin and Rioja Trough: (1) Basin state: exoreic/endoreic; (2) Amount of tectonic compression; (3) Lake size; (4) Amount of tectonic subsidence; (5) amount of erosion; (6) water divide location. The width of the bar indicates the relative importance of a feature. The miniatures at the right hand side correspond to Figure 5. In part, information has been used from Santaeulària 1996 & 1997, Mediavilla 1996, Pineda-Velasco 1996. Stratigraphy) Stratigraphic correlation of the Duero Basin, the Ebro Basin and the Rioja Trough. Epochs are divided into tecto-sedimentary episodes, hence the time axis is variable. Campos, Cuestas and Páramo 1/2 refer to Formation names. In part, information has been used from Mediavilla 1996 and Pineda-Velasco 1996.

3.1. Paleocene (65–55 Ma; Figure 4)

Paleocene to Lower Eocene: The alpine collision between Eurasia and Africa starts to create a compressional regime in the N Iberian plate in the Upper Cretaceous. The proto-Ebro foreland basin forms through flexural subsidence S of the Pyrenees, the rest of the basin being slightly tilted to the N. In the N part of this basin, medium- to fine-grained detritic sediment deposits from the Pyrenees and at its southern border alluvial braidplains and mudflats deposit medium- to fine-grained detritic sediments from the Iberian Range [16]. At this time the proto-Ebro Basin is open to the Mediterranean and connected to the proto-Duero Basin. The total subsidence rate at 58.0–56.0 Ma is +0.008–+0.018 mm a^{-1} and the total tectonic subsidence in this time interval is +16–+36 m [18].

The proto-Duero Basin forms through uplift of the Iberian Massif and strong flexural subsidence S of the Cantabrian Range, tilting the N part of the basin to the N. In the SW, along the Iberian Massif and the Central System and the SE, towards the Iberian Range, coarse detritic sediment deposits form. Between these two areas, in the S of the basin, medium to fine carbonate deposits form. At this time the proto-Duero Basin is connected to the proto-Ebro Basin. The total subsidence rate at 65.0–61.0 Ma is –0.006–+0.024 mm a^{-1} and the total subsidence is –24–+99 m [15].

In the proto-Almazán Basin there is some tectonic subsidence, and alluvial systems deposit detritic sediments [9]. Uplift of the S proto-Rioja Trough results in deposition of coastal/shallow marine sediments. The N proto-Rioja Trough is tilted through this process, resulting in deposition of marine sediments.

3.2. Eocene (55–34 Ma; Figure 4)

Alpine collision continues and thrusting starts from both the N (Pyrenees) and the S (Iberian Range) of the proto-Ebro Basin [11]. Flexural subsidence, however, continues at a slow pace. In the N of this basin alluvial fans and braidplains [17] deposit carbo-detritic-evaporitic sediments from the Pyrenees, and along its S and SW borders alluvial fans, braidplains and mudflats deposit coarse to fine-grained detritic sediments from the Iberian Range [16]. The proto-Ebro Basin remains connected to both the Mediterranean and the proto-Duero Basins. The total subsidence rate at 56.0–37.0 Ma is –0.002–+0.009 mm a^{-1} and the total subsidence in this time interval is –37–+191 m [18].

In the proto-Duero Basin, uplift continues to the W (Iberian Massif), the S (Central System) and starts to the E (Iberian Range and Demanda-Cameros Massif) of the proto-Duero Basin [9, 11]. Fine carbonate deposits form in the W, along the Iberian Massif. The proto-Duero Basin remains connected to the proto-Ebro Basin. The total subsidence rate at 61.0–36.0 Ma is –0.002–0.000 mm a^{-1} and the total subsidence in this time interval is –50–+99 m [15].

Thrusting of the Iberian Range starts creating the proto-Almazán Basin through flexural subsidence [9]. In this basin alluvial fans and alluvial systems deposit coarse to fine siliciclastics along the borders and carbonates in the centre [9]. The proto-Almazán Basin is only open to the proto-Duero Basin. Thrusting of the Demanda-Cameros Massif to the N initiates flexural subsidence in the S proto-Rioja Trough with marine sedimentation and tilting in the N proto-Rioja Trough with coastal/shallow marine sedimentation. In the E half of the proto-Rioja Trough, alluvial fans deposit coarse- to medium-grained detritics in the S-SW, marls in the centre, and potash salts in the NE with paleocurrents to the N-NE [14, 16]. The proto-Rioja Trough is open to both the proto-Ebro and the proto-Duero Basins.

3.3. Oligocene (34–24 Ma; Figure 4)

A major alpine compressional event occurs in the N Iberian plate, invoking the fastest rates of subsidence and the largest sedimentary sequences in both the Ebro and the Duero Basins. The Ebro Basin is closed to the Mediterranean through the compression from the N (Pyrenees), the SW (Iberian Range), and the SE (Catalan Coastal Ranges) and is reduced to a narrow area surrounded by orogens. In the N, alluvial fans and braidplains deposit coarse- to fine-grained detritics from the Pyrenees [17]. In the S and SE, alluvial fans, braidplains, and deltas deposit coarse- to fine-grained detritics from the Iberian Range [17] and the Catalan Coastal Ranges [10]. In the centre of the basin lies a lake where lacustrine muds, fine carbonates and evaporate deposits form [17]. The total subsidence rate at 36.8–23.6 Ma is +0.018–+0.214 mm a^{-1} and the total subsidence in this time interval is +217–+2 466 m [18].

The Duero Basin is closed to the E by the Iberian Range and the Demanda-Cameros Massif. Alluvial systems from all around the basin deposit coarse- to fine-grained carbo-detritic sediments throughout the basin, with patches of fine carbo-detritic sediments that locally contain evaporates. The total subsidence rate at 36.0–24.5 Ma is 0.000–+0.224 mm a^{-1} and the total subsidence in this time interval is –24–+1 884 m [15].

