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Drainage reorganization and divide migration induced by the excavation of the Ebro basin (NE Spain)

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Abstract

Intracontinental endorheic basins are key elements of source-to-sink systems as they preserve sediments eroded from surrounding catchments. Drainage reorganization in such a basin has strong implications on the sediment routing system and on the landscape evolution at a cratonic scale.

The Ebro and Duero basins in the north Iberian plate represent two foreland basins, which were filled in relation with the growing of surrounding compressional orogens as the Pyrenees and the Cantabrian mountains to the north, the Iberian and Central Ranges to the south, and the Catalan Coastal Range to the east. They were once connected as endorheic basins in the Early Oligocene. By the end of the Miocene, they were disconnected and started to flow into the Mediterranean Sea and the Atlantic Ocean, respectively, in a post-orogenic context.
Although these two hydrographic basins recorded similar histories, they are characterized by very different morphologic features. The Ebro basin is highly excavated, whereas the Duero basin is well preserved and may be considered as almost still endorheic.

These two bordering basins then show contrasting preservation states of their endorheic stages and represent an ideal natural laboratory to study what factors (internal / external) control drainage divide mobility, and drainage network and landscape evolution in post-orogenic basins.
To that aim, we use field and map observations and we apply the Chi-analysis of river profiles across the divide along the boundary between the Ebro and Duero drainage basins in the Northern Iberian Peninsula to evaluate the migration of their divide.

We show here that contrasting excavation of the Ebro and Duero basins drives a reorganization of their drainage network through a series of captures and resulted in the southwestward migration of their main drainage divide. Fluvial captures have strong impact on drainage areas, fluxes, and so on incision capacity, especially for the captured basin.
Thus, we conclude that drainage reorganization, and capture of the Duero rivers by the Ebro ones, independently from tectonics and climate, enable endorheism in the Duero basin due to drainage area loss.

1. Introduction

Landscapes subjected to contrasted erosion rates between adjacent drainage basins shows a migration of their drainage divide toward the area of lower erosion rates (Bonnet, 2009). This is the case for example in mountain ranges characterized by gradients in precipitation rates due to orography, once landscapes are in a transient state and are not adjusted to precipitation differences (Bonnet, 2009). It can also occur when drainage reorganized in response to capture (Yanites et al., 2013; Willett et al., 2014). River capture actually drives a discrete drop in the location of drainage divide (Prince et al. 2011) but also drives a wave of erosion in the capture reach (Yanites et al., 2013) that may also impact divide position. Historically, migration of divides has been inferred for instance by changes in the provenance of sediments stored in sedimentary basins (*e.g.* Kuhlemann et al., 2001). It is however a process that is generally very difficult to document in erosional landscapes. Recent developments have been performed to infer divide migration from landscape analysis (Bonnet, 2009; Castelltort et al., 2012; Willett et al., 2014; Whipple et al., 2017). Among them the recently-developed Chi-method for analyzing longitudinal profiles of rivers (Perron and Royden, 2013) is based on the recognition of disequilibrium along river profiles, disequilibrium being defined by the departure from an ideal equilibrium shape. The application of this method to some natural landscapes, also verified by similar analyses performed on numerically-simulated ones, has allowed to demonstrate contrasts in the equilibrium state of rivers across divide and then to infer their migration (Willett et al., 2014). The applicability of this method is however limited to settings where the response time of rivers is larger compared to the rate of divide migration, so they can actually show disequilibrium in their longitudinal profiles (Whipple et al., 2017).

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In this study, we use field observations and we apply the Chi-analysis of river profiles across divide along the boundary between the Ebro and Duero drainage basins in the Northern Iberian Peninsula to evaluate the migration of their divide. These two drainage basins show geological and geomorphological evidences indicating that they record very contrasted erosional histories during the Neogene. They went through a long endorheic stage since the Early Oligocene before being opened toward the Atlantic Ocean (Duero) or the Mediterranean Sea (Ebro) during the Late Miocene, in a post-orogenic context. The Ebro basin's opening led to important unfilling and excavation (Garcia-Castellanos et al., 2003), whereas opening of the Duero basin did not drive excavation of its upstream part, that can then be considered as almost still endorheic (Antón et al., 2012). The Duero River shows a pronounced knickpoint (knickzone) in the downstream end of its longitudinal profile that limits an upstream domain of high mean elevation (~800 m) where the sedimentary filling of its endorheic stage is relatively well preserved. These two bordering basins are then characterized by contrasting preservation states of their endorheic stages and represent an ideal natural laboratory to study what factors control drainage divide mobility, and drainage network and landscape evolution in post-orogenic basins.

We show here that contrasting excavation between the Ebro and Duero basins drives a reorganization of their drainage network through a series of captures and resulted in the southwestward migration of their main drainage divide. Fluvial captures have strong impact on drainage areas, fluxes, and so on incision capacity, especially for the captured basin. Thus, we conclude that drainage reorganization, and capture of the Duero rivers by the Ebro ones, independently from tectonics and climate, enable endorheism in the Duero basin due to drainage area loss.

2. Geological setting

2.1 The Ebro and Duero basins

The Ebro and Duero basins represent two hydrographic basins covering the northern part of the Iberian Peninsula (Fig. 1). The bedrock of the Ebro and Duero drainage basins mainly consists on Cenozoic deposits, and Mesozoic and Paleozoic rocks in their headwaters (Fig. 2). They used to form a unique foreland basin during the Cenozoic, connected in the Rioja Trough (Mikeš, 2010), due to flexural subsidence related to the orogenic growth of their surroundings :

the Pyrenees and the Cantabrian mountains to the north (Pulgar et al., 1999), the Iberian and Central Ranges to the south (Guimerà et al., 2004; De Vicente et al., 2007), and the Catalan Coastal Range (CCR) to the east (López-Blanco et al., 2000 ; Salas et al., 2001), during collision between Iberia and Europe since the Late Cretaceous.

Since early stage of collision, the Ebro and Duero basins were essentially filled by siliciclastic and carbonated alluvial sediments, and opened toward the Bay of Biscay (Alonso-Zarza et al., 2002). During the Late Eocene – Early Oligocene, uplift in the Western Pyrenees (Puigdefàbregas et al., 1992) led to the closure of the Ebro and Duero basins and to continentalization in an endorheic setting (Costa et al., 2010). The center of these two basins became long-lived lakes filled with lacustrine, sandy, and evaporitic deposits from the Oligocene to the Miocene (Riba et al., 1983; Alonso-Zarza et al., 2002; Pérez-Rivarés et al., 2002, 2004; Garcia-Castellanos et al, 2003; Garcia-Castellanos, 2006; Larrasoaña et al., 2006; Vázquez-Urbez et al., 2013). Opening of the Ebro basin through the Catalan Coastal Range toward the Mediterranean Sea to the East occurred during the Late Miocene, leading to important unfilling and excavation recorded throughout the basin (Fillon and Van der Beek, 2012; Fillon et al., 2013; Garcia-Castellanos and Larrasoaña, 2015). However, its exact timing and its relation to the Messinian Salinity Crisis, as well as what processes is underlying this opening, has long been debated (Coney et al., 1996; Garcia-Castellanos et al., 2003; Babault et al., 2006; Urgeles et al., 2010; Garcia-Castellanos and Larrasoaña, 2015). By contrast, incision in the Duero basin appears very limited, although opening through the Iberian Massif toward the Atlantic Ocean to the west occurred progressively from west to east by river capture, from the Late Miocene-Early Pliocene to the Late Pliocene-Early Pleistocene (Martín-Serrano, 1991). The upstream Duero basin is characterized nowadays by a low relief topography (Fig. 1) at 700-800 m above sea level to the west, and at 1000-1100 m a.s.l. to the north, northeast, and to the east in the Almazan subbasin, close to the divide with the Ebro basin.

In the following, we review the geological evolution of the different domains that constitute today the drainage divide between the Ebro and Duero drainage basins as well as evidences for drainage mobility already recognized in previous studies. The current Ebro and Duero drainage networks are separated by a divide running from the Cantabrian belt to the NW, toward the SE in the Iberian Range (Figs. 1, 2, 3). The easternmost part of the Duero river is opposed to the Ebro tributaries that are the Jalon, Huecha, Queiles, Alama, Cidacos, Iregua, and Najerilla rivers, whereas the Arlanzon and Pisuerga rivers (Duero tributaries) are opposed to the Najerilla, Tiron, Oca, and Rudron rivers, and to the westernmost part of the Ebro river (Fig. 3).

The Northeastern part of the Duero basin (the easternmost Duero river, the Arlanzon and Pisuerga rivers) mainly consists in broad flat valleys characterized by low incision depth, with low-gradient streams dominated by concave longitudinal profiles (Antón et al., 2012, 2014). By contrast, the western part of the Ebro basin is characterized by more incised valleys, especially in the Cantabrian and in the Cameros – Iberian Range domains, with more complex longitudinal profiles (knickpoints, remnants of high elevated surfaces).

2.2 Geology and drainage divide in The Iberian Range

The Iberian Range (Figs. 2, 4) is a double vergent fold-and-thrust belt resulting from inversion of rift-related Mesozoic basins since the Late Cretaceous in response to Iberia – Europe convergence (Salas et al., 2001; Guimerà et al., 2004; Martín-Chivelet et al., 2002). It is divided into two NW-SE orientated branches, the Aragonese and the Castillian branches, separated by the Tertiary Almazan subbasin, which results from flexural subsidence due to thrusting in the Iberian Range (Bond, 1996). The Almazan subbasin is connected to the Duero basin since the Early Miocene (Alonso-Zarza et al., 2002).

