

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

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10  
11 **Abstract**

12  
13 Intracontinental endorheic basins are key elements of source-to-sink systems as they preserve  
14 sediments eroded from the surrounding catchments. Drainage reorganization in such a basin in  
15 response to changing boundary conditions has strong implications on the sediment routing  
16 system and on landscape evolution. The Ebro and Duero basins represent two foreland basins,  
17 which developed in response to the growth of surrounding compressional orogens, the Pyrenees  
18 and the Cantabrian mountains to the north, the Iberian Ranges to the south, and the Catalan  
19 Coastal Range to the east. They were once connected as endorheic basins in the early Oligocene.  
20 By the end of the Miocene, new post-orogenic conditions led to the current setting in which the  
21 Ebro and Duero basins are flowing in opposite directions, towards the Mediterranean Sea and  
22 the Atlantic Ocean. Although these two hydrographic basins recorded a similar history, they are  
23 characterized by very different morphologic features. The Ebro basin is highly excavated,  
24 whereas relicts of the endorheic stage are very well preserved in the Duero basin. The  
25 contrasting morphological preservation of the endorheic stage represents an ideal natural  
26 laboratory to study the drivers (internal / external) of post-orogenic drainage divide mobility,  
27 drainage network and landscape evolution. To that aim, we use field and map observations and  
28 we apply the  $\chi$ -analysis of river profiles along the divide between the Ebro and Duero drainage  
29 basins. We show here that the contrasting excavation of the Ebro and Duero basins drives a  
30 reorganization of their drainage network through a series of captures, which resulted in the  
31 southwestward migration of their main drainage divide. Fluvial captures have strong impact on  
32 drainage areas, fluxes, and so on their respective incision capacity. We conclude that drainage  
33 reorganization driven by the capture of the Duero rivers by the Ebro drainage system explains

34 the first-order preservation of endorheic stage remnants in the Duero basin, due to drainage area  
35 loss, independently from tectonics and climate.

36

## 37 1. Introduction

38

39 Landscapes subjected to contrasted erosion rates between adjacent drainage basins show a  
40 migration of their drainage divide toward the area of lower erosion rates (Bonnet, 2009; Willett  
41 et al., 2014). This is the case for mountain ranges characterized by gradients in precipitation  
42 rates due to orography, once landscapes are in a transient state and are not adjusted to  
43 precipitation differences (Bonnet, 2009). It also occurs when drainage reorganized in response  
44 to capture (Yanites et al., 2013; Willett et al., 2014). River capture actually drives a drop in the  
45 [spatial position](#) of drainage divide (Prince et al. 2011) but also produces a wave of erosion in  
46 the captured reach (Yanites et al., 2013) that may impact divide position. Historically, migration  
47 of divides has been inferred by changes in the provenance of sediments stored in sedimentary  
48 basins (e.g. Kuhlemann et al., 2001). It is however a process that is generally very difficult to  
49 document in erosional landscapes. Recent developments have provided models and analytical  
50 approaches to identify divide migration in the landscape (Bonnet, 2009; Castelltort et al., 2012;  
51 Willett et al., 2014; Whipple et al., 2017). Among them the recently-developed  $\chi$ -[analysis of](#)  
52 longitudinal profiles of rivers (Perron and Royden, 2012) is based on the recognition of  
53 disequilibrium along river profiles, disequilibrium being defined by the departure from an ideal  
54 equilibrium shape. The application of this method to both natural and numerically-simulated  
55 landscapes, has allowed to demonstrate contrasts in the equilibrium state of rivers across divide  
56 and then to infer their migration (Willett et al., 2014). The applicability of this method is  
57 however limited to settings where the response time of rivers is larger compared to the rate of  
58 divide migration, so they can actually show disequilibrium in their longitudinal profiles  
59 (Whipple et al., 2017).

60

61 The Ebro and Duero drainage basins in the Northern Iberian Peninsula show geological and  
62 geomorphological evidence of very contrasted erosional histories during the Neogene. They  
63 initially recorded a long endorheic stage from the Early Oligocene to the Late Miocene ([Riba  
64 et al., 1983; Garcia-Castellanos et al., 2003](#)). Since then, both basins opened toward the Atlantic  
65 Ocean (Duero) or the Mediterranean Sea (Ebro). The Ebro basin's opening is reflected in the  
66 landscape by evidence of river incision (Garcia-Castellanos et al., 2003), whereas the Duero  
67 Basin does not show significant incision in its upstream part as a large relict of its endorheic

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71 morphology is preserved (Antón et al., 2012). The Duero river long profile actually shows a  
72 pronounced knickpoint (knickzone) defining an upstream domain of high mean elevation (~800  
73 m) and low relief where the sediments deposited during the endorheic stage are relatively well  
74 preserved. Then, these two adjacent basins are characterized by differences in incision and in  
75 the preservation of their endorheic stages. They thus represent an ideal natural laboratory to  
76 evaluate divide migration in response to differential post-orogenic incision. Following a  
77 presentation of the geological context, we first compile evidence of fluvial captures along the  
78 Ebro-Duero divide, based on previous studies and our own investigations, and we map the  
79 location of knickpoints and relict portions of the drainage network. We use all these  
80 observations to reconstruct a paleo-divide position and to estimate the impact of divide  
81 migration in terms of drainage area and stream power. We complement this dataset by providing  
82 a map of  $\chi$  across divide (Willett et al., 2014) to highlight potential disequilibrium state between  
83 rivers of the Ebro and Duero catchments.

84

## 85 2. Geological setting

86

### 87 2.1 The Ebro and Duero basins

88

89 The Ebro and Duero basins represent two hydrographic basins located in the northern part of  
90 the Iberian Peninsula (Fig. 1). The bedrock of the Ebro and Duero drainage basins mainly  
91 consists of Cenozoic deposits, and Mesozoic and Paleozoic rocks in their headwaters (Fig. 2).  
92 They formed once a unique foreland basin during the Cenozoic controlled by the flexural  
93 loading by the surrounding mountain belts: the Pyrenees and the Cantabrian mountains to the  
94 north (Pulgar et al., 1999), the Iberian and Central Ranges to the south (Guimerà et al., 2004;  
95 De Vicente et al., 2007), and the Catalan Coastal Range (CCR) to the east (López-Blanco et al.,  
96 2000 ; Salas et al., 2001), during collision between Iberia and Europe since the Late Cretaceous.