Thrusting of the Iberian Range continues to the NE, but at a lesser rate, enabling the alluvial systems to fill the Almazán Basin partially, leaving a smaller lake with carbonate deposition in the centre [9]. The Rioja Trough continues to subside due to thrusting to the S from the Pyrenees and to the N from the Demanda-Cameros Massif resulting in continental sedimentation. In the E half of the trough, alluvial fans and braidplains deposit coarse- to fine-grained detritics and limestones in the SW and gypsum in the centre and NE, with paleocurrents to the N-NE [14, 16]. The Demanda-Cameros Massif plunges W-NW into the Duero Basin as a large anticline with reversed faults. In the highest Oligocene evaporates dominate with clastic facies along the borders of the basin [14]. A smaller anticline bridges the gap to the Cantabrian Range, at the position of the present escarpment and drainage divide. This high supposedly disconnects the Rioja Trough from the Duero Basin.

3.4. Lower Miocene (24–16.4 Ma; Figure 4)

Another major alpine event occurs in the N Iberian plate, resulting in fast rates of subsidence and important sedimentary sequences in both the Ebro and the Duero Basins. The Valencia Trough starts to open [11], causing subsidence in the E Ebro Basin and rift-flank uplift in the Catalan Coastal Ranges due to isostatic compensation from crustal thinning [12]. Advancement of the Pyrenean external zone narrows the basin and creates a huge sediment source. Alluvial fans and braidplains deposit coarse- to medium-grained detritics along the entire N [17] and SW [16] borders of the Ebro Basin, with particularly large fans in the N. In the centre of the basin lies a lake where mud, evaporate, and sulphate deposits form [8, 16]. The total subsidence rate at 23.6–14.6 Ma is +0.014–+0.115 mm a^{-1} and the total subsidence in this time interval is +903–+2 719 m [18].

The Duero Basin subsides along a NE-SW axis in the NE mostly due to isostatic rebound from sedimentary loading. Alluvial fans and braidplains deposit coarse- to fine-grained detritics ("Rojas" Formation) from the N (Cantabrian Range), the E (Demanda-Cameros Massif), and the SE (Central System) towards the centre of the basin [1], and presumably from all around it [2]. Along the NE-SW orientated depocentre, carbonate and evaporate ("Dueñas" Formation) deposits form in a lake [1, 2] The total subsidence rate at 24.5–16.0 Ma is +0.005–+0.116 mm a^{-1} and the total subsidence in this time interval is +175–+2 229 m [15].

In the Almazán Basin alluvial systems continue to fill in the basin, and the carbonate lake in the centre continues to diminish [9]. The Rioja Trough subsides in the W, and the Oligocene high submerges, hence reconnecting the Rioja Trough to the Duero Basin. In the N of this passage mud deposits form, and in the centre and in the S mud and evaporate [2]. The E half of the Rioja Trough remains higher, and alluvial systems continue to deposit coarse- (SW) to medium-grained (NE) detritics [14, 16]. This indicates that the W Rioja Lake does not drain into the Ebro Lake, and, hence, the centre of the Bureba forms the disconnection between the Duero and the Ebro basins. Paleocurrents are presumably E in the E part and W in the W part of the trough.

3.5. Middle Miocene (16.4–11.2 Ma; Figure 4)

In this epoch tectonic compression continues, as well as tectonic extension in the Valencia Trough, whence crustal thinning results in subsidence in the E Ebro Basin and uplift of the Catalan Coastal Ranges [12]. Alluvial systems deposit medium- to fine-grained detritics from all along the Iberian Range [16] and the Pyrenees [8]. Deltaic systems deposit muds in the Ebro Lake, which is strongly increased in area with respect to Lower Miocene [8, 16]. The total subsidence rate at 14.6–9.0 Ma is +0.010–+0.011 mm a^{-1} and the total subsidence in this time interval is +1,506–+2 780 m [18].

The Duero Basin also subsides due to isostatic rebound from sedimentary loading and in places experiences some uplift [15]. Alluvial systems deposit coarse- to fine-grained detritics (poligenic conglomeratic facies) from the Cantabrian Range, the Central System and the Demanda-Cameros Massif [1], and presumably from the Iberian Massif as well [2]. Deltaic systems deposit medium- to fine-grained detritics (“Tierra de Campos” Formation) that intercalate with calcretes and paleosoils in the Duero Lake, which is strongly reduced in size with respect to the Lower Miocene [1, 2]. The total subsidence rate at 16.0–10.4 Ma is –0.002–+0.013 mm a^{-1} and the total subsidence in this time interval is +319–+2 219 m [15].

Alluvial systems fill the Almazán Basin from the sides with medium- to fine-grained detritics and the lake in the centre increases [9]. The Rioja Trough remains connected to the Duero Basin. In the NE of this passage carbonate deposits form and in the SW muds [2]. The E half of the Rioja Trough remains higher and alluvial systems still deposit coarse- (SW) to medium-grained (NE) detritics [14, 16]. The Ebro and the Duero Basins continue to be disconnected at the centre of the Rioja Trough. Paleocurrents are presumably E in the E part and W in the W part of the trough.

3.6. Early Upper Miocene (11.2–9.6 Ma; Figure 4)

Extension in the Valencia Trough continues [11] and, through crustal thinning, invokes subsidence of the E Ebro Basin and uplift of the Catalan Coastal Ranges [12]. Alluvial systems deposit medium- to fine-grained detritics from the Iberian Range [16] and the Pyrenees [8] and lacustrine mud deposits form in a lake that is strongly reduced in size with respect to the Middle Miocene [8].

The Duero experiences slow subsidence and, in places, uplift. First, fine carbonate and evaporate (“Cuestas” Formation) deposits form in the lake, and then, fine carbonates with levels of mud (“Lower Páramo” Formation or “Páramo 1”). The Duero Lake is now strongly increased in size with respect to the Middle Miocene [1, 2]. The total subsidence rate at 10.4–9.4 Ma is +0.001–+0.041 mm a^{-1} and the total subsidence in this time interval is +360–+2 220 m [15].