The Iberian Range is essentially made of marine carbonates to continental clastic sediments from the Late Permian to the Albian, covering a Hercynian basement. The Cameros subbasin to the NW represents an Early Cretaceous highly subsiding trough almost exclusively filled by continental siliciclastic deposits (Martín-Chivelet et al., 2002 and references therein; Del Rio et al., 2009). Shortening is recorded up to the Early Miocene, and accomodated by hercynian inherited NW-SE structures (Gutiérrez-Elorza and Gracia, 1997; Guimerà et al., 2004; Gutiérrez-Elorza et al., 2002). This event is responsible for the opening of the Calatayud basin in the Aragonese branch during the Early Miocene, as dextral and inverse deformations are recorded on its southern margin (Daroca area) (Colomer and Santanach, 1988). It is followed during the Pliocene and the Pleistocene, by pulses of extensive deformations leading to fault reactivations in the Calatayud basin, and to the formation of new depressions, as the Daroca, Munébrega, Gallocanta, and Jiloca grabens (Fig. 4; Colomer and Santanach, 1988; Gutiérrez-Elorza et al., 2002; Capote et al., 2002). This is also outlined by the occurrence of breccias and glacis levels deposited in the Daroca and Jiloca grabens from the Late Pliocene to the Early Pleistocene (Gracia, 1992, 1993a; Gracia and Cuchi, 1993; Gutiérrez-Santolalla et al., 1996). These Neogene troughs are filled by continental deposits and pediments, up to the Quaternary (Fig. 4).

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The Neogene tectonic history of the Iberian Range is characterized by tectonic pulses intercalated with quiescence periods responsible for the formation of erosion surfaces from the Early Miocene to the Late Pliocene – Early Pleistocene (Gutiérrez-Elorza and Gracia, 1997). These surfaces are highly reworked and/or deformed due to subsequent tectonic activity, except for the youngest one, which appears only affected by surface processes as fluvial incision (Gutiérrez-Elorza and Gracia, 1997).

Uplift in the Iberian Range and Cameros basin resulted in the isolation of the Almazan subbasin (Alonso-Zarza et al., 2002) separating the Duero from the Ebro, whereas they are still connected to the Northwest, especially through the proto-Rioja trough (Mikeš, 2010). Compression in the Northwest Iberian Range continues and the inverted Cameros basin is deformed as a large anticline that plunges to the W-NW, finally connecting to the Cantabrian domain through the Rioja trough in the Late Oligocene. This disconnects the Ebro from the Duero basins, localizing the divide further East from its present-day location (Mikeš, 2010). During the Early Miocene, the Almazan subbasin, initially connected to the Ebro, became connected to the Duero basin (Alonso-Zarza et al., 2002), whereas in the Iberian Range, the formation of the Calatayud basin separated the Ebro from the Almazan-Duero basin.

The Almazan subbasin (Figs. 2, 4) is currently partly drained by the Ebro drainage network and especially by the Jalon river (Fig. 4). To capture this domain, the Jalon river had to cross the Mesozoic and Neogene strata and the two Paleozoic ridges of the Aragonese branch of the Iberian Range. According to morpho- and chrono-stratigraphic evidences, the Jalon river captured the Calatayud basin after the Messinian (Gutiérrez-Santolalla et al., 1996). Its tributary, the Jiloca river, captured the Daroca graben to the east during the Late Pliocene – Early Pleistocene, and the Jiloca graben, to the southeast, from the Early to Late Pleistocene (Gutierrez-Santolalla et al., 1996). It is finally followed by the capture of the Munébraga graben to the southwest, by the Jalon river (Gutierrez-Santolalla et al., 1996), toward the easternmost part of the Almazan subbasin.

2.3 Geology and drainage divide in the Rioja trough and the Bureba high

The Rioja trough (Figs. 2, 5) recorded important subsidence, especially during the Cenozoic (> 5 km), related to compression and thrusting on its borders (Jurado and Riba, 1996). As thrusting initiated in the Pyrenean-Cantabrian belt and in the Iberian Range and Cameros basin, the Rioja trough became an important bypass domain connecting the Ebro and Duero basins. During the

Paleocene, a marine environment took place, becoming more and more continental up to the Late Eocene. Thrusting continued during the Oligocene resulting in the formation of an anticline connecting the Cantabrian domain and the Cameros inverted basin. This morphologic high (the Bureba anticline) located in the center of the area is supposed to have disconnected the Duero and Ebro basins (Mikeš, 2010), as suggested by the repartition of detritic alluvial fans on both sides of this structure (Muñoz-Jiménez and Casas-Sainz, 1997; Villena et al., 1996). During the Miocene, deformations ceased as evidenced by the deposition of undeformed middle Miocene to Holocene strata. The Bureba anticline is cored by Albian strata and topped by Santonian limestones and Oligocene conglomerates controlling the location of the current main drainage divide between the Ebro and Duero river networks.

The western part of the Rioja trough to the west of the NE-SW directed branch of the Bureba anticline (Fig. 5), used to be drained toward the Duero basin since the Oligocene (Mikeš, 2010). The westward migration of the divide to its current location is thought to have occurred in several steps as shown by the occurrence of remnants of escarpments during the Late Miocene - Pliocene (Mikeš, 2010). Once the eastern branch of the Bureba anticline has been incised, the Ebro tributaries captured the western part of the Rioja trough, up to the E-W branch of the Bureba anticline to the southwest, from the Late Miocene to the Pliocene. Finally, the upper reach of the Jordan (Ubierna - Duero) river to the west has been captured by the Homino (Oca - Ebro) river during the Quaternary (Fig. 5). The Bureba area is then considered as dynamically stable as witnessed by the good superposition of the current streams and Quaternary fluvial deposits (Mikeš, 2010).

2.4 Climatic evolution

Climate exerts a major control on valley incision, sediment discharge, and on the evolution of drainage network (Bonnet, 2009; Whitfield and Harvey, 2012; Stange et al., 2014). The mean annual precipitation map for the North Iberian Peninsula (Hijmans et al., 2005) shows a similar pattern for both the Ebro and Duero basins as they record very low precipitation, associated to global subarid conditions, with the exception of the Cameros basin that record a slighlty higher precipitation rate (Fig. 6). There is a strong contrast to the north, toward the Mediteranean Sea and the most elevated areas in the Cantabrian and Pyrenean belts, where precipitations drastically increase.

The paleoclimatic evolution from the Late Cretaceous to the Neogene is linked both with the effects of surrounding mountains uplift, and with the latitudinal variation due to the rotation of

Iberia, from 30°N in the Cretaceous to ~40°N during Late Neogene times. The hot-humid tropical climate of the Late Cretaceous became more and more dry and arid from the Paleocene to the Middle Miocene (López-Martínez et al., 1986), favouring the development of endorheic lakes (Garcia-Castellanos, 2006). During the Middle-Late Miocene and Early Pliocene, the northern Iberia recorded more humid and seasonal conditions (Calvo et al., 1993; Alonso-Zarza and Calvo, 2000) with alternations of cold-wet and hot-dry periods (Bessais and Cravatte, 1988; Rivas-Carballo et al., 1994; Jiménez-Moreno et al., 2010). More humid and colder conditions then took place in the Late Pliocene, characterized by dry glacial periods and humid interglacials (Suc and Popescu, 2005; Jiménez-Moreno et al., 2013). Climatic contrasts increased, triggering intense glaciers fluctuations in the surrounding mountain ranges during the Lower-Middle Pleistocene transition (1.4-0.8 Ma) (Moreno et al., 2012; Duval et al., 2015; Sancho et al., 2016), and throughout the Late Pleistocene period, which record important glacial / interglacial oscillations, as evidenced by pollen identification (Suc and Popescu, 2005; Jiménez-Moreno et al., 2010, 2013; Barrón et al., 2016; García-Ruizet al., 2016) and speleothem studies (Moreno et al., 2013; Bartolomé et al., 2015).

Glaciers are considered as the most efficient erosion tool in continental environment. They are likely to influence drainage divide migration (Brocklehurst and Whipple, 2002). There is large evidence of glaciers development especially for the Late Pleistocene in the Pyrenees (Delmas et al., 2009; Nivière et al., 2016; García-Ruiz et al., 2016), in the Cantabrian belt (Serrano et al., 2013, 2016; García-Ruiz et al., 2016), and in the Central Range (Palacios et al., 2011, 2012; García-Ruiz et al., 2016). However, although numerous moraines have been mapped throughout the Iberian Range (Ortigosa, 1994; García-Ruiz et al., 1998; Pellicer and Echeverría, 2004), there is no evidence of U-shaped valleys and because of the lack of very high elevated massifs (>2500 m), the occurrence of active ice tongue is considered as limited, if not precluded (García-Ruiz et al., 2016).

3. Morphometric analyses

As mentioned above, it has already been shown that the Jalon and Homino rivers, which belong to the Ebro basin, have recently captured parts of the Duero basin in the Iberian Range and in the Rioja trough, respectively (Gutiérrez-Santolalla et al., 1996; Mikeš, 2010). Such evolution has been recorded by the occurrence of geomorphological markers as wind gaps and elbows of captures, as well as by the presence of knickpoints and/or remnants of high elevated surfaces in river long profiles. To highlight this dynamic evolution, we performed a morphometric analysis of rivers all around the divide separating the Ebro basin from the Duero basin, with particular attention given to the Aragonese branch of the Iberian Range (Fig. 4) and to the Rioja Trough (Fig. 5) where captures have already been described.

The studied basins were digitally mapped using high-resolution (~30 meters) digital elevation models (DEMs) from SRTM 1 Arc-Second Global elevation data available at the U.S. Geological Survey (www.usgs.gov). The different DEMs were assembled using the ENVI software. We also used 1:50,000 geological maps from the Instituto Géologico y Minero de España (www.igme.es).

We used the TopoToolbox, a MATLAB-based software developed by Schwanghart and Scherler (2014), to extract the river network and long profiles in our study area.