97

98 From the Late Cretaceous, the Ebro and Duero basins were essentially filled by clastic deposits,  
99 and opened toward the Atlantic Ocean in the Bay of Biscay (Alonso-Zarza et al., 2002). During  
100 the Late Eocene – Early Oligocene, the uplift in the Western Pyrenees (Puigdefàbregas et al.,  
101 1992) led to the closure of the Ebro and Duero basins as attested by the Ebro basin  
102 continentalization dated at ~36 Ma (Costa et al., 2010). The center of these two basins became  
103 long-lived lakes filled with lacustrine, sandy, and evaporitic deposits from the Oligocene to the  
104 Miocene (Riba et al., 1983; Alonso-Zarza et al., 2002; Pérez-Rivarés et al., 2002, 2004; Garcia-

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109 Castellanos et al, 2003; Garcia-Castellanos, 2006; Larrasoña et al., 2006; Vázquez-Urbez et  
110 al., 2013). The opening of the Ebro basin through the Catalan Coastal Range toward the  
111 Mediterranean Sea occurred during the Late Miocene, leading to kilometer-scale excavation  
112 throughout the basin (Fillon and Van der Beek, 2012; Fillon et al., 2013; Garcia-Castellanos  
113 and Larrasoña, 2015). The exact timing and processes driving the opening, as well as the  
114 role of the Messinian Salinity Crisis, have long been debated (Coney et al., 1996 (post-  
115 Messinian); Garcia-Castellanos et al., 2003 (13-8.5 Ma); Babault et al., 2006 (post-Messinian);  
116 Urgeles et al., 2010; Cameselle et al. (2014) (Serravallian-Tortonian); Garcia-Castellanos and  
117 Larrasoña, 2015 (12-7.5 Ma)). In contrast with the Ebro basin, incision in the upper Duero  
118 basin appears much less significant. The Duero basin is characterized by a low relief topography  
119 (Fig. 1) in its upstream part, at 700-800 m above sea level to the west, and at 1000-1100 m a.s.l.  
120 to the north, northeast, and to the east in the Almazan subbasin, close to the divide with the  
121 Ebro basin. The connection of the Duero River with the Atlantic Ocean occurred from the Late  
122 Miocene-Early Pliocene to the Late Pliocene-Early Pleistocene (Martín-Serrano, 1991). The  
123 current Ebro and Duero drainage networks are separated by a divide running from the  
124 Cantabrian belt to the NW, toward the SE in the Iberian Range (Figs. 1, 2, 3). In the following,  
125 we review the geological evolution of the different domains that constitute this drainage divide  
126 between the Ebro and Duero drainage basins.

127

## 128 2.2 The Iberian Range

129

130 The Iberian Range (Figs. 2, 4) is a double vergent fold-and-thrust belt resulting from Late  
131 Cretaceous inversion of Late Jurassic-Early Cretaceous rift basins during Iberia – Europe  
132 convergence (Salas et al., 2001; Guimerà et al., 2004; Martín-Chivelet et al., 2002). It is divided  
133 into two NW-SE directed branches, the Aragonese and the Castillian branches, separated by the  
134 Tertiary Almazan subbasin (Bond, 1996). The Almazan subbasin is connected to the Duero  
135 basin since the Early Miocene (Alonso-Zarza et al., 2002).

136 The Iberian Range is essentially made of marine carbonates and continental clastic sediments  
137 ranging from Late Permian to Albian, overlying a Hercynian basement. The Cameros subbasin  
138 to the NW represents a late Jurassic-Early Cretaceous trough almost exclusively filled by  
139 continental siliciclastic deposits (Martín-Chivelet et al., 2002 and references therein; Del Rio  
140 et al., 2009). Shortening in the Iberian Range occurred from the Late Cretaceous to the Early  
141 Miocene, along inherited Hercynian NW-SE structures (Gutiérrez-Elorza and Gracia, 1997;  
142 Guimerà et al., 2004; Gutiérrez-Elorza et al., 2002). The opening of the Calatayud basin in the

143 Aragonese branch occurred during the Early Miocene in response to right-lateral transpression  
144 on the southern margin of the Iberian Range (Daroca area) (Colomer and Santanach, 1988). It  
145 is followed during the Pliocene and the Pleistocene, by pulses of extension reactivating faults  
146 in the Calatayud basin, and the formation of grabens such as the Daroca, Munébraga,  
147 Gallocanta, and Jiloca grabens (Fig. 4; Colomer and Santanach, 1988; Gutiérrez-Elorza et al.,  
148 2002; Capote et al., 2002). This is also outlined by the occurrence of Late Pliocene to Early  
149 Pleistocene breccias and glaciais levels in the Daroca and Jiloca grabens (Gracia, 1992, 1993a;  
150 Gracia and Cuchi, 1993; Gutiérrez-Santolalla et al., 1996). These Neogene troughs are filled by  
151 continental deposits and pediments, up to the Quaternary (Fig. 4). The Neogene tectonic pulses  
152 in the Iberian are interrupted by periods of quiescence during which erosion surfaces developed  
153 (Gutiérrez-Elorza and Gracia, 1997).

154 Deformation and uplift of the Iberian Range and Cameros basin resulted in the development of  
155 a new drainage divide between the Duero and Ebro basins and in the isolation of the Almazan  
156 subbasin (Alonso-Zarza et al., 2002). In contrast, the connection between the Duero the Ebro  
157 basins has not been affected by significant deformation and uplift in the proto-Rioja trough  
158 (Mikes, 2010).

159

### 160 2.3 The Rioja trough and Bureba high

161

162 The Rioja trough (Figs. 2, 5) recorded important subsidence, especially during the Cenozoic (>  
163 5 km), related to compression and thrusting on its borders (Jurado and Riba, 1996). As thrusting  
164 initiated in the Pyrenean-Cantabrian belt and in the Iberian Range and Cameros basin, the Rioja  
165 trough became domain of important synorogenic sediment transfer between the Ebro and Duero  
166 basins. During the Paleocene, the Rioja trough was a marine depositional environment. With  
167 the increase of sediment fluxes that originated from the exhumation of surrounding mountain  
168 belts, sedimentation became essentially continental in the Eocene. Thrusting continued during  
169 the Oligocene resulting in the formation of an anticline connecting the Cantabrian domain and  
170 the Cameros inverted basin. This morphologic high (the Bureba anticline, Fig. 5) located in the  
171 center of the area is supposed to have triggered the disconnection between the Duero and Ebro  
172 basins (Mikes, 2010), as suggested by the repartition of alluvial fans on both sides of this  
173 structure (Muñoz-Jiménez and Casas-Sainz, 1997; Villena et al., 1996). During the Miocene,  
174 deformation ceased as evidenced by the deposition of undeformed middle Miocene to Holocene  
175 strata. The Bureba anticline is cored by Albian strata and topped by Santonian limestones and

176 Oligocene conglomerates controlling the location of the current main drainage divide between  
177 the Ebro and Duero river networks (Fig. 5).

178

#### 179 2.4 Climate evolution

180

181 Climate exerts a major control on valley incision, sediment discharge, and on the evolution of  
182 drainage networks (Willet, 1999; Garcia-Castellanos, 2006; Bonnet, 2009; Whipple, 2009;  
183 Whitfield and Harvey, 2012; Stange et al., 2014). The mean annual precipitation map for the  
184 North Iberian Peninsula (Hijmans et al., 2005) shows a similar pattern for both the Ebro and  
185 Duero basins as they record very low precipitation, associated with global subarid conditions,  
186 with the exception of the Cameros basin that record a slightly higher precipitation rate (Fig. 6).  
187 There is a strong contrast to the north, toward the Mediterranean Sea and the most elevated  
188 areas in the Cantabrian and Pyrenean belts, where precipitation drastically increases.