Alluvial systems fill the Almazán Basin from the borders with medium- to fine-grained detritics, and the lake in the centre remains as large as in the Middle Miocene [9]. Uplift of the Mesozoic anticline W of the Rioja Trough disconnects the trough from the Duero Basin. In the E half of the trough, alluvial fans deposit coarse- to medium-grained detritics [14, 16]. In the W half of the trough, there is no deposition [2]. The entire Rioja Trough seems to be connected to the Ebro Basin and hence transport is presumably W-E.

3.7. Middle Upper Miocene (9.6–8.3 Ma; Figure 4)

Extension in the Valencia trough ceases. The Ebro Basin possibly opens to the Mediterranean by a passage in the Catalan Coastal Ranges [11], which empties the Ebro Lake and sets off erosion in the basin. The rapid and dramatic drop of the base level causes spectacular erosion of the entire basin by means of the Ebro river network [11], leaving essentially no deposition in the Ebro Basin. The question is: to which point has the Ebro River knick point advanced? We think it’s to the E border of the Rioja Trough.

Subsidence in the Duero Basin has practically come to a stop. Huge alluvial fans deposit coarse- to fine-grained detritics (siliceous conglomeratic facies) from the N (Cantabrian Range), the S (Central System), and the E (Demanda-Cameros Massif). Deltas deposit fine detritics and carbonates (Detrital-carbonate “Upper Páramo” Formation or ”Páramo 2”) in a small lake in the NE of the basin. The total subsidence rate at 9.4–4.8 Ma is 0.000 mm a^{-1} and the total subsidence in this time interval is 1 800 m [15].

An alluvial fan deposits coarse- to medium-grained detritics in the whole Almazán Basin. Alluvial fans deposit coarse-grained detritics in the S (and the whole) Rioja Trough, which suggests that the knick point of the Ebro River has not reached the Rioja Trough yet. Supposedly, all transport in the Rioja Trough is W-E.

3.8. Late Upper Miocene (8.3–5 Ma; Figure 4)

In this epoch the Ebro River network continues to erode the basin, which supposedly invokes uplift due to isostatic compensation from unloading. At one locality, in the SW of the basin, an alluvial fan deposits coarse- to fine-grained colluvial detritics, the so-called “Raña” Formation. The Ebro Basin is definitely open to the Mediterranean. The paleo-Ebro river network occupies the same position as at present. The valleys are deeply incised, densely spaced, and have sharp crested hilltops and wide, concave valleys. The question is, again, to which point has the Ebro River knick point advanced? We think to the centre of the Rioja Trough.

In early Late Upper Miocene the Duero Basin must have experienced differential uplift inverting the sense of flow to the W-SW [13]. At the same time the Duero Basin possibly has opened to the Atlantic through a passage in the Iberian Massif. The drop in base level is small, so the erosion in the basin by the Duero River is minor. Alluvial fans deposit coarse- to fine-grained colluvial detritics ("Raña" Formation) on Miocene paleofans along the N, E, SE, SW, and NW basin margins. The paleo-Duero river network occupies the same position as at present. The valleys are slightly incised, widely spaced, and have wide convex hilltops and sharp, narrow courses.

An alluvial fan deposits coarse- to fine-grained colluvial detritics ("Raña" Formation) in the N Almazán Basin. There is no sedimentation in the Rioja Trough. Supposedly, the Ebro river network has eroded most of the Tertiary sediments, and the Ebro River knick-point has started its retreat through the Rioja Trough. Transport through the Rioja Trough is probably W-E.

3.9. Pliocene (5–2 Ma; Figure 8)

Erosion continues virtually everywhere in both basins and in the Rioja Trough. The Duero Basin is definitely open to the Atlantic and the incision of valleys in both basins reaches its maximum. Although compression continues at a very slow pace, it has no significant effect on the geometry of the basins. The knick point of the Ebro River reaches its actual location, where it is retained by the resistant rocks of the Mesozoic anticline. This, and the isostatic uplift due to the erosion in the Duero and the Ebro, create the geomorphic expression of the escarpment and the wind gaps as they are at present. Both the Duero and the Ebro River reach their equilibrium profiles as they are at the moment, with their respective remnant escarpments as witnesses of their distinct erosional phases.

3.10. Quaternary (2–0 Ma; Figure 8)

The dramatic erosion in both basins is brought down to a low rate. The paleo-Ebro River and its primary tributaries partially fill the Pliocene valleys with alluvia. The paleo-Segre and -Cinca rivers and their tributaries deposit alluvia both in their valleys, as well as on their corresponding paleo-alluvial fans (NE, Ebro Basin). The paleo-Ebro River network occupies the same position as at present.

The paleo-Duero, -Pisuerga, and -Arlanzón rivers completely fill the Pliocene valleys with alluvia. The paleo-Esla, -Carrión, -Adaja, and -Cega rivers (N, Duero Basin) and their tributaries deposit alluvia both in their valleys, as well as on their corresponding paleo-alluvial fans. The paleo-Duero River network occupies the same position as at present.

The paleo-Duero River and its tributaries fill the valleys in the Almazán Basin with alluvia. The paleo-Hormino, -Oca, -Oroncillo, and -Urbión rivers continue to erode most of the W Rioja Trough, only depositing alluvia in the N (W, Bureba region), while the paleo-Oja, -Najerilla, and -Iregua rivers (E, Bureba region) deposit alluvia in their respective Pliocene valleys. In the Rioja Trough, valleys are only slightly incised. The smooth but prominent paleorelief seems to be formed by Miocene lithological entities (facies). The base level of erosion in the Rioja Trough seems to be controlled by Mesozoic structures, which essentially form a flat-based syncline with orientation E-W.

3.11. Present (0 Ma; Figure 8)

Both the Ebro and the Duero basins seem to experience neither important erosion nor sedimentation. The Ebro and the Duero river networks have changed neither position nor pattern and their drainage divide has been stationary since the Quaternary. Both the passage of the Ebro River through the Catalan Coastal Ranges and the passage of the Duero River through the Iberian Massif have remained stationary, suggesting that both of their river profiles have reached states of equilibria.