3.1 River capture evidences from geological, morphological and morphometric analyses

There are several evidences of recent river captures between the Ebro and Duero basins, as previously described in the Jalon river and Bureba sectors (Gutiérrez-Santolalla et al., 1996; Mikeš, 2010). This is also witnessed by the occurrence of high elevated surfaces at ~1000 m a.s.l. delimited by major knickpoints in several river long profiles.

3.1.1 Jalon river area

The current Jalon river and its tributaries drain the Aragonese branch of the Iberian Range and the eastern half of the Almazan subbasin, its western part belonging to the Duero catchment (Fig. 4). Gutiérrez-Santolalla et al. (1996) pointed out several chronostratigraphic evidences that allow to build a relative chronology of capture events in the Jalon network history. First, the incision of the northern Paleozoic ridge and capture of the Calatayud basin by the Jalon river is attributed to a post-Messinian age. The Jiloca river, the easternmost main Jalon tributary, is then thought to capture the Daroca graben area to the east during the Late Pliocene – Early Pleistocene. This is followed from the Early to Late Pleistocene by the capture of the Jiloca graben to the southeast. As shown by our river long profile analyses, all these captures are witnessed by knickpoints (Fig. 4). For instance, the capture of the Jiloca graben corresponds to a major knickpoint in the Jiloca river profile that appears very smoothed, and that is followed by an upstream ~50 km long flat domain preserved at ~1000 m high above sea level. This imparts a convex shape to the Jiloca profile (Fig. 4). Due to the short period of time between the formation of the Jiloca graben (the earliest glacis deposits are attributed to the Middle

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Pliocene) and its capture (Early Pleistocene), we suggest this domain was a short-lived endorheic domain that has never been drained before being captured by the Ebro network. In the northwestern part of the Jiloca graben, the Cañamaria river, a tributary of the Jiloca river, heads to the northwest, reaching the Gallocanta basin, also considered as a former graben (Gracia, 1993b; Gracia et al., 1999; Gutiérrez-Elorza et al., 2002). The upstream part of its river long profile is characterized by a sharper knickpoint at the entrance of the basin, and is followed by a ~15 km long flat domain (Fig. 4). Similarly to the Jiloca graben, the Gallocanta basin appears to be a short-lived endorheic domain that has been more recently captured by the Jiloca river network.

According to Gutiérrez-Santolalla et al. (1996), the Jalon river reached the southern Paleozoic ridge of the Aragonese branch, to the southwest of the Calatayud basin, captured the Munébrega graben and the Almazan subbasin (also characterized by a pronounced knickpoint) during the Pleistocene-Holocene, slightly after the capture of the Jiloca graben by the Jiloca river. This is coherent with morphological evidences as the major knickpoint related to the capture of the Jiloca graben appears very smoothed, whereas knickpoints observed in the west are sharper suggesting they are younger.

For instance, the Piedra river (Jalon tributary) long profile shows major sharp knickpoints and two successive ~30 km long almost flat domains in the Almazan subbasin, at ~900-1000 m above sea level (Fig. 4). In addition, the upper reach of the river long profiles of the Jalon river, and of its tributary the Blanco river, are characterized by major sharp knickpoints, and by a ~15 km long flat domain at ~1000-1100 m above sea level, in the Mesozoic Castillan branch of the Iberian Range (Fig. 4).

3.1.2 The Rioja trough area

The Bureba area consists in folded Middle Cretaceous to Early Miocene series, covered by undeformed Middle Miocene to Holocene deposits (Fig. 5). The main structural feature is the Bureba anticline, orientated E-W to the west and NE-SW to the east, cored by Albian strata and topped by Santonian limestones and dolomites. The western part of the anticline forms a topographic ridge that controls the current location of the main drainage divide between the Ebro and Duero river networks (Fig. 5). This ridge is incised by four rivers that are from west to east, the Ubierna with the Jordan river, the Hoz, the Rioseras, and the Nava Solo rivers (Figs. 5, 7). Further east, the Diablo river does not incise the ridge and its headwater is located in the core of the eastern branch of the Bureba anticline, the Fuente Valley (Fig. 5). The five last streams are tributaries of the Ubierna river, which is a tributary of the Arlanzon river and so, of the Duero river. To the north, the Ebro river system is represented, from west to east, by the Homino river (a tributary of the Oca river) and its four tributaries, the Molina, the Fuente Monte, the Zorica, and the San Pedro rivers (Figs. 5, 7). All these streams are outlined by Late Pleistocene to Holocene alluvial series that are deposited at the bottom of their respective valleys. Valleys from the Duero side appears larger than those from the Ebro side, which are significantly more incised.

The Jordan river's headwater is located north of the ridge. We can continuously follow its valley deposits northward along a broadly gentle slope, up to the locality of Coraegula (Fig. 5). However, the current course of the Jordan river is cut ~8 km south, in the vicinity of Hontomin, by the Homino (Ebro) river (Figs. 5B, C, 7). This fluvial capture is characterized by a well-defined and highly incised elbow of capture and its river long profile shows a sharp knickpoint located on Hontomin. Finally, there is a small wind gap on the divide between the two opposite rivers (Figs. 5, 7).

To the southeast, the headwater of the Hoz river is located on the second ridge incision. However, such incision is unlikely to result from the action of this headwater only as it would necessitate more important water and sediment discharges, and so a larger drainage area upstream. To the north, in the exact prolongation of the Hoz river, the Molina river shows a remarkable bend similar to the elbow of capture previously described for the Homino river (Fig. 7). There is a minor knickpoint located on this elbow, according to the extracted river long profile and such a ridge incision represents a well-defined wind gap between the two opposite rivers (Figs. 5, 7, 8). Thus, it is likely that the Molina river used to represent the upper reach of the Hoz river, before being captured by the Ebro network.

To the east, the Rioseras and the Nava Solo rivers have their headwater located on the third and fourth ridge incision, respectively, also representing pronounced wind gaps. Similarly, in their exact prolongations, the Fuente Monte and the Zorica rivers show important elbows of capture with minor knickpoints. They may also represent former upper reaches of Duero streams that have been captured by the Ebro network (Figs. 5, 7, 8).

Further east, the headwater of the Diablo river is located on the depression represented by the core of the eastern branch of the Bureba anticline, the Fuente valley. In its prolongation to the northeast, the San Pedro river incises the northeastern termination of the anticline from the north before entering the valley, leading to a remarkable southward retreat of the divide (Fig. 5). Capture is again evidenced by important incision contrast between Ebro and Duero systems,

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and by sharp knickpoints on the upper reach of the San Pedro river long profile when crossing the Santonian dolomites (Fig. 8).

According to this whole set of observations, and in agreement with Mikeš (2010), we propose that the western part of the Rioja trough has been recently captured by the Ebro drainage network leading to a significant southwestward retreat of the main drainage divide, toward the Duero basin (Fig. 7E).

3.1.3 Other capture features along the Ebro/Duero drainage divide

A similar capture pattern can be observed further west in the continuity of the Bureba anticline (Fig. 5). The San Anton river shows a well-defined elbow of capture accompanied by a smoothed knickpoint (See Fig. S1 in the Supplement) at its junction with the Rudron river (Ebro tributary). The river course is highly incised toward the east, along the northern flank of the WNW – ESE anticline, almost connecting to the upper reach of the Ubierna river. Valley deposits are also observed in the continuity of the Ubierna valley, which former route is witnessed by a wind gap (Fig. 5). However, this domain is no longer connected to its network as it is now wandered from the North by the Nava river, a tributary of the Moradillo river, which is a tributary of the Rudron river. This domain clearly recorded captures leading to divide migration toward the Duero, in favor of the Ebro basin.

Both the Ebro river and several tributaries show high elevated ~10-20 km long flat domains at ~800 – 1200 m a.s.l. and major knickpoints in the upper reach of their long profiles as the Rudron, Queiles, and Alama rivers, as well as the Homino river and its tributaries: the Puerta Nogales and Valdelanelala rivers (Figs. 5, 8; Fig. S1). All these domains may not be related to surface uplift as they are not clearly associated to active tectonic features.
It has been shown that the occurrence of high elevated, low-relief surfaces, may result from drainage reorganization leading to isolation and starvation of a drainage area, rather than remnants of ancient erosional conditions or uplift (Yang et al., 2015). The Duero basin is characterized by a high mean elevation (~1000 m) and by a very limited incision in the vicinity of the Ebro/Duero drainage divide. A sudden divide migration toward the Duero basin is then expected to isolate such high elevated and relatively preserved surfaces.

We suggest these flat domains have been recently captured by Ebro tributaries, and represent remnants of Duero drainage areas, isolated due to important divide retreat toward the Duero basin.

A lot of Ebro tributaries also show major knickpoints at ~1000 m a.s.l. close to the divide (Fig. 9; Fig. S1) that may also be linked with drainage divide migration. Overall, we consider a paleodrainage divide delimited by these high-elevated knickpoints and flat domains, except for the Jiloca graben area to the southeast, characterized by the occurrence of short-lived endorheic domains (Fig. 9).