189 The paleoclimatic evolution from the Late Cretaceous to the Neogene is linked both with the  
190 effects of surrounding mountains uplift, and with the latitudinal variation drift of Iberia from  
191 30°N in the Cretaceous to ~40°N during Late Neogene times. The hot-humid tropical climate  
192 of the Late Cretaceous became drier and arid from the Paleocene to the Middle Miocene (López-  
193 Martínez et al., 1986), favouring the development of endorheic lakes (Garcia-Castellanos,  
194 2006). During the Middle-Late Miocene and Early Pliocene, the northern Iberia recorded more  
195 humid and seasonal conditions (Calvo et al., 1993; Alonso-Zarza and Calvo, 2000) with  
196 alternations of cold-wet and hot-dry periods (Bessais and Cravatte, 1988; Rivas-Carballo et al.,  
197 1994; Jiménez-Moreno et al., 2010). More humid and colder conditions took place in the Late  
198 Pliocene, characterized by dry glacial periods and humid interglacials (Suc and Popescu, 2005;  
199 Jiménez-Moreno et al., 2013). Climatic contrasts increased, triggering intense glaciers  
200 fluctuations in the surrounding mountain ranges during the Lower-Middle Pleistocene transition  
201 (1.4-0.8 Ma) (Moreno et al., 2012; Duval et al., 2015; Sancho et al., 2016), and throughout the  
202 Late Pleistocene period, which record glacial / interglacial oscillations, as evidenced by pollen  
203 identification (Suc and Popescu, 2005; Jiménez-Moreno et al., 2010, 2013; Barrón et al., 2016;  
204 García-Ruiz et al., 2016) and speleothem studies (Moreno et al., 2013; Bartolomé et al., 2015).  
205 Glaciers are considered as very efficient erosion tool in continental environment. They are  
206 likely to influence drainage divide migration (Brocklehurst and Whipple, 2002). There is large  
207 evidence of glaciers development especially for the Late Pleistocene in the Pyrenees (Delmas  
208 et al., 2009; Nivière et al., 2016; García-Ruiz et al., 2016), in the Cantabrian belt (Serrano et  
209 al., 2013, 2016; García-Ruiz et al., 2016), and in the Central Range (Palacios et al., 2011, 2012;

210 García-Ruiz et al., 2016). However, although numerous moraines have been mapped throughout  
211 the Iberian Range (Ortigosa, 1994; García-Ruiz et al., 1998; Pellicer and Echeverría, 2004),  
212 there is no evidence of U-shaped valleys and because of the lack of very high elevated massifs  
213 (>2500 m), the occurrence of active ice tongues are considered as limited, if not precluded  
214 (García-Ruiz et al., 2016).

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### 216 3. Evidence of divide mobility between the Duero and Ebro catchments

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218 The easternmost part of the Duero river is opposed to the Ebro tributaries that are the Jalon,  
219 Huecha, Queiles, Alama, Cidacos, Iregua, and Najerilla rivers, whereas the Arlanzon and  
220 Pisuerga rivers (Duero tributaries) are opposed to the Najerilla, Tiron, Oca, and Rudron rivers,  
221 and to the westernmost part of the Ebro river (Fig. 3). The northeastern part of the Duero basin  
222 (the easternmost Duero river, the Arlanzon and Pisuerga rivers) mainly consists of broad flat  
223 valleys characterized by low incision depth and low-gradient streams with concave longitudinal  
224 profiles (Antón et al., 2012, 2014). By contrast, the western part of the Ebro basin is  
225 characterized by more incised valleys, especially in the Cantabrian and in the Cameros – Iberian  
226 Range domains, with more complex longitudinal profiles (knickpoints, remnants of high  
227 elevated surfaces). Previous studies (Gutiérrez-Santolalla et al., 1996; Pineda, 1997; Mikes,  
228 2010) already shown that the Jalon and Homino rivers, which belong to the Ebro basin, have  
229 recently captured parts of the Duero basin in the Iberian Range and in the Rioja trough,  
230 respectively. Such evolution has been recorded by the occurrence of geomorphological markers  
231 as wind gaps and elbows of captures, as well as by the presence of knickpoints and/or remnants  
232 of high elevated surfaces in river long profiles. To highlight this dynamic evolution, we  
233 performed a morphometric analysis of rivers all around the divide separating the Ebro basin  
234 from the Duero basin, with particular attention given to the Aragonese branch of the Iberian  
235 Range (Fig. 4) and to the Rioja Trough (Fig. 5), where captures have already been described.

236 The studied basins were digitally mapped using high-resolution (~30 meters) digital elevation  
237 models (DEMs) from SRTM 1 Arc-Second Global elevation data available at the U.S.  
238 Geological Survey ([www.usgs.gov](http://www.usgs.gov)). The different DEMs were assembled using the ENVI  
239 software. We also used 1:50,000 geological maps from the Instituto Geológico y Minero de  
240 España ([www.igme.es](http://www.igme.es)). We used the TopoToolbox, a MATLAB-based software developed by  
241 Schwanghart and Scherler (2014), to extract the river network and longitudinal profiles and the  
242  $\chi$ -analysis Tool developed by Mudd et al. (2014).

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### 245 3.1 Fluvial captures and related knickpoints in the Iberian Range

246

247 Neogene tectonics in the Iberian range controlled the uplift of topographic ranges and the  
248 formation of several basins whose connection with the Ebro or the Duero has occasionally  
249 changed through time. Nowadays, the western part of the Almazan subbasin (Figs. 2, 4) belongs  
250 to the Duero catchment, its eastern part being drained by the Ebro drainage network and  
251 especially by the Jalon river and its tributaries (Fig. 4). Gutiérrez-Santolalla et al. (1996)  
252 proposed that the Jalon river captured this domain after cutting into the Mesozoic and Neogene  
253 strata and the two Paleozoic ridges of the Aragonese branch of the Iberian Range. They used

254 chronostratigraphic evidence to build a relative chronology of capture events in the Jalon area.

255 First, the incision of the northern Paleozoic ridge and capture of the Calatayud basin by the  
256 Jalon river is attributed to a post-Messinian age. The Jiloca river, the easternmost main Jalon  
257 tributary, is then thought to capture the Daroca graben area to the east during the Late Pliocene  
258 – Early Pleistocene. This is followed from the Early to Late Pleistocene by the capture of the  
259 Jiloca graben to the southeast and finally by the capture of the Munébraga graben to the  
260 southwest, by the Jalon river (Gutiérrez-Santolalla et al., 1996), toward the easternmost part of  
261 the Almazan subbasin.

262 The Jalon river and tributaries show knickpoints in their longitudinal profiles (Fig. 4), at  
263 locations that are consistent with the events of captures proposed by Gutiérrez-Santolalla et al.  
264 (1996), suggesting that these captures are actually witnessed by knickpoints. The capture of the  
265 Jiloca graben corresponds to a major knickpoint in the Jiloca river profile that appears very  
266 smoothed, and that is followed by an upstream ~50 km long flat domain preserved at ~1000 m  
267 high above sea level. This imparts a convex shape to the Jiloca profile (Fig. 4). Due to the short  
268 period of time between the formation of the Jiloca graben (the earliest glacial deposits are  
269 attributed to the Middle Pliocene) and its capture (Early Pleistocene; Gutiérrez-Santolalla et al.,  
270 1996), we suggest this upstream domain was a short-lived endorheic domain that has never  
271 been externally drained before being captured by the Ebro network. In the northwestern part of  
272 the Jiloca graben, the Cañamaria river, a tributary of the Jiloca river, heads to the northwest,  
273 reaching the Gallocanta basin, also considered as a former graben (Gracia, 1993b; Gracia et al.,  
274 1999; Gutiérrez-Elorza et al., 2002). The upstream part of its river long profile is characterized  
275 by a sharper knickpoint at the entrance of the basin, and is followed by a ~15 km long flat  
276 domain (Fig. 4). Similarly to the Jiloca graben, the Gallocanta basin appears to be a short-lived  
277 endorheic domain that has been more recently captured by the Jiloca river network.