The Bureba escarpment, coinciding with both the water divide and the Mesozoic anticline, has not moved since the Quaternary, with the exception of the N Ubierna River that has been captured by the Homino River. However, deep wind gaps dipping to the SW and cutting through the Mesozoic anticline appear to have been part of a fluvial system that drained towards the Duero Basin, similar to the present wind gap of the Ubierna River. This system supposedly covered the entire Bureba region and possibly the W half of the Rioja Trough.

4. PART II: Geomorphology (Pliocene–recent)

The results in this section were obtained in the following way: a geomorphic analysis of the style and of the extent of erosion was made by compiling digital elevation models and lithostratic maps from ENRESA, and with data from unpublished work by Pineda-Velasco on the Bureba area, together with the results from a modelling study [3]. The river profile, drainage pattern and sediment distribution in the Quaternary were then used to reconstruct the evolution of the hydrographic basins of the Duero and the Ebro, the position of their water divide and their particular styles of erosion. The above results were used to reconstruct subsequent capture of Ebro on Duero tributaries and the escarpment retreat through the Rioja.

Subordinate questions of this part are the following: (1) How did erosion advance through the Rioja Trough? (2) How stable is the present escarpment? (3) Why is the escarpment a high? The results in this section are based on a variety of data, i.e. previous interpretations of geomorphology, hydrography, and climate, on the one hand, and digital data of geomorphology, cross-sections, drainage patterns, and numerical modelling, on the other. Cross-sections through the Rioja Trough (Figure 6) show the Mesozoic basement to outcrop at the westernmost limit of the trough, form a plateau under most of the trough, and to descend under the Ebro Basin.

The present river profiles of the Duero and the Ebro Rivers (Figure 7) show that the Ebro grades to a lower knick-point than the Duero River. The profile over the Bureba Escarpment reveals some more interesting features. (1) The escarpment sits significantly above the main river profiles; (2) The eastern part of the escarpment is significantly steeper than the western part; (3) The eastern profile of the escarpment contains a step at the eastern limit of the Rioja Trough.

These features seem to indicate, that: (1) the Bureba area is not in hydrodynamic equilibrium and its retreat might be hampered by existing Mesozoic structures; and (2) erosion occurred in a number of discrete phases, presumably preceded by tectonic activity.

The erosional evolution of Duero and Ebro Basins starts with the emptying of the basins to their respective repositories. The Duero River breaks through the Iberian Massif to the Atlantic between 9.5 and 8.5 Ma [11, 19], whereas the Ebro River breaks through the Catalan Coastal Ranges to the Mediterranean between 9.5 and 5.5 Ma [19]. Both river profiles exhibit a knick-point at their respective ranges.

Erosion through the Ebro Basin advances in a more dramatic fashion than through the Duero, both vertically and laterally, which has been food for debate. Generally the moment of opening has been ascribed as the major cause, principally, since the youngest sediments in the Duero Basin were believed to be much younger than in the Ebro Basin. That is without counting the Pliocene and the Quaternary. Now that recent age dates have shown the youngest Miocene sediments to be of equal age in both basins, i.e. 9.5 Ma [19], this explanation might be insufficient.

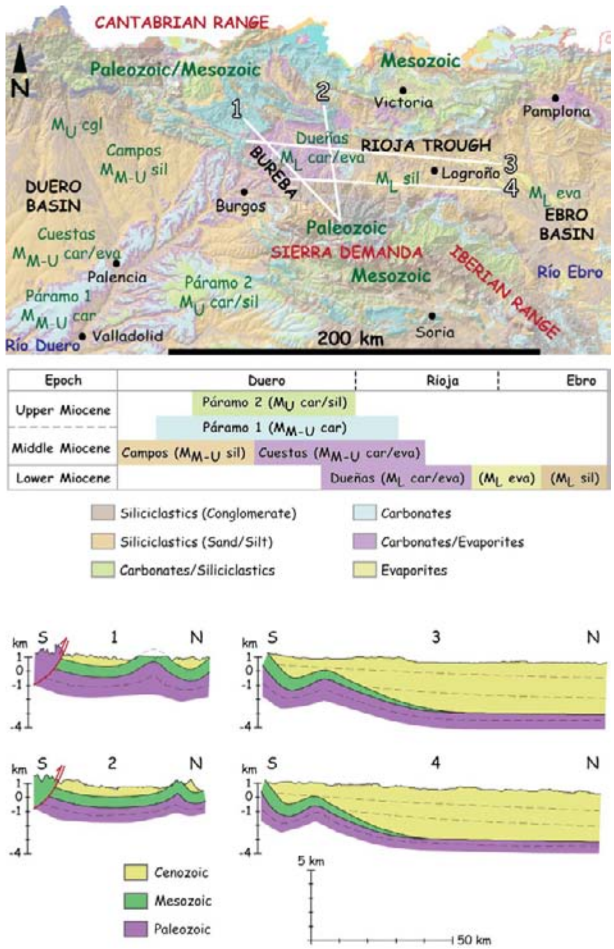

Figure 6. Geological map of the Rioja Trough and surroundings. M_L = Lower Miocene, M_M = Middle Miocene, M_U = Upper Miocene; cgl = conglomerates, sil = siliciclastics, car = carbonates, eva = evaporates; Campos, Cuestas and Páramo 1/2 refer to Formation names, Paleozoic and Mesozoic units non-discriminated. Cross-sections N-S show the Mesozoic syncline deepening to the E and thrusting in Mesozoic/Paleozoic. Cross-sections W-E show a shallow Bureba syncline and an anticline before deepening into E-Rioja (lithostratic map and units from ENRESA, profiles interpreted from a combination of cross-sections from [6], Muñoz-Jiménez and [14] and IGME).

We believe that the solution is to be found in the geomorphic expressions of both basins: (1) The Ebro River profile grades to a lower knick-point than the Duero River profile, yielding higher vertical channel incision. (2) The Duero Basin predominant-limestones yield few but narrow river valleys, whereas the Ebro Basin predominant-sandstones and evaporates yield to numerous wide river valleys. The lithologies themselves might contribute to the amount and style of erosion.