3.2 Chi (*X*) map

3.2.1 Background

The shape of the longitudinal profile of a river s classically described by a power law which relates the local slope of the river to its drainage area (Flint, 1974):

$$\frac{dz}{dx} = k_s A^{-\theta} \quad (1)$$

with z the elevation, x the distance, k_s a constant termed the channel steepness index, A the drainage area and θ a constant termed the concavity index. In fluvial systems, the erosion rate E is often expressed as a stream power erosion law (Whipple and Tucker, 1999):

$$\frac{dz}{dt} = KA^m \left(\frac{dz}{dx}\right)^n \quad (2)$$

where t is the time, K is an erodibility coefficient, and m and n are constants. Under the assumption of a steady-state between erosion (E) and uplift (U), that is $U = E = K\,A^m \left(\frac{dz}{dx}\right)^n$, the expression of the stream power law can be rearranged to predict the steady-state shape of a longitudinal profile of a river under constant climatic and tectonic forcing conditions:

$$\frac{dz}{dx} = \left(\frac{U}{K}\right)^{\frac{1}{n}} A^{-\frac{m}{n}} \quad (3)$$

The comparison between equations (1) and (3) show that ks may vary according to the uplift rate and by consequent spatial variations in ks can potentially be used to infer spatial variations in U (Kirby and Whipple, 2012). In a region where spatial variations in U are not expected, variations in ks may also reflect disequilibrium along the river, on the form of a knickpoint for example (Whipple and Tucker, 1999). Although the slope-area analysis of channel profiles is potentially a powerful tool to evidence differences in the equilibrium state of rivers across divide, and then to infer their migration (Willett et al., 2014), this method is limited and even biased by the quality of the topographic data. Indeed, both a low-resolution of the DEM and corrections brought to the DEM (filling or carving), lead to substantial uncertainties that are automatically transferred to the slope, k_s and θ data. To avoid slope measurements, Royden et al. (2000) proposed a procedure based on a coordinate transformation allowing linearizing river profiles by using the elevation of each point along the profile (x) instead of the slope in the stream power equation.

Considering steady-state with constant uplift rate and erodibility in time and space, Equation (3) may be solved as follows:

$$z(x) = z_b(x_b) + \frac{U}{KA_0^m}\frac{1}{n}X \quad (4)$$

where z_b is the elevation at the river's base level, A_0 is a reference scaling drainage area, and chi is an integral function of the drainage area along the channel network.

$$X = \int_{x_b}^{x}\left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx \quad (5)$$

A « *X*plot » (elevation versus *X* diagram) of a steady-state channel is then shown as a straight line (Perron and Royden, 2013; Royden and Perron, 2013). This implies that channels pulled away from this line are in disequilibrium and are expected to attempt to reach equilibrium. Mapping chi on several watersheds and comparing chi across drainage divides is then a potential way to elucidate the basins dynamics and reorganizations through captures (Willett et al., 2014).

We used the Chi Analysis Tool developed by Mudd et al. (2014) to select the best m/n ratio and to calculate chi throughout the connection between the Ebro and Duero basins from a similar base level at 850 m a.s.l.

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The best mean m/n ratio for all our streams is 0.425, which falls in the typical range (~0.4 – 0.6) characteristic of simple settings with uniform substrate, uplift rate and climate (Kirby and Whipple, 2001, 2012; Wobus et al., 2006). The resulting map (Fig. 10) shows X values calculated on different opposite streams in the vicinity of the Ebro/Duero drainage divide. Similar values on both sides of the divide suggest the two opposite streams are at equilibrium, whereas strong contrasted X values imply disequilibrium leading to divide migration, continuously or through fluvial capture, toward the high values stream (Willett et al., 2014).

3.2.2 Application to the divide between the Ebro and Duero basins

The map of X values actually shows significant contrasting values across the Ebro/Duero divide. We comment here these contrasts along the divide from the SE to the NW of the area considered (Fig. 10).

There is a strong contrast in X values between the headwater of the Jalon river (Fig. 10), characterized by low values (~300 m), and the closest part from the divide of the Bordecorex river (Fig. 4), a tributary of the Duero river (~500 m). Such a disequilibrium implies divide migration toward the Duero basin, predicting the capture of the uppermost reach of the Bordecorex river by the Jalon river. To the north, tributaries of the Jalon river show slightly lower X values than the tributaries of the Duero river. This suggests a relative equilibrium although little captures may occur toward the Duero basin. A higher contrast is observed around the easternmost part of the Duero basin, which is surrounded by the Ebro basin. The Araviana river (tributary of the Duero river) seems to be taken in a bottleneck between the Manubles river to the south and the Queiles river to the north (Fig. 4), which both show lower X values (Fig. 10). Toward the east, there is a strongest X values contrast between headwaters of the Araviana river (>700 m) and of the Isuela (Jalon tributary) and Huecha rivers (<100 m). This domain appears clearly in disequilibrium and is expected to be captured by the Ebro drainage network. Such high X values differences appear also to the northwest (Fig. 10), in the southern part of the Cameros basin where the Duero river and its tributaries' headwaters show X values >500-700 m, whereas the facing rivers (Alama, Cidacos, Iregua, and Najerilla) are all characterized by low X values <100 m. This predicts important disequilibrium and divide migration and fluvial captures toward the south. Northwestward, X values between Duero and Ebro network are more similar indicating that the divide is relatively more stable, up to the westernmost part of the Ebro basin (Fig. 10). However, there are some slight localized X values contrasts (~200

/ ~450 m) as observed between the Tiron and the Arlanzon rivers, between the Rudron and the Ubierna and Urbel rivers, and between the Ebro and the Pisuerga rivers (Fig. 10). These suggest minor local captures toward the Duero basin.

To sum up, *X* values calculated in the vicinity of the drainage divide between the Ebro and Duero river networks show a general disequilibrium (Fig. 10) as the Ebro network is characterized by low *X* values (up to ~200-300 m) compared to those for the Duero network (up to ~450-700 m). In complement with all the evidences of divide displacements described previously this allows predicting a general divide migration toward the Duero basin through headwater retreat and river captures, in favor of the Ebro tributaries, especially around the Almazan subbasin, which is expected to be entirely captured by the Ebro basin.

4. Discussion

4.1 A long term trend of divide migration

The oldest capture evidence in our study area corresponds to the incision of the northern part of the Iberian Range by the Jalon river and by the capture of the Calatayud basin, attributed to the post-Messinian (Gutiérrez-Santolalla et al. 1996). We show, by using morphological evidences (Fig. 4) and in agreement with stratigraphic data, that the Jalon river system then captured the Jiloca graben to the east since the Early Pleistocene, before progressively capturing the Almazan subbasin toward the west, up to the Holocene (Gutiérrez-Santolalla et al. 1996). From *X* analysis (Fig. 10), we deduced that the eastern part of the Duero basin, the Almazan subbasin, is being actively captured by Ebro tributaries that drained the Iberian Range and the Cameros basin. Despite low contrasts in *X* values, local captures are also evidenced in the vicinity of the Ebro / Duero drainage divide toward the northwest. Capture is also well witnessed by the occurrence of numerous high elevated (~1000 m) knickpoints and low-relief surfaces (Figs. 5, 8, 9, 10).
Thus, there is a good correlation between *X* predictions and morphological and stratigraphic data implying for a long continuity for capture and divide migration in favor of the Ebro basin during Pliocene, Pleistocene, and Holocene times.

The pursuit of such a long capture trend can be driven by tectonic and/or climatic forcing (Willett, 1999; Montgomery et al., 2001; Sobel et al., 2003; Sobel and Strecker, 2003; Bonnet, 2009; Whipple, 2009; Castelltort et al., 2012; Kirby and Whipple, 2012; Goren et al., 2015; Van der Beek et al., 2016). However, such long-term trend of drainage reorganization may also occur in tectonically quiescent domains, independently of such external forcing (Prince et al., 2011). Here, the Iberian Range and the Cameros basin recorded extension pulses from the Late Miocene to the Early Pleistocene, responsible for the formation of several grabens as previously described (Gutiérrez-Santolalla et al., 1996; Capote et al., 2002). Extension events are also recorded during the Holocene, nevertheless, the youngest erosion surface of Late Pliocene-Early Pleistocene age observed in our study area shows no tectonic-related deformation and reworking, suggesting that tectonic activity is reduced here (Gutiérrez-Elorza and Gracia, 1997). This is also consistent with the relative scarcity of seismic activity observed in our study area, compared, for instance, to the Pyrenees, or to the Betics (Herraiz et al., 2000; Lacan and Ortuño, 2012). We consequently propose that local tectonic activity is not the main driver to the capture histories documented here, as most capture events postdate the cessation of tectonic activity, and occur during intermediate quiescence episodes (Gutiérrez-Santolalla et al., 1996).

Although the Cameros basin shows relatively high mean annual precipitations up to ~1000 mm/an (Fig. 6) that are correlated with relatively high elevation (~1400-2200 m), the Ebro and Duero basins show very similar and low values of ~400-500 mm/an (Hijmans et al., 2005), due to global subarid climatic conditions. The Cameros area is the only place where a contrast in precipitation pattern (Fig. 6) could potentially drive the migration of the divide toward the drier, Duero area. Given that the same pattern is observed everywhere, even where there isn't any precipitation difference, we suggest however that the present day climatic condition is unlikely to control the general pattern of current drainage reorganization between the Ebro and Duero basins. During the Pliocene and the Pleistocene, the climatic record in the northern Iberia Peninsula is characterized by alternance between similar subarid conditions and intense glaciation. However, there is no clear evidence of important glaciers development and related erosion in our study area, especially for the Cameros basin and the Iberian Range (Ortigosa, 1994; García-Ruiz et al., 1998, 2016; Pellicer and Echeverría, 2004). This indicates that drainage evolution between the Ebro and Duero basins is not clearly related to climatic evolution.

4.2 Excavation of the Ebro basin as the main factor controlling drainage reorganization, drainage divide migration and limiting incision of the Duero river

A striking morphological feature for river capture in our study area is that it is associated to an important contrast in incision (e.g. Fig. 1B) from one side of the divide to the other, in association with frequent knickpoints in the capturing reach (Fig. 9). This suggests that the incision capacity of the river network is the main driver for capture and divide migration in our setting. Then, to first order, both tectonic and climatic forcing does not appear to control drainage reorganization between the Ebro and Duero basins.