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282 According to Gutiérrez-Santolalla et al. (1996), the Jalon river reached the southern Paleozoic  
283 ridge of the Aragonese branch, to the southwest of the Calatayud basin, captured the Munébrega  
284 graben and the Almazan subbasin (also characterized by a pronounced knickpoint) during the  
285 Pleistocene-Holocene, slightly after the capture of the Jiloca graben by the Jiloca river. This is  
286 coherent with morphological analysis of longitudinal profiles, as the major knickpoint related  
287 to the capture of the Jiloca graben appears very smoothed, whereas knickpoints observed in the  
288 west are sharper, suggesting they are younger. However, we cannot ruled out some local  
289 influence of the lithology on the shape of these knickpoints.

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

296

### 297 3.2 Fluvial captures and related knickpoints in the Rioja trough area

298

299 In the Rioja trough area, the position of the Ebro-Duero divide is partly controlled by the Bureba  
300 anticline. It consists of folded Middle Cretaceous to Early Miocene series, covered by  
301 undeformed Middle Miocene to Holocene deposits (Fig. 5). The anticline is orientated E-W to  
302 the west and NE-SW to the east. The western part of the Rioja trough to the west of the NE-SW  
303 directed branch of the Bureba anticline (Fig. 5), used to be drained toward the Duero basin since  
304 the Oligocene (Pineda, 1997; Mikes, 2010). The westward migration of the divide to its current  
305 location is thought to have occurred in several steps of captures as shown by the occurrence of  
306 remnants of escarpments during the Late Miocene - Pliocene (Mikes, 2010). Once the eastern  
307 branch of the Bureba anticline has been incised, the Ebro tributaries captured the western part  
308 of the Rioja trough, up to the E-W branch of the Bureba anticline to the southwest, from the  
309 Late Miocene to the Pliocene. The western part of the anticline forms a topographic ridge that  
310 is incised by Jordan river (Fig. 5) in a place where the divide between the Ebro and Duero river  
311 networks is located to the north of the ridge. To the East of this location however, the  
312 topographic ridge formed by the Bureba anticline controls the current location of the main  
313 drainage divide (Fig. 5). Here, the ridge exhibits several wind gaps, located on the northward  
314 prolongation of the Hoz, Rioseras, and Nava Solo rivers (Figs. 5, 7). Further east, the Diablo  
315 river does not incise the ridge and its headwater is located in the core of the eastern branch of

317 the Bureba anticline, the Fuente Valley (Fig. 5). These last streams are tributaries of the Ubierna  
318 river, which is a tributary of the Arlanzon river and so, of the Duero river. To the north, the Ebro  
319 river system is represented, from west to east, by the Homino river (a tributary of the Oca river)  
320 and its four tributaries, the Molina, the Fuente Monte, the Zorica, and the San Pedro rivers (Figs.  
321 5, 7). All these streams are outlined by Late Pleistocene to Holocene alluvial series that are  
322 deposited at the bottom of their respective valleys. Valleys from the Duero side appears larger  
323 than those from the Ebro side, which are significantly more incised.

324 The Jordan river's headwater is located north of the ridge formed by the Bureba anticline. We  
325 can continuously follow its valley deposits northward along a broadly gentle slope, up to the  
326 locality of Coraegula (Fig. 5). However, the current course of the Jordan river is cut ~8 km  
327 south, in the vicinity of Hontomin, by the Homino (Ebro) river (Figs. 5B, C, 7). This fluvial  
328 capture is characterized by a well-defined and highly incised elbow of capture, already  
329 described by Pineda (1997) and Mikes (2010). The longitudinal profile of the Homino river  
330 shows a sharp knickpoint located on Hontomin (Fig. 7C). Finally, there is a small wind gap on  
331 the divide between the two opposite rivers (Figs. 5, 7).

332 To the southeast, the headwater of the Hoz river is located to the south of a wind gap cut into  
333 the Bureba ridge (Fig. 7C). To the north, in the exact prolongation of the Hoz river, the Molina  
334 river shows a bend similar to the elbow of capture previously described for the Homino river  
335 (Fig. 7) and there is a minor knickpoint located on this elbow, according to the extracted river  
336 long profile. Thus, it is likely that the Molina river used to represent the former upper reach of  
337 the Hoz river, in a period when the Ebro-Duero divide was located northward, before being  
338 captured by the Ebro network.

339 To the east, the Rioseras and the Nava Solo rivers have also their headwater located to the South  
340 of wind gaps in the Bureba ridge (Fig. 7). Similarly, in their exact prolongations, the Fuente  
341 Monte and the Zorica rivers show important elbows of capture with minor knickpoints. They  
342 may also represent former upper reaches of Duero streams that have been captured by the Ebro  
343 network (Figs. 5, 7, 8).

344 Further east, the headwater of the Diablo river is located on the depression represented by the  
345 core of the eastern branch of the Bureba anticline, the Fuente valley. In its prolongation to the  
346 northeast, the San Pedro river incises the northeastern termination of the anticline from the  
347 north before entering the valley, leading to a southward retreat of the divide (Fig. 5). Capture is  
348 again evidenced by important incision contrast between Ebro and Duero systems, and by sharp  
349 knickpoints on the upper reach of the San Pedro river long profile when crossing the Santonian  
350 dolomites (Fig. 8). According to this whole set of observations, and in agreement with previous

351 findings of Pineda (1997) and Mikes (2010), we propose that the western part of the Rioja  
352 trough, in the Bureba area has been recently captured by the Ebro drainage network leading to  
353 a sequence of southwestward retreat of the main drainage divide, toward the Duero basin (Fig.  
354 7E).

355

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

366

367 3.3 Past position of the Ebro-Duero divide and implication for stream-power of the Duero River

368

369 We used all observations that support divide migration in the Iberian Range and Rioja trough  
370 to estimate a paleo-position of the drainage divide between the Duero and Ebro drainage basins  
371 (Fig. 9). For this purpose, we considered the location of major knickpoint along the rivers where  
372 fluvial captures are defined. Both the Ebro river and several tributaries show high elevated ~10-  
373 20 km long flat domains at ~800 – 1200 m a.s.l. and major knickpoints in the upper reach of  
374 their long profiles as the Rudron, Queiles, and Alama rivers, as well as the Homino river and  
375 its tributaries: the Puerta Nogales and Valdelanelala rivers (Figs. 5, 8; Fig. S1). All these flat  
376 domains may not be related to surface uplift as they are not clearly associated with active  
377 tectonic features. The Duero basin being characterized by a high mean elevation (~1000 m) and  
378 by a very limited incision in the vicinity of the Ebro/Duero drainage divide, a sudden divide  
379 migration toward the Duero basin is then expected to isolate such high elevated and relatively  
380 preserved surfaces. We suggest these flat domains have been recently captured by Ebro  
381 tributaries, and represent remnants of Duero drainage areas, integrated into the Ebro catchment  
382 from divide retreat toward the Duero basin. Overall, we consider a paleodrainage divide  
383 delimited by these high-elevated knickpoints and flat domains, except for the Jiloca graben area  
384 to the southeast, characterized by the occurrence of short-lived endorheic domains (Fig. 9).