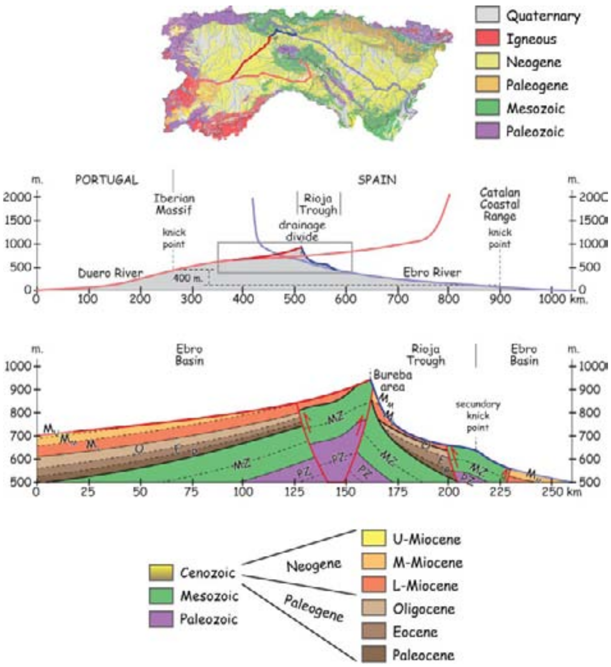

Figure 7. River profiles of the Duero and Ebro Rivers (faded red and blue). Notice high main knick-point of the Duero River, midway in the river's course, and the low main knick-point of the Ebro River, close to its mouth. The profiles across the escarpment (bright red and blue) show a gentle slope in the Duero and a steep slope in the Ebro tributary. Notice also a secondary escarpment in the Ebro. The detail shows a tentative geological cross-section and the profile across the escarpment.

A critical point of correlation between the two basins, in terms of both stratigraphy as well as tectonics, has always been their connection, the Rioja Trough. At present the water divide between the Duero and the Ebro hydrographic basins sits at the westernmost limit of the trough, whereas stratigraphy shows it in earlier times to have sat in its centre, and to have migrated to the west during the Upper Miocene to the Pliocene.

In the Latest Upper Miocene (8.3–5 Ma) the Ebro River knick-point starts its retreat through the Rioja Trough. In the Pliocene (5–2 Ma) the Ebro River knick-point reaches its actual location, where it is retained by the resistant rocks of the Mesozoic anticline that sits right at and under the Bureba escarpment. In the Quaternary (2–0 Ma) the Rioja Trough valleys are only slightly incised. The smooth but prominent paleorelief seems to be formed by Miocene lithologic entities. The base level of erosion in the Rioja Trough seems to be controlled by Mesozoic structures, which essentially form a flat-based syncline with a N-S trend.

In the Quaternary, piedmonts and fluvial terraces fill the incised valleys. Since the Quaternary, the Bureba escarpment hasn't moved significantly, as witnessed by the similarity of Quaternary valley fills and the present river patterns (Figure 8). The only exception to this is the upper reach of the Ubierna River that is captured by the Homino River.

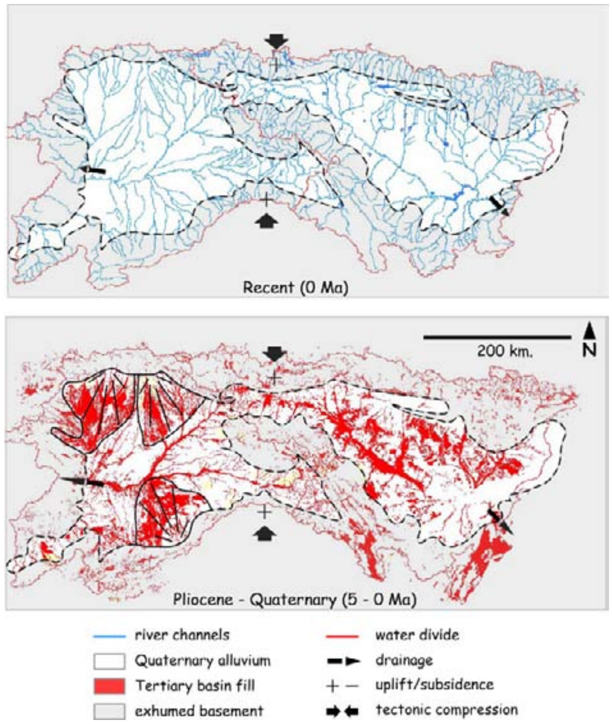

Figure 8. Geomorphic map from Pliocene to Recent (5–0 Ma). Quaternary) There is sedimentation only in the valleys and on the alluvial fans. Recent): The river channels of the Duero and the Ebro coincide with the Quaternary alluvium, indicating that the drainage pattern from the Quaternary to the Recent is virtually stable.

The river profiles of the Duero and Ebro Rivers reveal distinct episodes of erosion (Figure 9). Erosion in the Ebro Basin takes place in several episodes. In a first stage, during the Upper Miocene, erosion reaches the E limit of the Rioja Trough. In Pliocene, continued elevation of the Rioja Trough through compression and possibly isostatic rebound [3] cause increased incision in NW Duero and erosive retreat in 4 steps, each leaving behind a relict escarpment.