The opening of the Ebro basin toward the Mediterranean Sea during the Late Miocene led to important unfilling and widespread excavation (Garcia-Castellanos et al., 2003, Garcia-Castellanos and Larrasoaña, 2015), also favored by more humid and seasonal climatic conditions (Calvo et al., 1993; Alonso-Zarza and Calvo, 2000). By contrast, incision related to the opening of the Duero basin toward the Atlantic Ocean is concentrated to the west in the Iberian Massif, characterized by a largescale knickzone (150 km long and 500 m high) in the Duero river long profile (Fig. 1B), whereas propagation of incision eastward in the Cenozoic part of the basin is limited (Antón et al., 2012, 2014), despite similar climatic conditions than for the Ebro basin. An explanation resides in the fact that the resistant Iberian Massif basement rocks may have controlled and limited incision and drainage reorganization in the Cenozoic Duero basin (Antón et al., 2012). Then, the Duero profile upstream of this major knickzone may be considered as a high elevated base level for its tributaries there. This contrast between the Ebro and Duero base-levels implies a major contrast in fluvial dynamics, especially regarding incision rate. We suggest the systematic and long-term trend of divide migration toward the Duero basin and fluvial capture in favor of the Ebro basin since the Early Pliocene is driven by this different incision behavior and from the widespread excavation resulting from the opening of the Ebro basin toward the Mediterranean Sea since the Late Miocene.

The opening of the Ebro basin toward the Mediterranean Sea resulted in a drastic base level down drop. We suggest this results in the establishment of an upstream-migrating incision wave that propagates to every tributary of the Duero network, responsible for knickpoints migration (Schumm et al., 1987; Whipple and Tucker, 1999; Yanites et al., 2013) and for drainage reorganization and divide migration. The Chi analysis that we performed along the current Ebro-Duero divide (Fig. 10) highlights areas where geomorphic disequilibrium still stands today, which suggests that they are areas where divide is still mobile. The modelling study performed by Garcia-Castellanos and Larrasoaña (2015) suggests that the re-opening of the

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Ebro basin occurred between 12.0 and 7.5 Ma. This indicates that the growth of the drainage network of the Ebro basin and the establishment of new steady-state conditions is a long-lived phenomenon, which is still not achieved today.

Incision in the Ebro basin leads to the capture of new drainage areas, whereas the Duero basin recorded important loss of its own surface. The present day drained area of the Cenozoic Duero basin, upstream of the major knickzone observed to the west in the Iberian Massif is ~63000 km^2. We described several domains along the Ebro-Duero divide that have clearly been recently captured by the Ebro drainage network as the eastern part of the Almazan subbasin. In Figure 9, we have connected all these domains to define a « recent » captured area that used to belong to the Duero basin. This area represents ~7700 km^2, which corresponds to ~12% of the present-day Cenozoic Duero basin drainage area. Moreover, some of these captured domains record relatively high precipitation rates as in the Cameros basin compared to the center of the Duero basin. Such a reduction of the drainage area could have strong implications on the evolution of the Duero basin, as important lowering of water and sediment fluxes, and so of incision throughout the basin.

To better resolve the impact of such drainage area reduction on incision capacity, we perform a stream power analysis of the Duero river. We consider the specific stream power, ω, defined as $\omega = \rho\ g\ Q\ S\ /\ W$, where ρ is water density, g is gravitational acceleration, Q is discharge, S is local river gradient, and W is river width (see the Supplement for details of the calculation).

We calculate ω for the present-day Duero river, and for a restored ancient Duero river that drained this 12% of lost area. We plot the difference (ancient – present day) between the two curves in Figure 11, with the Duero river long profile. Calculated difference in specific stream power values are relatively low (< 2 W m^{-2}) for the upstream part of the basin, but increase to ~5 W m^{-2} when approaching the major knickzone at a distance of ~350 km from the river mouth. The knickzone is characterized by peak values exceeding 10 W m^{-2}, which rapidly decrease to ~0 W m^{-2} at the base of the knickzone (~200 km) and up to the river mouth (Fig. 11). Some alternating peak and null values are observed in the lower reach of the river and may be related to the occurrence of numerous dams along the river.

Overall, the specific stream power calculated for the ancient Duero river show higher values than for the present day from the base of the knickzone to the uppermost reach of the river (Fig. 11). This implies a general decrease of the Duero river's incision capacity between this ancient state to the present day. The remarkable difference of stream power values in the vicinity of the knickzone (Fig. 11) suggests that drainage area reduction limits erosion in the Duero basin as it helps for preservation of the lithologic barrier to the west, considered as an intermediate base level (Antón et al., 2012).

This stream power calculation does not take into account possible captures and divide migration in other areas around the Duero basin, nor the full history of the divide migration through time. Some contrasts of incision are also observed in the Central Range to the South, and in the Cantabrian domain to the North. Both show more important incision than in the Duero basin suggesting potential river captures and divide migration at the expense of the Duero basin, increasing the total of lost drainage area, especially in domains where precipitation rates are higher than inside the basin (Fig. 6).

We then suggest that the area loss for the Duero basin partly due to important capture and incision in the Ebro basin is responsible for an important decrease of the incision capacity in the Duero basin. Then, active exorheism in the Ebro basin is likely responsible for the present day quasi-endorheic state of the Duero basin.

Conclusions

The Ebro and Duero basins both recorded a long endorheic stage during Oligocene and Miocene times. Since the Late Miocene, the Ebro basin is opened to the Mediterranean Sea and record important unfilling. This results in important incision driven by a very active drainage network. By contrast, the Duero basin is opened to the Atlantic Ocean since the Late Miocene – Early Pliocene and record only limited incision. Its upper part is considered as still almost endorheic. Such contrast in river-driven incision leads to important drainage reorganization between the two basins as shown by numerous occurrences of river captures by the Ebro basin network, and divide migration toward the Duero basin. Drainage area lost results then in the lowering of the incision capacity of the Duero basin favoring its almost endorheic stage.

Author contributions

AV undertook morphometric modeling and interpretation, and wrote the paper. SB and FM contributed to the interpretation and the writing.

Competing interests.

The authors declare that they have no conflict of interest.

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Figure captions:

Figure 1: A) Topographic map of the Duero and Ebro basins and surrounding belts. B) Averaged topographic section throughout the Duero and Ebro basins showing important incision contrast between the two basins. The Duero basin recorded low incision, especially for its upper part, whereas the Ebro basin is highly excavated.

Figure 2: Simplified geological map of the study area.

Figure 3: Topographic map of the study area with all the rivers considered in this study. The red lines represent drainage divides between main hydrographic basins.

Figure 4: Zoom in the geological map of the Iberian Range showing the location of the Jalon river tributaries. The river long profiles of these streams and the location of knickpoints are shown to the left.

Figure 5: A) Zoom in the geological map of the Bureba sector. B) Zoom in the Homino river (Ebro tributary) capturing the upper reach of the Jordan river (Duero tributary). C) Schematic representation of this capture using river long profiles and map orientation, showing the associated knickpoint and wind gap.

Figure 6: Mean annual precipitation map for the study area obtained from Hijmans et al. (2005).

Figure 7: A) 3D topographic map of the Bureba sector showing important incision in the Ebro basin contrasting with the well-preserved Duero basin, and river capture evidences (elbows of capture, knickpoints and wind gaps). B) Google Earth image around the locality of Hontomin where the Homino river is capturing the upper reach of the Jordan river. C) and D) Remarkable wind gaps located on the Bureba anticline. Pictures have been taken from the north of this structure toward the south. E) Possible three steps evolution of the southwestward divide retreat through multiple river captures witnessed in the area.

Figure 8: River long profiles for all the streams described in the Bureba area showing remarkable evidences of river capture. Colors are given to rivers that are linked in these capture processes.

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Figure 9: Topographic map showing the location of all the knickpoints and low relief surfaces that may be associated to river capture. The black dashed line represents a possible paleodrainage divide between the Ebro and Duero basins. The area between this dashed line and the present-day location of the divide in red may have belonged the Duero basin before being captured by the Ebro basin.

Figure 10: Topographic map with X values calculated on different opposite streams in the vicinity of the Ebro/Duero drainage divide. This map shows significant contrasting values between the Ebro and Duero drainage networks.

Figure 11: The Duero river long profile (black line) is compared to the difference between the specific stream power calculated for the possible ancient and for the present-day Duero river, in grey. Positive values suggest a diminution of the incision capacity of the Duero river, through time. Details on calculation are available in the Supplement (Section S1).