385 Incision in the Ebro basin leads to the capture of new drainage areas, whereas the Duero basin  
386 recorded important loss of its own surface. The present day drainage area of the Cenozoic Duero  
387 basin, upstream of the major knickzone observed to the west in the Iberian Massif is ~63000  
388 km<sup>2</sup>. We used the paleo-divide position shown in Figure 9 to define a « recent » captured area  
389 that used to belong to the Duero basin. This area represents ~7700 km<sup>2</sup>, which corresponds to  
390 ~12% of the present-day Cenozoic Duero basin drainage area. Such a reduction of the drainage  
391 area could have strong implications on the evolution of the Duero basin, as important lowering  
392 of water and sediment fluxes, and so of incision throughout the basin. To better resolve the  
393 impact of such drainage area reduction on incision capacity, we perform a stream power analysis  
394 of the Duero river. We consider the specific stream power,  $\omega$ , defined as  $\omega = \rho g Q S / W$ , where  
395  $\rho$  is water density,  $g$  is gravitational acceleration,  $Q$  is discharge,  $S$  is local river gradient, and  
396  $W$  is river width (see the Supplement for details of the calculation). We calculate  $\omega$  for the  
397 present-day Duero river, and for a restored ancient Duero river that drained this 12% of lost  
398 area. We plot the difference (ancient – present day) between the two curves in Figure 10, with  
399 the Duero river long profile. Calculated difference in specific stream power values are relatively  
400 low (< 2 W m<sup>-2</sup>) for the upstream part of the basin, but increase to ~5 W m<sup>-2</sup> when approaching  
401 the major knickzone at a distance of ~350 km from the river mouth. The knickzone is  
402 characterized by peak values exceeding 10 W m<sup>-2</sup>, which rapidly decrease to ~0 W m<sup>-2</sup> at the  
403 base of the knickzone (~200 km) and up to the river mouth (Fig. 10). Some alternating peak  
404 and null values are observed in the lower reach of the river and may be related to the occurrence  
405 of numerous dams along the river. Overall, the specific stream power calculated for the ancient  
406 Duero river show higher values than for the present day from the base of the knickzone to the  
407 uppermost reach of the river (Fig. 10). This implies a general decrease of the Duero river's  
408 incision capacity between this ancient state to the present day, magnified on the knickzone.

409

#### 410 3.4 $\chi$ map

411

412 The comparison of the shape of longitudinal profiles of rivers across divide is a way that has  
413 been proposed recently to infer disequilibrium between rivers and the potential migration of  
414 their divide (Willett et al., 2014). [The  \$\chi\$ -analysis of river profiles \(Perron and Royden, 2012\)](#)  
415 is a powerful tool to evidence differences in the equilibrium state of rivers across divide, and  
416 then to infer their migration (Willett et al., 2014). [This method is based on a coordinate](#)  
417 transformation allowing linearizing river profiles [\(Perron and Royden, 2012\)](#). Considering

**Supprimé:** Although the slope-area analysis of channel profiles (e.g. Whipple and Tucker, 1999; Kirby and Whipple, 2012)

**Supprimé:** potentially

**Supprimé:** , 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-area data. To avoid slope measurements,

**Supprimé:** Perron and Royden (2012) proposed a procedure

429 constant uplift rate (U) and erodibility (K) in time and space the  $\chi$ -transformed profile of a river  
430 is defined by the following equation (Perron and Royden, 2012; Mudd et al., 2014):

431

$$432 \quad z(x) = z_b(x_b) + \left(\frac{U}{KA_0^m}\right)^{1/n} \chi$$

433

434 with

$$435 \quad \chi = \int_{x_b}^x \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx$$

436 where  $z(x)$  is the elevation of the channel,  $x$  is the longitudinal distance,  $z_b$  is the elevation at  
437 the river's base level (distance  $x_b$ ),  $A$  is the drainage area,  $A_0$  is a reference drainage area, and  
438 exponents  $m$  and  $n$  are empirical constants.

439

440 When using the  $\chi$  variable instead of the distance for plotting the elevation  $z$  along channel, ( $\chi$ -  
441 plot), the longitudinal profile of a steady-state channel is shown as a straight line (Perron and  
442 Royden, 2012). Any channel pulled away from this line is in disequilibrium and is then expected  
443 to attempt to reach equilibrium. Mapping  $\chi$  on several watersheds and comparing  $\chi$  across  
444 drainage divides is then a potential way to high disequilibrium between rivers across divide and  
445 to elucidate divide migration and drainage reorganization through captures (Willett et al., 2014).

446 We used the  $\chi$ -analysis Tool developed by Mudd et al. (2014) to select the best  $m/n$  ratio by  
447 iteration (Perron and Royden, 2012) and to calculate  $\chi$  for rivers throughout the divide between  
448 the Ebro and Duero basins from a similar base level at 850 m a.s.l. The best mean  $m/n$  ratio for  
449 all our streams is 0.425, which falls in the typical range of values observed for rivers (~0.4 –  
450 0.6: e.g. Kirby and Whipple, 2012). The resulting map (Fig. 11) shows  $\chi$  values calculated on  
451 different opposite streams in the vicinity of the Ebro/Duero drainage divide. Similar values on  
452 both sides of the divide suggest the two opposite streams are at equilibrium, whereas strong  
453 contrasted  $\chi$  values imply disequilibrium leading to divide migration, continuously or through  
454 fluvial capture, toward the high  $\chi$  values (Willett et al., 2014). The map of  $\chi$  values actually  
455 shows significant contrasting values across the Ebro/Duero divide. We comment here these  
456 contrasts along the divide from the SE to the NW of the area considered (Fig. 11).