These steps are tentatively indicated by the position of the water divide in Figure 9. The last step (nr. 4), is the event of a single capture by the Homino River of the Ubierna River (Figure 10). The anterior step (nr. 3), represents erosion of the western Bureba area, capture of a larger area, and capture of numerous rivers that created important wind gaps (Figure 10) that were already documented by Martín [13]. The second step (nr. 2) represents

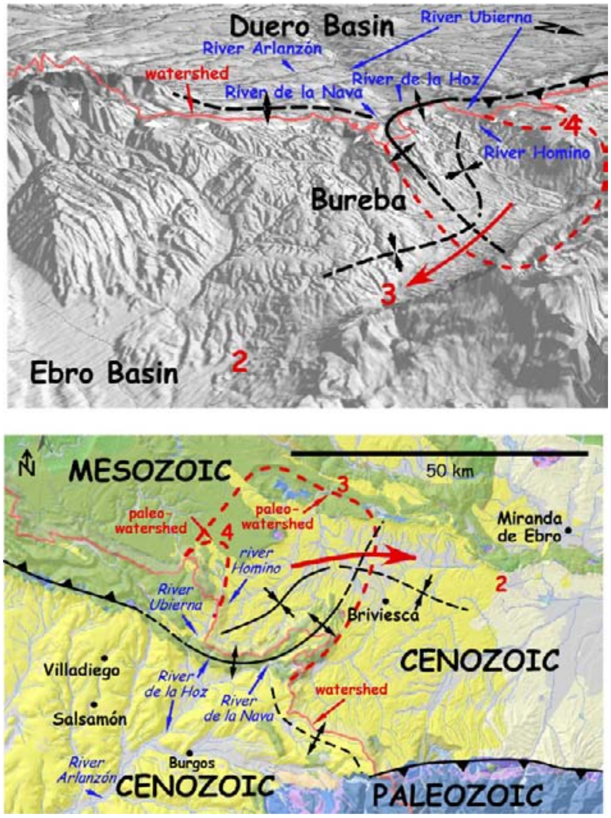

Figure 9. The Bureba area. Upper) Tri-dimensional view from the NE on the Bureba escarpment. Red = water divide, sitting at a Mesozoic anticline. Note the flat Bureba and accidented E-Rioja Trough. Notice a SW-NE anticline in the Bureba changing to a NW-SE trend in the Rioja. White lines and numbers indicate paleo-water divide locations. Lower) Map of the Bureba escarpment. Red = water divide, dashed red = paleo-water divides, again, the anticline at the water divide and the anticline orientation changing from Bureba to Rioja. Numbers indicate consecutive erosive steps from 4 youngest to 1 eldest. 1 falls outside the map and relates to the emptying of the Ebro Basin itself. The red arrow indicates erosive emptying of the Bureba.

erosion of the eastern Bureba area. The first step (nr. 1) represents erosion of the central and eastern part of the Rioja Trough.

Quite contrarily to that of the Ebro River, all of the Duero Basin erosion appears to have occurred during one erosional episode. The only second episode would be the one that lifted the Bureba escarpment and created the canyons that, at present, form the wind gaps at the water divide between the Duero and the Ebro hydrographic basins. This event would more or less coincide and/or precede the advance of the Ebro River's knick-point through the Rioja Trough westward to its present position.

The system of frontal and oblique anticlines, that constitutes the water divide between the Ebro and Duero fluvial systems, separates two basins with distinct geomorphic characteristics. The Ebro presents a low elevation with a relatively important local relief, whilst the Duero has a high elevation with minor local relief.

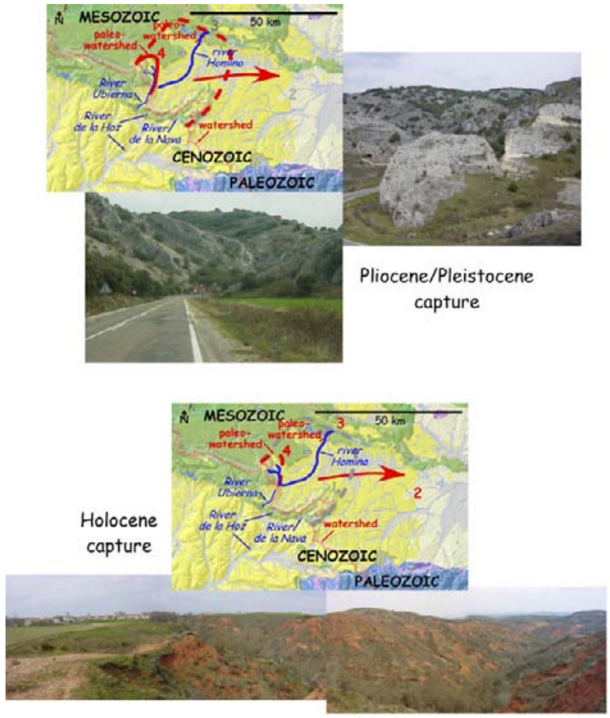

Figure 10. Photographs of captures in the Bureba area. Upper) Wind gaps in the Río de la Hoz. The right photograph is taken from the SW, the left from the NE. The photographs show the important incision of an ancient river that was flowing towards the SW and is now only a minuscule stream. The inset shows the location of the wind gaps at the water divide, i.e. the crossing of the River de la Hoz with the escarpment, and the thick red line the watershed after capture 4. The thin red line indicates the present watershed; the thick red dotted line indicates the watershed before the capture 3. The area between line 3 and 4 indicates the area that was captured by the Ebro from the Duero. Lower) Capture by Río Homino of Río Ubierna taken towards the W. The inset shows the location of the capture, i.e. where River Homino and Ubierna join and the thin red line the watershed after capture; the thick red dotted line indicates the watershed before capture 4. The area between line 4 and the present watershed is the area that the Ebro captured from the Duero. The left part of the picture is the smooth and gently sloped Ubierna drainage area, and the right part of the picture is the heavily incised and steep Homino drainage area.

In the NE part of the Duero hydrographic basin, the heads of current tributaries of the Ubierna River (a tributary of the Arlanzón) situate at the N limit of the Mesozoic limestones of the aforementioned anticlinal system. They are characterised by well-developed fluvial wind gaps that prevail, suspended at their arrival to the water divide (the rivers "de la Hoz", "Ríosera", and "de la Nava"). The gradient of these wind gaps to the Duero, their distribution along the folds parallel to the water divide, their significant incision, and their suspended character indicate that they were part of an ancient fluvial system that drained to the Duero Basin. This fluvial system was captured by tributaries of the Ebro in a similar fashion to the Homino River that captured the higher part of the Ubierna River in recent geologic history.