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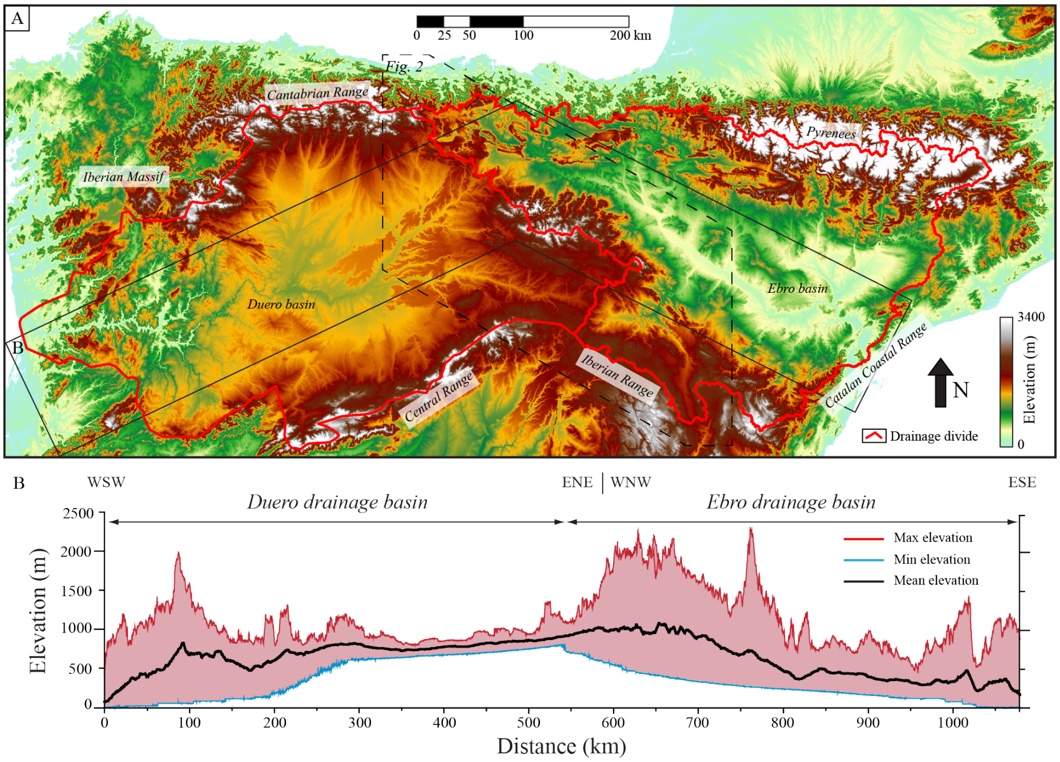

Figure 1

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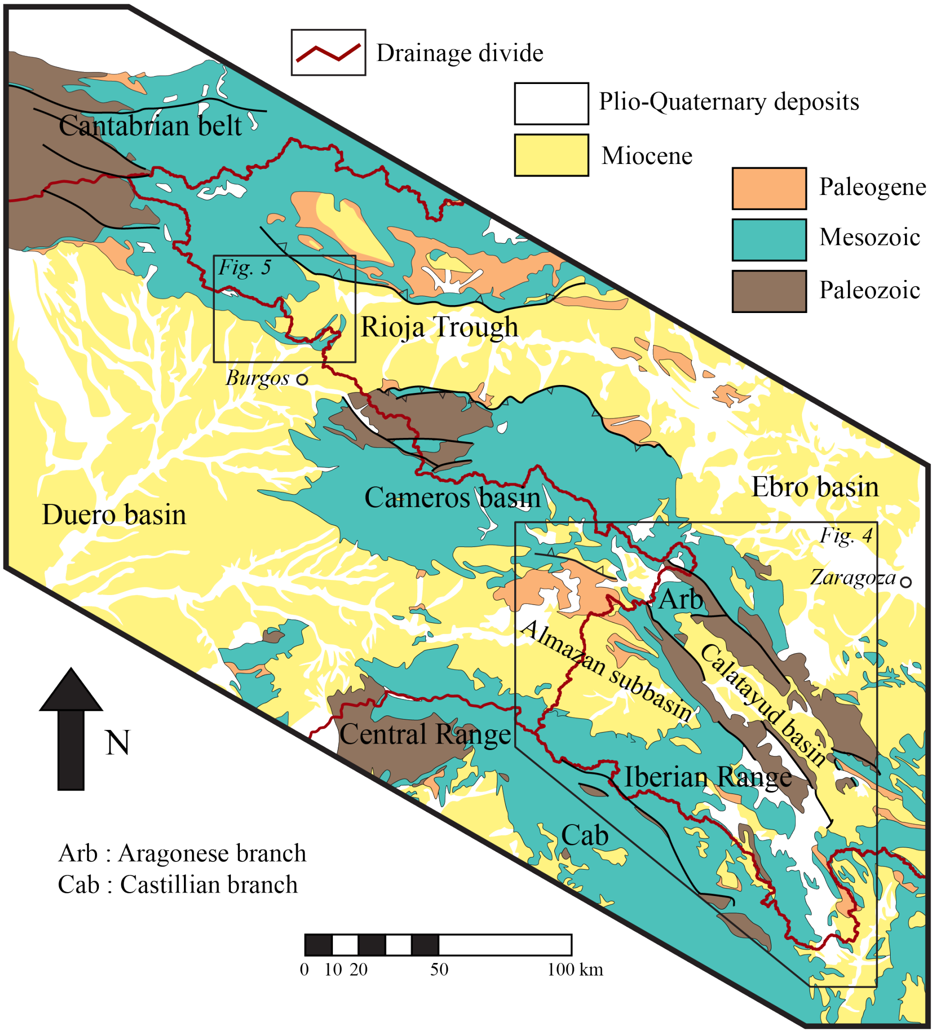

Figure 2

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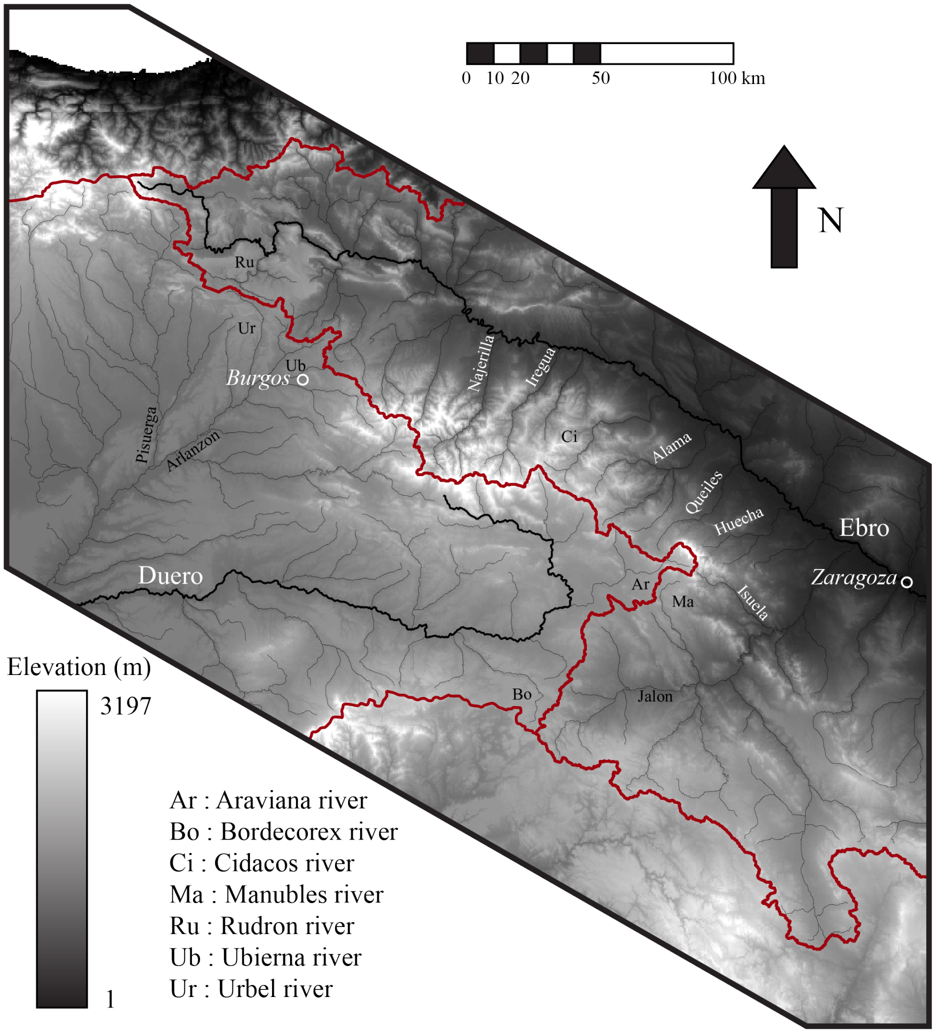

Figure 3

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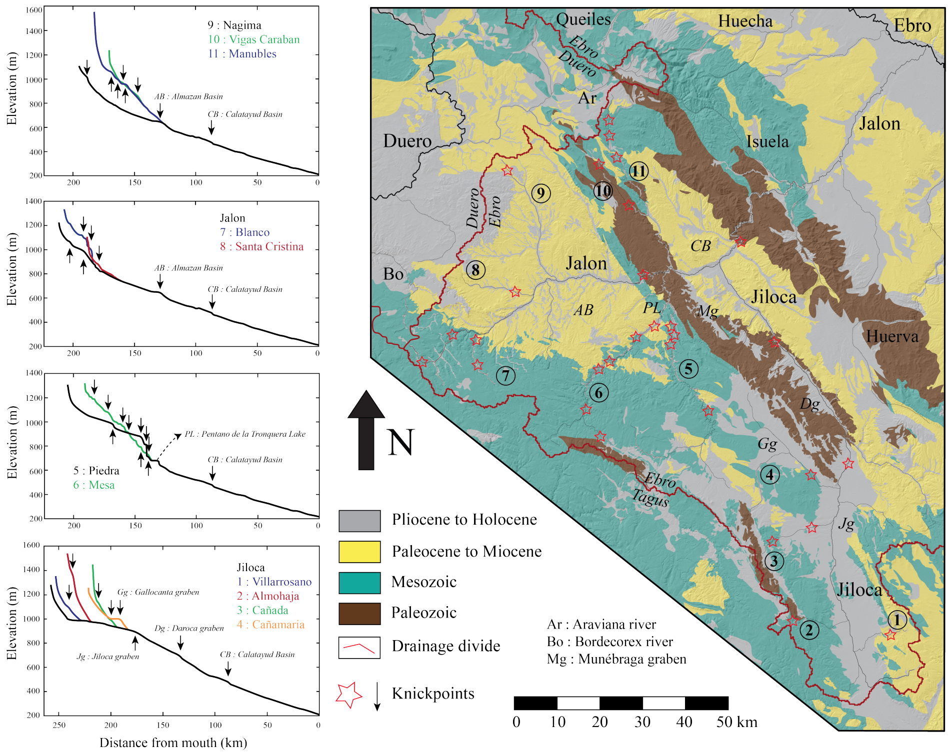