457 There is a strong contrast in  $\chi$  values between the headwater of the Jalon river (Fig. 11),  
458 characterized by low values (~300 m), and the closest part from the divide of the Bordecorex  
459 river (Fig. 4), a tributary of the Duero river (~500 m). Such a disequilibrium implies divide  
460 migration toward the Duero basin, predicting the capture of the uppermost reach of the

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462 Bordecorex river by the Jalon river. To the north, tributaries of the Jalon river show slightly  
463 lower  $\chi$  values than the tributaries of the Duero river. This suggests a relative stable situation  
464 although small captures may occur toward the Duero basin. A higher contrast is observed  
465 around the easternmost part of the Duero basin, which is surrounded by the Ebro basin. The  
466 Araviana river (tributary of the Duero river) seems to be taken in a bottleneck between the  
467 Manubles river to the south and the Queiles river to the north (Fig. 4), which both show lower  
468  $\chi$  values (Fig. 11). Toward the east, there is a strongest  $\chi$  values contrast between headwaters  
469 of the Araviana river (>700 m) and of the Isuela (Jalon tributary) and Huecha rivers (<100 m).  
470 This domain appears clearly in disequilibrium and is expected to be captured by the Ebro  
471 drainage network. Such high  $\chi$  values differences appear also to the northwest (Fig. 11), in the  
472 southern part of the Cameros basin where the Duero river and its tributaries' headwaters show  
473  $\chi$  values >500-700 m, whereas the facing rivers (Alama, Cidacos, Iregua, and Najerilla) are all  
474 characterized by low  $\chi$  values <100 m. This predicts important disequilibrium and divide  
475 migration and fluvial captures toward the south. Northwestward,  $\chi$  values between Duero and  
476 Ebro network are more similar indicating that the divide is relatively more stable here, up to the  
477 westernmost part of the Ebro basin (Fig. 11). However, there are some slight localized  $\chi$  value  
478 contrasts (~200 / ~450 m) as observed between the Tiron and the Arlanzon rivers, between the  
479 Rudron and the Ubierna and Urbel rivers, and between the Ebro and the Pisuergra rivers (Fig.  
480 11). It suggests minor local captures toward the Duero basin.

481

482 To sum up,  $\chi$  values calculated in the vicinity of the drainage divide between the Ebro and  
483 Duero river networks show a general disequilibrium (Fig. 11) as the Ebro network is  
484 characterized by low  $\chi$  values (up to ~200-300 m) compared to those for the Duero network  
485 (up to ~450-700 m). In complement with all the evidence of divide displacements induced by  
486 captures described previously this allows predicting a general divide migration toward the  
487 Duero basin through headwater retreat, in favor of the Ebro tributaries, especially around the  
488 Almazan subbasin, which is expected to be entirely captured by the Ebro basin.

489

#### 490 **4. Discussion**

491

##### 492 4.1 Long term trend of divide migration

493

494 The oldest capture evidence in our study area corresponds to the incision of the northern part  
495 of the Iberian Range by the Jalon river and by the capture of the Calatayud basin, attributed to  
496 the post-Messinian (Gutiérrez-Santolalla et al. 1996). We propose, based on morphological  
497 evidence (Fig. 4) and in agreement with stratigraphic data (Gutiérrez-Santolalla et al. 1996),  
498 that the Jalon river system captured the Jiloca graben to the east since the Early Pleistocene,  
499 before progressively capturing the Almazan subbasin toward the west in the Holocene  
500 (Gutiérrez-Santolalla et al. 1996). From  $\chi$ -analysis (Fig. 11), we deduce that the eastern part of  
501 the Duero basin, the Almazan subbasin, is being actively captured by Ebro tributaries that  
502 drained the Iberian Range and the Cameros basin. Despite low contrasts in  $\chi$  values, local  
503 captures are also suggested in the vicinity of the Ebro / Duero drainage divide toward the  
504 northwest. Capture is further implied by the occurrence of numerous high elevated (~1000 m)  
505 knickpoints and low-relief surfaces (Figs. 5, 8, 9, 11).

506 Thus, there is a good correlation between  $\chi$  [evidence](#) and morphological and stratigraphic data  
507 implying long-lasting captures and divide migration during Pliocene, Pleistocene, and  
508 Holocene times in favor of the Ebro basin.

509  
510 The pursuit of such a long-term capture trend may be driven by tectonic and/or climatic forcing  
511 (Willett, 1999; Montgomery et al., 2001; Sobel et al., 2003; Sobel and Strecker, 2003; Bonnet,  
512 2009; Whipple, 2009; Castellort et al., 2012; Kirby and Whipple, 2012; Goren et al., 2015; Van  
513 der Beek et al., 2016). However, such long-term trend in drainage reorganization may also occur  
514 in tectonically quiescent domains, independently of external forcing (Prince et al., 2011). Here,  
515 the Iberian Range and the Cameros basin recorded extension pulses from the Late Miocene to  
516 the Early Pleistocene, responsible for the formation of several grabens as previously described  
517 (Gutiérrez-Santolalla et al., 1996; Capote et al., 2002). Extension events are also recorded  
518 during the Holocene, nevertheless, the youngest erosion surface of Late Pliocene-Early  
519 Pleistocene age observed in our study area shows no tectonic-related deformation and  
520 reworking, suggesting that tectonic activity is reduced here (Gutiérrez-Elorza and Gracia,  
521 1997). This is also consistent with the relative scarcity of seismic activity observed in our study  
522 area, compared, for instance, to the Pyrenees, or to the Betics (Herraiz et al., 2000; Lacan and  
523 Ortuño, 2012). We consequently propose that local tectonic activity is not the main driver of  
524 the capture histories documented here, as most capture events postdate the cessation of tectonic  
525 activity, and occur during periods of quiescence (Gutiérrez-Santolalla et al., 1996).

526

Supprimé: predictions

528 The Cameros Massif is characterized by relatively high mean annual precipitation up to ~1000  
529 mm/an (Fig. 6) with high elevation (~1400-2200 m) in comparison with the surrounding areas.  
530 This contrasts with the adjacent Ebro and Duero basins where low precipitation rates, of ~400-  
531 500 mm/an (Hijmans et al., 2005), illustrate subarid climate conditions. The Cameros area is  
532 the only place in our study area where a contrast in precipitation pattern (Fig. 6) would  
533 potentially drive a migration of the divide toward the drier, Duero area. Given that the same  
534 pattern is observed everywhere, even where there isn't any precipitation difference, we suggest  
535 that the present day climatic condition is unlikely to control the general pattern of current  
536 drainage reorganization between the Ebro and Duero basins. During the Pliocene and the  
537 Pleistocene, the climatic record in the northern Iberia Peninsula is characterized by alternations  
538 between similar subarid conditions and intense glaciation. [Paleoclimate proxies do not allow to](#)  
539 [highlight past precipitation differences along the divide that could explain past drainage](#)  
540 [reorganization. Moreover, there is no clear evidence of important glacier development and](#)  
541 related erosion in our study area, especially for the Cameros basin and the Iberian Range  
542 (Ortigosa, 1994; García-Ruiz et al., 1998, 2016; Pellicer and Echeverría, 2004). This indicates  
543 that drainage evolution between the Ebro and Duero basins is unlikely to be related to climatic  
544 evolution.

545

546 4.2 Excavation of the Ebro basin as the main factor controlling divide migration and limiting  
547 incision of the Duero river

548

549 A striking morphological feature for river capture in our study area is the important contrast in  
550 the incision pattern (e.g. Fig. 1B) from one side of the divide to the other. This suggests that the  
551 incision capacity of the river network is the main driver for capture and divide migration. Both  
552 tectonic and climatic forcing does not appear to control drainage reorganization between the  
553 Ebro and Duero basins.