The last formations of the Duero Basin are a series of carbonates called Páramo 1 and 2. They represent the exhaustion of sediment and filling in of the lakes. Páramo 1 covers the area of the lake at its largest, whereas Páramo 2, at present, covers only the NE part of it. It is uncertain, whether this coverage represents its areal distribution at deposition or is only the erosional remnant of it. What is most indicative, however, is that the paralic Páramo 2 carbonates are inclined to the SW and increasingly so towards the Bureba. Since these carbonate deposits formed horizontally, their inclination must be tectonic of nature. A modelling study confirms that erosion in the Rioja Trough is capable of supplying this uplift through isostatic rebound [3].

These erosional surfaces are also indicative of the amount of erosion that occurred in the Duero Basin (Figure 11). Although the vertical incision is much less in the Duero than it is in the Ebro, the lateral extent of erosion is significant. The Páramo 2 sits at the few hill tops that are the remnants of ancient lake deposits and all around them the former alluvial braidplains have been eroded.

Figure 11. Photographs of the erosional surfaces of the NE Duero Basin and the remnants of stratigraphy up to the youngest Páramo 1. The upper photograph is taken from the NW, the lower from the SW. The photographs show the extension of the preserved carbonate surface. They also show that all the siliciclastics that were present in the past have been eroded to the level of the road. The inset shows the location of the surface.

5. Results / Interpretation

The combination of published data and our own field and modelling data facilitates a number of new interpretations. The youngest lacustrine sediments in the Ebro basin are 9.5 Ma [19], i.e. younger than considered before, 12.5 Ma [11]. This reduces the earliest moment of erosion significantly. On the other hand, the youngest lacustrine sediments in the Duero Basin appear to be also 9.5 Ma [19], i.e. older than considered before [2]. This contrasts with the interpretations that sedimentation in the Ebro Basin stopped long before it did in the Duero Basin and it means that the opening of the Ebro and Duero Basins might not have been so distant in time. It is assumed that the youngest lacustrine sediments mark the oldest moment of opening.

The sedimentary strata of Paleogene and Lower Miocene are progressively folded in both basins, indicating tectonic compression during all of this time. The Duero and the Ebro exhibit a distinct sedimentary evolution from the Oligocene on, suggesting that the Sierra Demanda must have been a topographic high as early as Oligocene times and remained so ever since. Most of tectonic shortening occurs from the Middle Miocene by thin-skinned thrusting and the Rioja Trough is therefore likely to be formed as such in Middle Miocene at soonest.

The youngest lacustrine sediments in the Duero Basin show progressive incision and progressive tectonic tilt towards the Bureba escarpment. We argue this to be related to isostatic rebound from erosion in Rioja Trough and surrounding mountain ranges. A modelling study corroborates this hypothesis [3].

The water divide of the hydrographic Duero sits in the Rioja Trough from its creation. In the Latest Miocene times, the escarpment reaches the Rioja Trough and subsequently retreats from its easternmost limit to its westernmost limit, where it sits until today. This appears to happen in three consecutive steps, the first of which erodes most of the Rioja Trough, the second the Bureba area, and the third, only a minor portion. Each of these erosional phases leaves behind a relict escarpment.

Although all the Rioja Trough now drains towards and belongs to the Ebro hydrographic Basin, at least the western half of this Trough must have drained towards and belonged to the Duero hydrographic Basin in Miocene times. This is witnessed by deep wind gaps at the present escarpment and a water divide that indicate erosion by fluvial channels that drained toward the SW.

The similarity of the Quaternary valley fills and of the present-day river pattern appears to witness no cut-offs since Quaternary times. This would indicate that the last cut-off, by the Homino River of the Ubierna River, must have been geologically recent, and that the Ebro tributary captured only a miniature portion of the Duero tributary. All signs seem to indicate stasis of this area, i.e. no more tectonic subsidence, no more escarpment retreat. The Bureba escarpment seems to be indeed virtually stabilized by both geomorphic and lithologic constraints.

6. Discussion / Conclusions

The Rioja Trough becomes a tecto-sedimentary entity in the Oligocene, when the Sierra Demanda is formed, dividing the Pyrenean foreland basin in two, and hence separating it into the Duero and Ebro Basins. Both basins are at the time endoreic. The hydrographic disconnection between the Duero and the Ebro is a fact in the Earliest Miocene. The water divide between the Duero and the Ebro migrates from the centre to the W border of the Rioja Trough.

The evolution of the area can be divided into ten tecto-sedimentary units, which in turn can be grouped into six epochs. The Bureba evolution runs more or less parallel to these phases: (I) 65-34 Ma, creation of surrounding orogens and exoreic foreland basin; (II) 34-11.2 Ma, creation of Sierra Demanda and endoreic Duero and Ebro Basins, and Rioja Trough and Almazán Basin; (III) 11.2-8.3 Ma, subsidence of endoreic basins; (IV), 8.3-5 Ma, erosion of basins; (V), 5-2 Ma, infill of valleys; (VI) 0 Ma, stasis.

The Ebro Basin becomes exoreic between 9.5–8.5 Ma, whereas the Duero Basin becomes exoreic between 9.5–5.5 Ma. Erosion of the Ebro creates wide, concave valleys and sharp hill tops. Erosion of the Duero Basin creates narrow, sharp valleys and convex hill tops. Erosion of the Ebro is dramatic, through a high base level drop. Erosion of the Duero is modest, through a low base level drop.

The geomorphic expression of the Rioja Trough is the result of the escarpment retreating through it. Retreat has stopped at the E margin of the Trough in Upper Miocene times. At this time, the W Rioja Trough drained to the Duero Basin. In the Latest Miocene and Pliocene times, the escarpment retreated through most of the Rioja Trough virtually to its present position. The last, and miniature, cut-off by Ebro tributaries has happened only recently. The Bureba escarpment seems indeed to have come to a stop.