Figure 4

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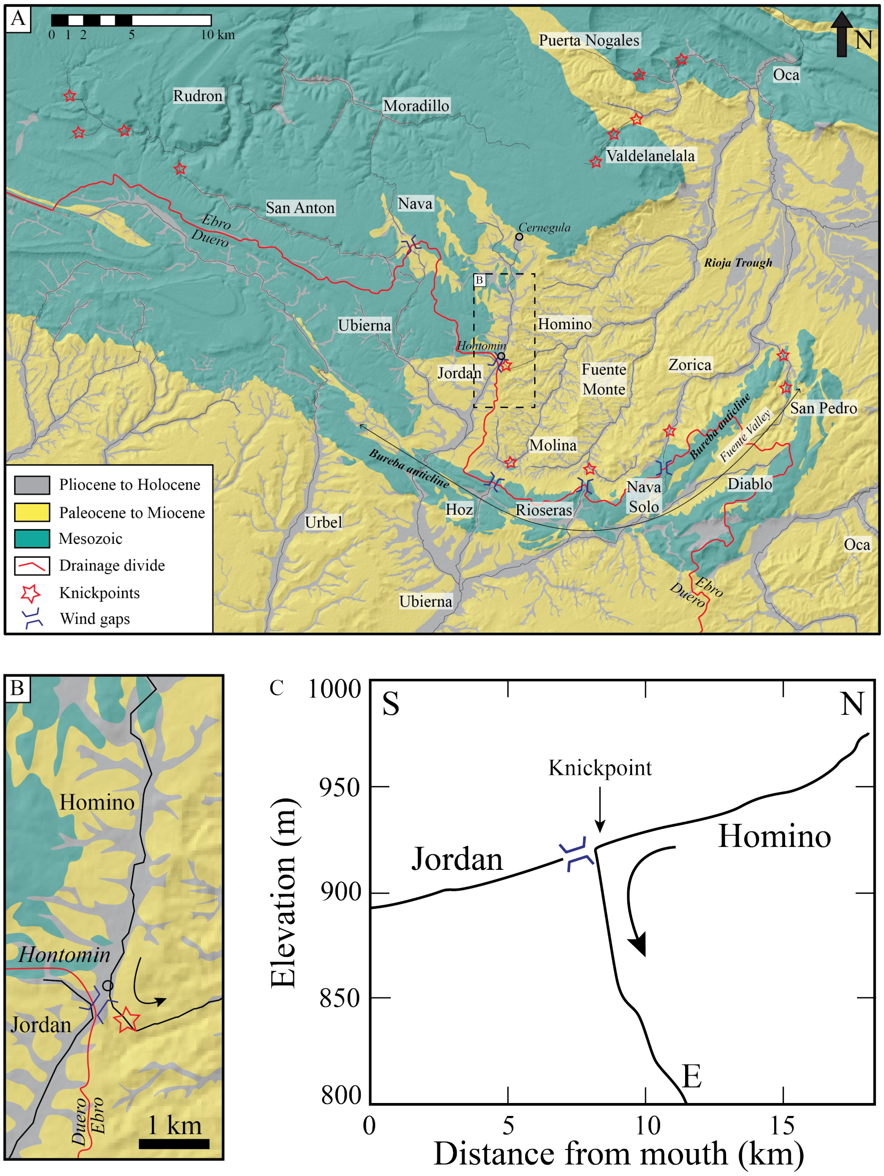

Figure 5

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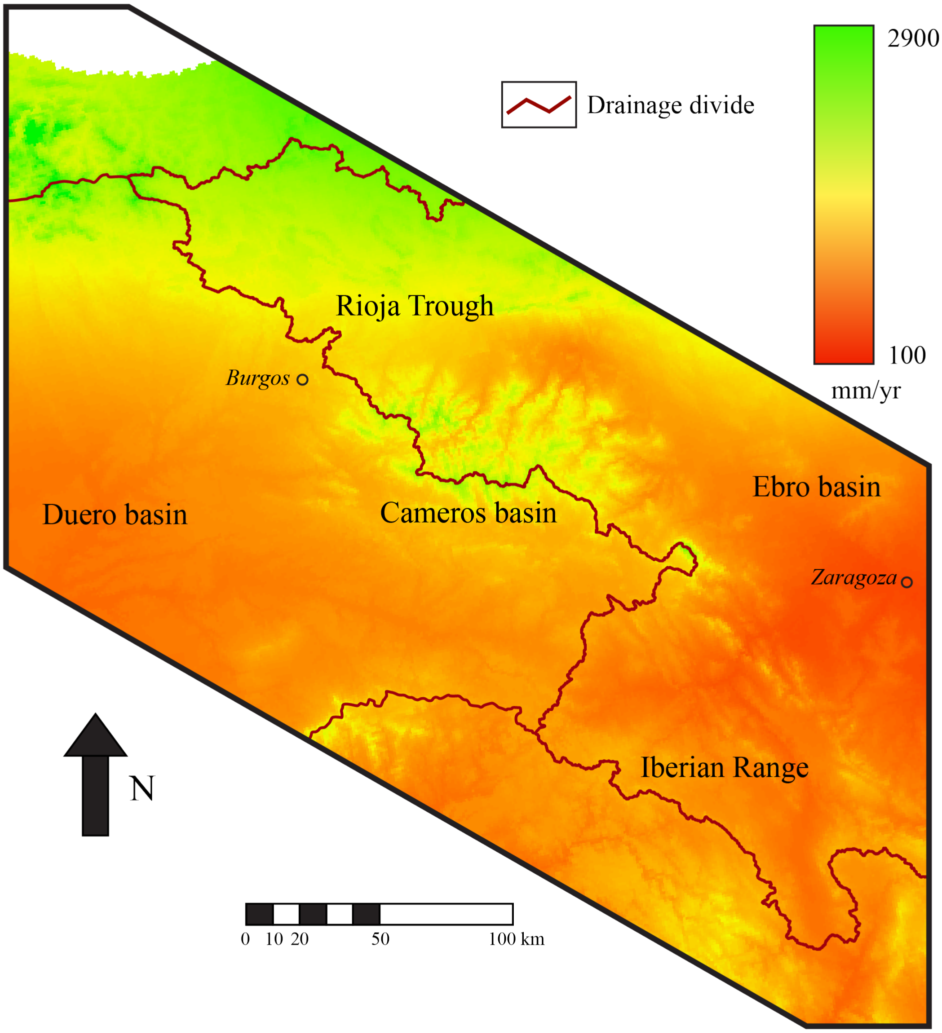

Figure 6

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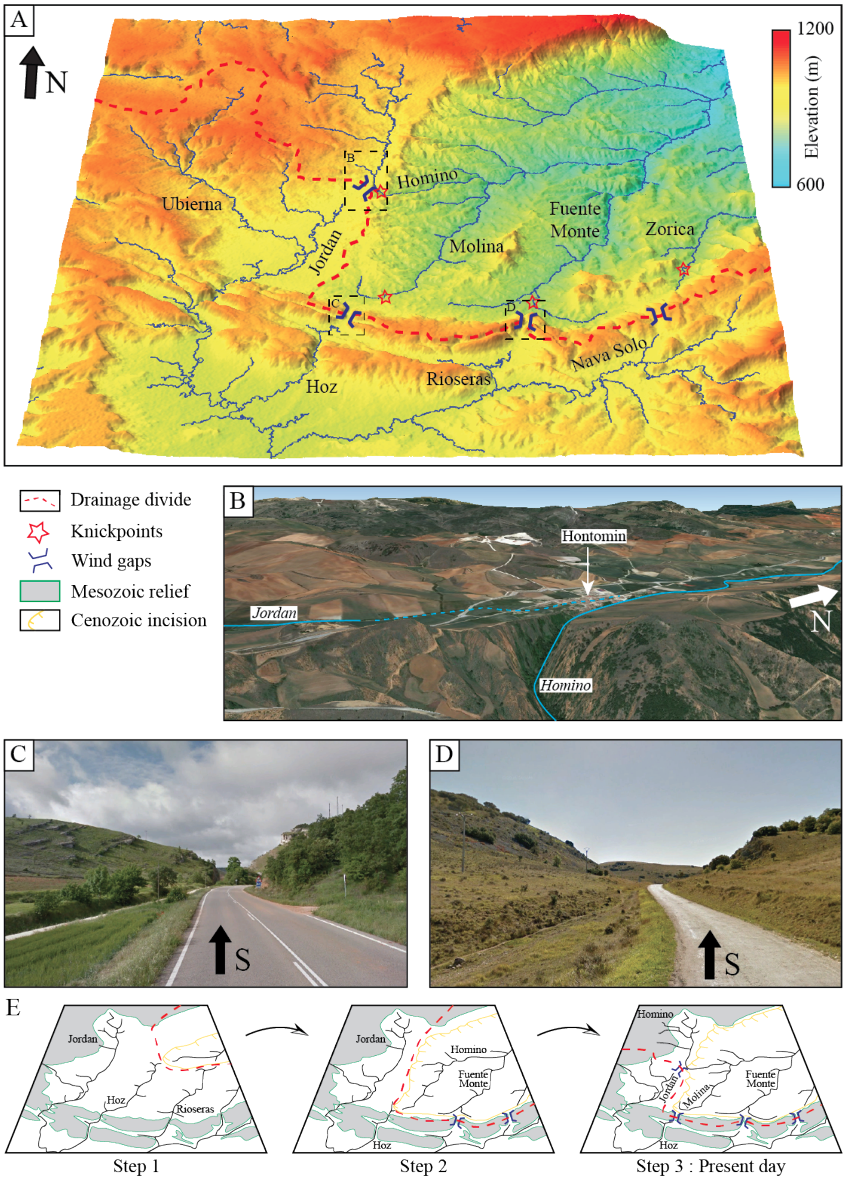