554 The opening of the Ebro basin toward the Mediterranean Sea during the Late Miocene led to  
555 widespread excavation (García-Castellanos et al., 2003, García-Castellanos and Larrasoña,  
556 2015), favored by more humid and seasonal climatic conditions (Calvo et al., 1993; Alonso-  
557 Zarza and Calvo, 2000). By contrast, incision related to the opening of the Duero basin toward  
558 the Atlantic Ocean is concentrated to the west in the Iberian Massif, characterized by a  
559 largescale knickzone (150 km long and 500 m high) in the Duero river long profile (Fig. 1B).  
560 This contrasts with the limited eastward propagation of incision in the Cenozoic part of the  
561 basin (Antón et al., 2012, 2014), despite climatic conditions similar to the Ebro basin. An

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563 explanation resides in the fact that the resistant Iberian Massif basement rocks may have  
564 controlled and limited incision and drainage reorganization in the Cenozoic Duero basin (Antón  
565 et al., 2012). The Duero profile upstream of this major knickzone may be considered as a high  
566 elevated local base level for its tributaries there. Difference between the Ebro and Duero base-  
567 levels implies a major contrast in fluvial dynamics. We suggest the systematic and long-term  
568 trend of divide migration toward the Duero basin and fluvial capture in favor of the Ebro basin  
569 is driven by the differential incision behavior, controlled by base-level difference.

570 Our stream power analysis along the Duero river (Fig. 10) shows that the difference in drainage  
571 area of the Duero inferred from our paleo-divide map (Fig. 9) induces a noticeable decrease of  
572 stream power values of the Duero in the vicinity of the knickzone. This stream power is a  
573 minimum estimate because calculation does not take into account possible captures and divide  
574 migration in other areas along the Duero basin divide, nor the full history of the divide migration  
575 through time and the related ongoing decrease in water discharge as documented in laboratory-  
576 scale landscape experiments (Bonnet, 2009). Some contrasts of incision are also observed in  
577 the Iberian Range along the southern border of the Duero, and in the Cantabrian domain to the  
578 North. Both show more important incision than in the Duero basin, suggesting potential river  
579 captures and divide migration at the expense of the Duero basin, increasing the total of lost  
580 drainage area. Even if it gives minimal estimate, our stream power analysis suggests that  
581 drainage area reduction may have limited the erosion in the Duero basin. This provides an  
582 explanation for the preservation of the lithologic barrier to the west, along the main knickzone  
583 of the Duero considered as an intermediate, local base level (Antón et al., 2012). We propose  
584 that the reduction of the Duero drainage area caused by captures and incision in the Ebro basin,  
585 is responsible for a significant decrease of the incision capacity in the Duero basin. We infer  
586 that the ongoing drainage network growth in the Ebro basin may be responsible for the current  
587 preservation of large morphological relicts of the-endorheic stage in the Duero basin.

588 The opening of the Ebro basin toward the Mediterranean Sea resulted in a drastic base level  
589 drop. This results in the establishment of an upstream-migrating incision wave that propagates  
590 to every tributary of the Ebro network, responsible for knickpoints migration (Schumm et al.,  
591 1987; Whipple and Tucker, 1999; Yanites et al., 2013) and for drainage reorganization and  
592 divide migration. The  $\chi$ -analysis that we performed along the current Ebro-Duero divide (Fig.  
593 11) highlights areas where geomorphic disequilibrium is still ongoing, which suggests that they  
594 are areas where divide is currently mobile. The modelling study performed by Garcia-  
595 Castellanos and Larrasoña (2015) suggests that the re-opening of the Ebro basin occurred  
596 between 12.0 and 7.5 Ma. This indicates that the growth of the drainage network of the Ebro

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598 basin and the establishment of new steady-state conditions is a long-lived phenomenon, which  
599 is still not achieved today.

600

## 601 **Conclusion**

602

603 In this paper we present a morphometric analysis of the landscape along the divide between the  
604 Ebro and Duero drainage basins located in the northern part of the Iberian Peninsula. This area  
605 shows numerous evidence of river captures by the Ebro drainage network resulting in a long-  
606 lasting migration of their divide, toward the Duero basin. Although these two basins record a  
607 similar geological history, with a long endorheic stage during Oligocene and Miocene times,  
608 they show a very contrasted incision and preservation state of their original endorheic  
609 morphology. Since the Late Miocene, the Ebro basin was opened to the Mediterranean Sea and  
610 record important erosion. On the opposite, the Duero was opened to the Atlantic Ocean since  
611 the Late Miocene – Early Pliocene but its longitudinal profile exhibits a pronounced knickpoint,  
612 which delimits an upstream domain of low relief and limited incision, likely representing a  
613 relict of its endorheic topography. We propose that this contrast of incision is the main driver  
614 of the migration of divide that we document. The morphological analysis of rivers across the  
615 divide highlights areas where geomorphic disequilibrium is still ongoing, which suggests that  
616 the Ebro-Duero divide is currently mobile. The quantification of the decrease of the drainage  
617 area of the Duero based on the reconstruction of a paleo-position of the Ebro-Duero divide  
618 shows that the divide migration results in a significant lowering of the stream power of the  
619 Duero river, particularly along its knickzone. We suggest that divide migration induces a  
620 decrease of the incision capacity of the Duero river, thus favoring the preservation of large  
621 relicts of the endorheic morphology in the upstream part of this basin.

622

623

## 624 **Author contributions**

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

627

628

## 629 **Competing interests.**

630 The authors declare that they have no conflict of interest.

631

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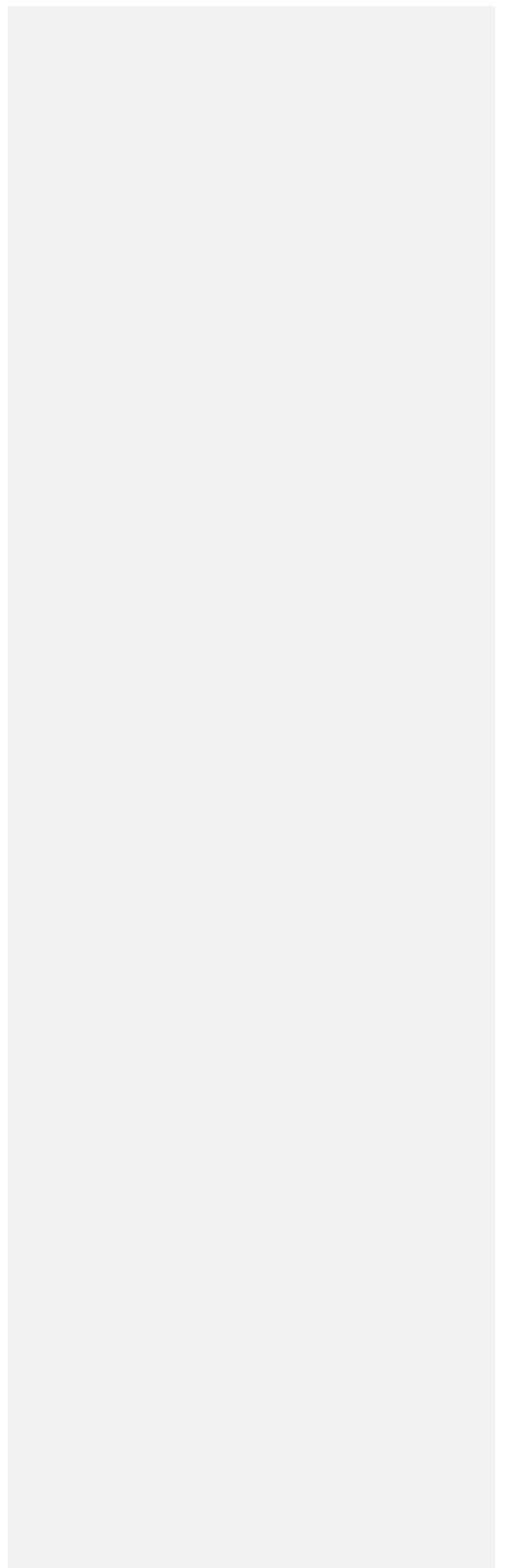


Figure captions:

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 in 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 (data from Hijmans et al., 2005).