Acknowledgements

We are grateful to Gemma Sánchez for her work on the GIS data of the Duero and Ebro basins. We acknowledge the cooperation of the Enresa for supplying us the GIS data of both basins. We are grateful to Josep-Lluís Peña for his efforts in the field, to Jaume Vergès for the opportunity to do this study. Last but not least we are indebted to Juan Plaza for coordinating this project. ENRESA supplied the large-scale cross-sections, the digital elevation models and the digital geological maps. IGME supplied the small-scale cross-sections of the Rioja area. Daniel Mikeš was supported by the ENRESA. Gratitude goes to Antonio Pineda Velasco for sharing his knowledge and pre-reviewing the manuscript.

References

[1] Mediavilla R., Dabrio C.J., Martín-Serrano A., Santisteban J.I., Lacustrine Neogene Systems of the Duero Basin: Evolution and Controls, In: Friend P.F., Dabrio C.J. (Eds.), Tertiary Basins of Spain the Stratigraphic Record of Crustal Kinematics: World and Regional Geology. Cambridge University Press, Cambridge, 1996, 228-236

[2] Pineda Velasco A., El enlace y la paleogeografía neógena entre las cuencas del Duero y del Ebro en la Bureba (Burgos), Boletin Geológico y Minero de España, 1996, 107, 14-28

[3] Mikeš D., Forward modelling of the Bureba escarpment (Rioja Trough, N-Spain), Cent. Eur. J. Geosc., 2009, 1, 463-471

[4] Sanz De Galdeano C.M., Tertiary Tectonic Framework of the Iberian Peninsula, In: Friend P.F., Dabrio C.J. (Eds.), Tertiary Basins of Spain of Stratigraphic of Crustal Kinematics: World and Regional Geology. Cambridge University Press, Cambridge, 1996, 9-14

[5] Evans G., Arche A., The flux of siliciclastic sediment from the Iberian peninsula with particular reference to the Ebro, Geol. Soc. Spec. Publ., 134, 2002, 199-208

[6] Jurado M.J., Riba O., The Rioja Area (Westernmost Ebro Basin): a Ramp Valley with Neighbouring Piggybacks, In: Friend P.F., Dabrio C.J. (Eds.), Tertiary Basins of Spain the Stratigraphic Record of Crustal Kinematics: World and Regional Geology. Cambridge University Press, Cambridge, 1996, 173-179

[7] Lanaja J.M., Contribución de la exploración petrolífera al conocimiento de la geología de España, Instituto geológico y minero de España, Madrid, 1987

[8] Arenas C., Pardo G., Latest Oligocene-Late Miocene lacustrine systems of the north-central part of the Ebro Basin (Spain): sedimentary facies model and palaeogeographic synthesis, Palaeogeogr., Palaeocl., 1999, 151, 127-148

[9] Bond J., Tectono-Sedimentary Evolution of the Almazán Basin, NE Spain., In: Friend P.F., Dabrio

C.J. (Ed), Tertiary Basins of Spain the Stratigraphic Record of Crustal Kinematics: World and Regional Geology. Cambridge University Press, Cambridge, 1996, 203-213

[10] Cabrera L., Cabrera M., Gorchs R., De Las Heras F.X., Lacustrine basin dynamics and organosulphur compound origin in a carbonate-rich lacustrine system (Late Oligocene Mequinenza Formation, SE Ebro Basin, NE Spain), Sediment. Geol., 2002, 148, 289-317

[11] García-Castellanos D., Vergés J., Gaspar-Escribano J., Cloetingh S., Interplay between tectonics, climate and fluvial transport during the Cenozoic evolution of the Ebro Basin (NE Iberia): from endorheic infill to exorheic erosion, J. Geophys. Res., 2003, 108 (B7), doi: 10.1029/2002JB002073

[12] Gaspar-Escribano J., Van Wees J.D., Ter Voorde M., Cloetingh S., Roca E., Cabrera L., Muñoz J.A., Ziegler P.A., et al., Three-dimensional flexural modelling of the ebro Basin (NE Iberia), Geophys. J. Int., 2001, 145, 349-368

[13] Martín-Serrano A., La definición y el encajamiento de la red fluvial actual sobre el Macizo Hespérico en el marco de su geodinámica alpina, Revista de la Sociedad Geológica de España, 1991, 4, 337-351

[14] Muñoz-Jiménez A., Casas-Sainz A.M., The Rioja Trough (N Spain): tectonosedimentary evolution of a symmetric foreland basin, Basin Res., 1997, 9, 65-85

[15] Santaeulària T., López-Blanco M., Vergés J., Muñoz J.A., Geohistoria de la Cuenca Sedimentaria del Duero: Enterramiento y Exhumación, Enresa, 1996

[16] Villena J., Pardo G., Pérez A., Muñoz A., González A., The Tertiary of the Iberian Margin of the Ebro Basin: Paleogeography and Tectonic Control, In: Friend P.F., Dabrio C.J. (Eds.), Tertiary Basins of Spain the Stratigraphic Record of Crustal Kinematics: World and Regional Geology. Cambridge University Press, Cambridge, 1996, 83-88

[17] Friend P.F., Lloyd M.J., Mcelroy R., Turner J., Van Gelder A., Vincent S.J., Evolution of the Central Part of the Northern Ebro Basin Margin, as indicated by its Tertiary Fluvial Sedimentary Infill. In: Friend P.F., Dabrio C.J. (Eds.), Tertiary Basins of Spain the Stratigraphic Record of Crustal Kinematics: World and Regional Geology. Cambridge University Press, Cambridge, 1996, 166-172

[18] Santaeulària T., López-Blanco M., Vergés J., Muñoz J.A., Geohistoria de la Cuenca Sedimentaria del Ebro: Enterramiento y Exhumación, Enresa, 1997

[19] Krijgsman W., Garces M., Langereis C.G., Daams R., Van Dam J., Van Der Meulen A.J., Agusti J., Cabrera L., A new chronology for the middle to late Miocene continental record in Spain, Earth Planet. Sc. Lett., 1996, 142, 367-380