Figure 7

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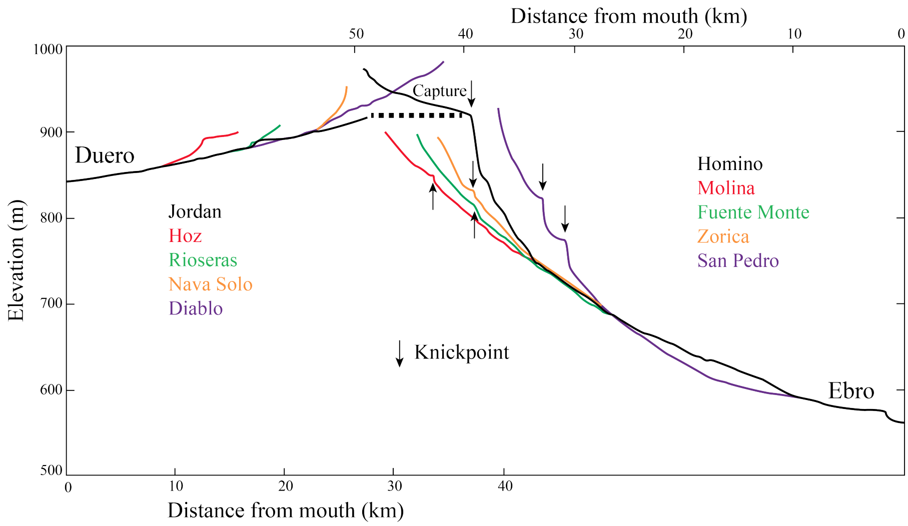

Figure 8

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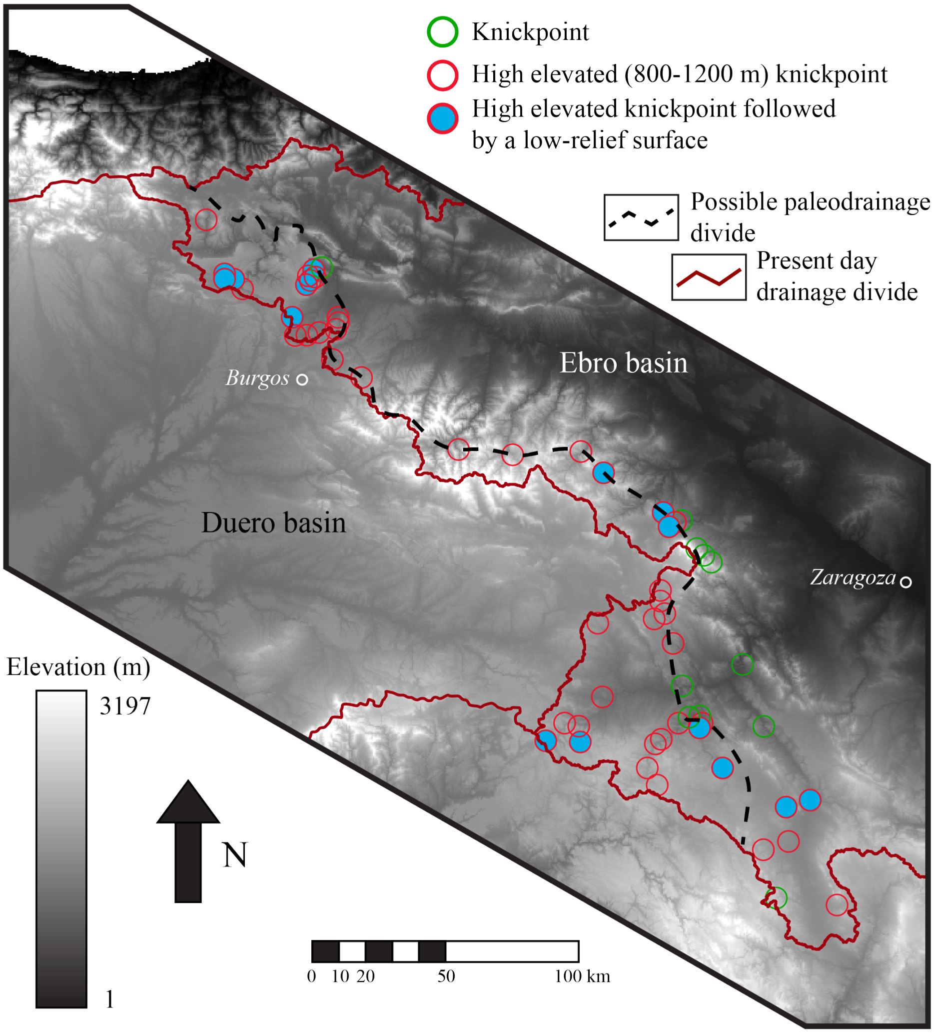

Figure 9

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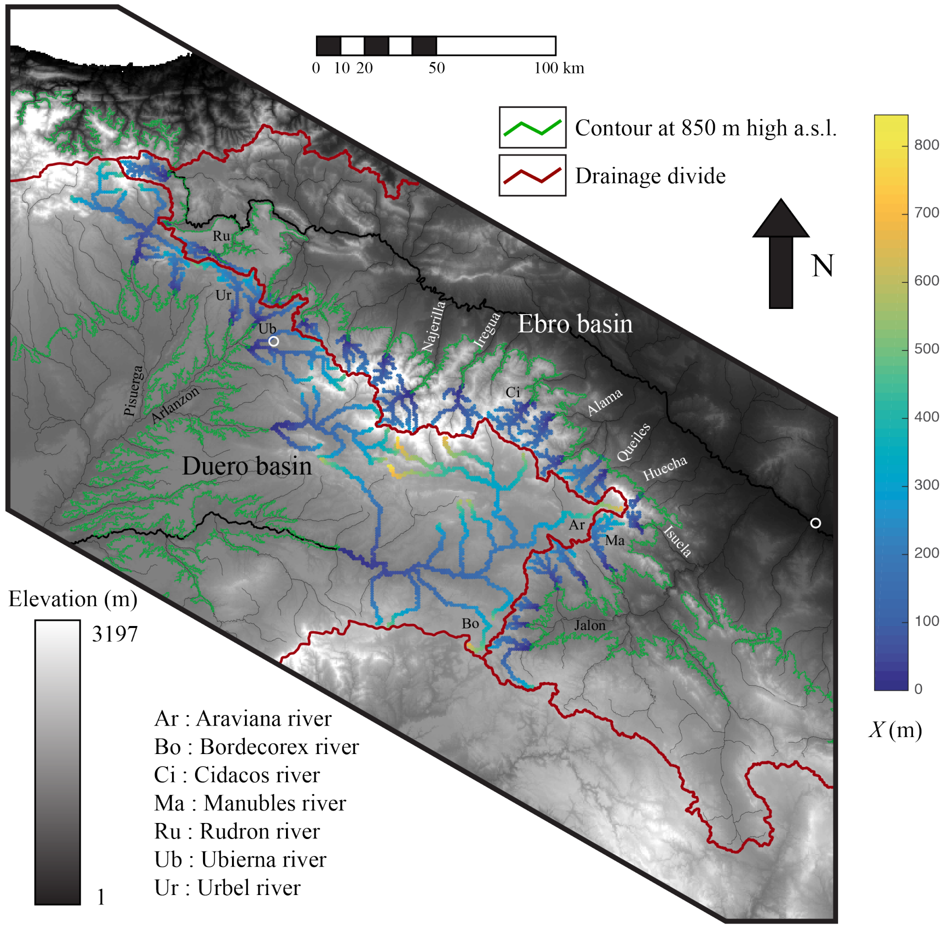

Figure 10

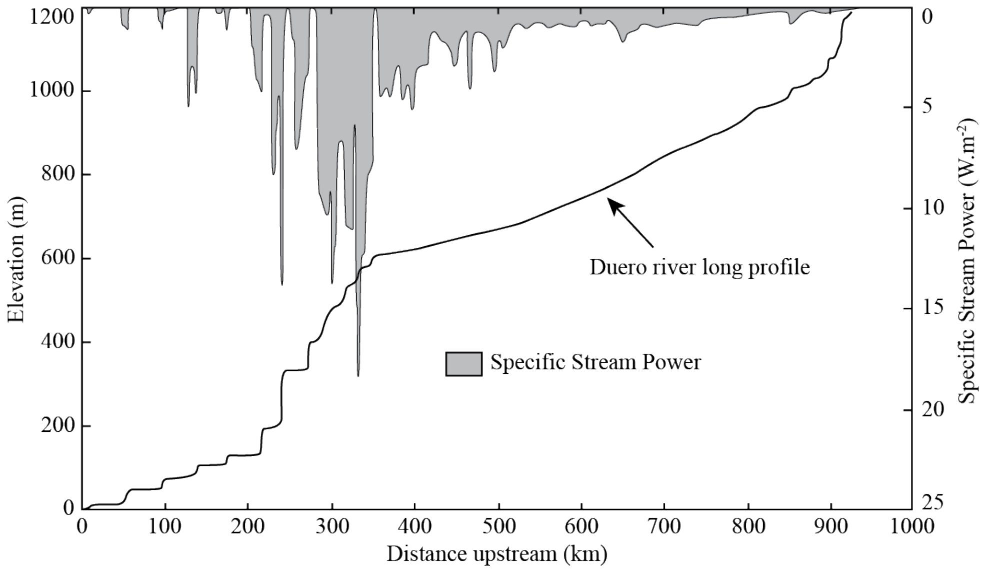
1200
1000
800
600
400
200
0
Elevation (m)
0
5
10
15
20
25
Specific Stream Power (W.m-2)
0
100
200
300
400
500
600
700
800
900
1000
Distance upstream (km)
Duero river long profile
Specific Stream Power

Figure 11