Figure 7: A) 3D view of the DEM of the Bureba sector showing important contrast of incision between the Ebro and Duero basins across their divide (red dashed line) and river capture evidence (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) Wind gaps cut into the Bureba anticline (see location on Fig. 7A). 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 evidence of river capture. Colors are given to rivers that are linked in these capture processes.



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: Duero river long profile (black line) and difference in the specific stream power of the river (grey) calculated by considering the paleo and present-day position of its divide. Positive values suggest a significant diminution of the incision capacity of the Duero river, particularly along the knickzone of its longitudinal profile. Details on calculation are available in the Supplement (Section S1).

Figure 11: Topographic map with  $\chi$  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.

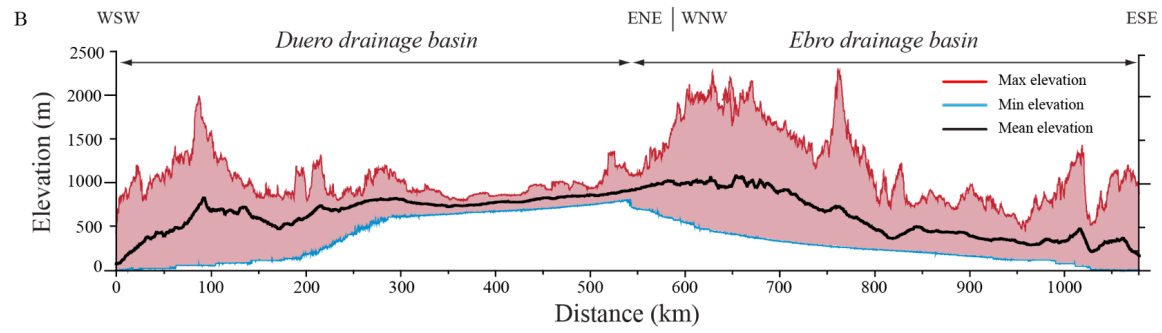
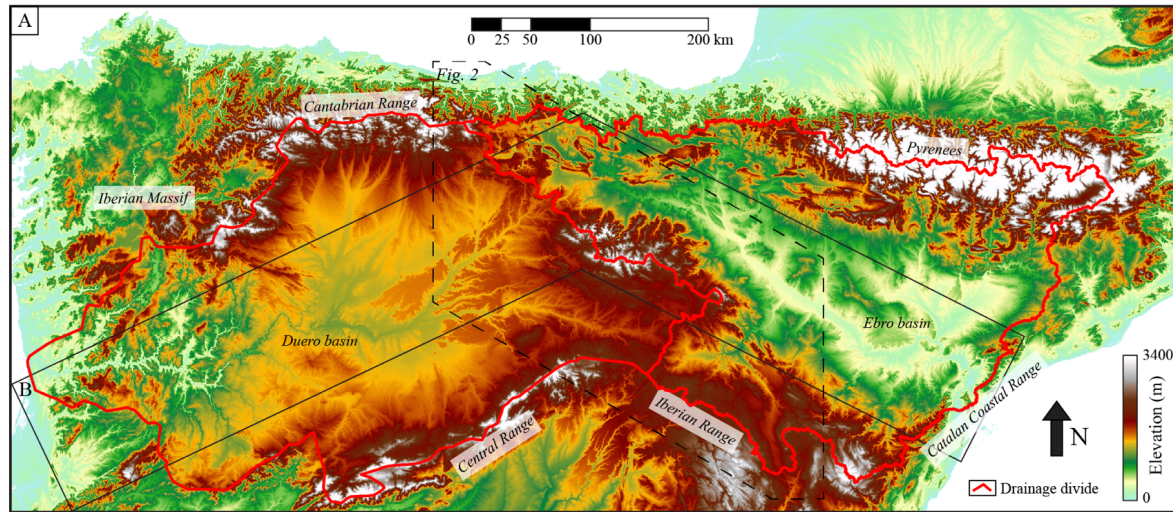


Figure 1

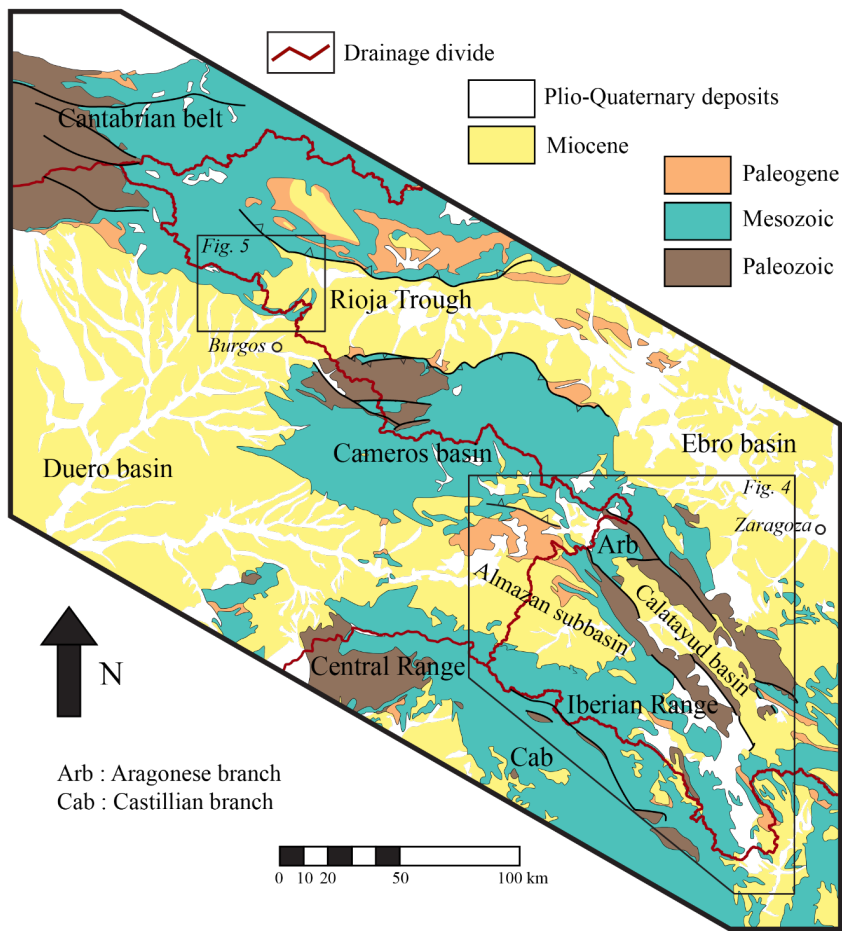


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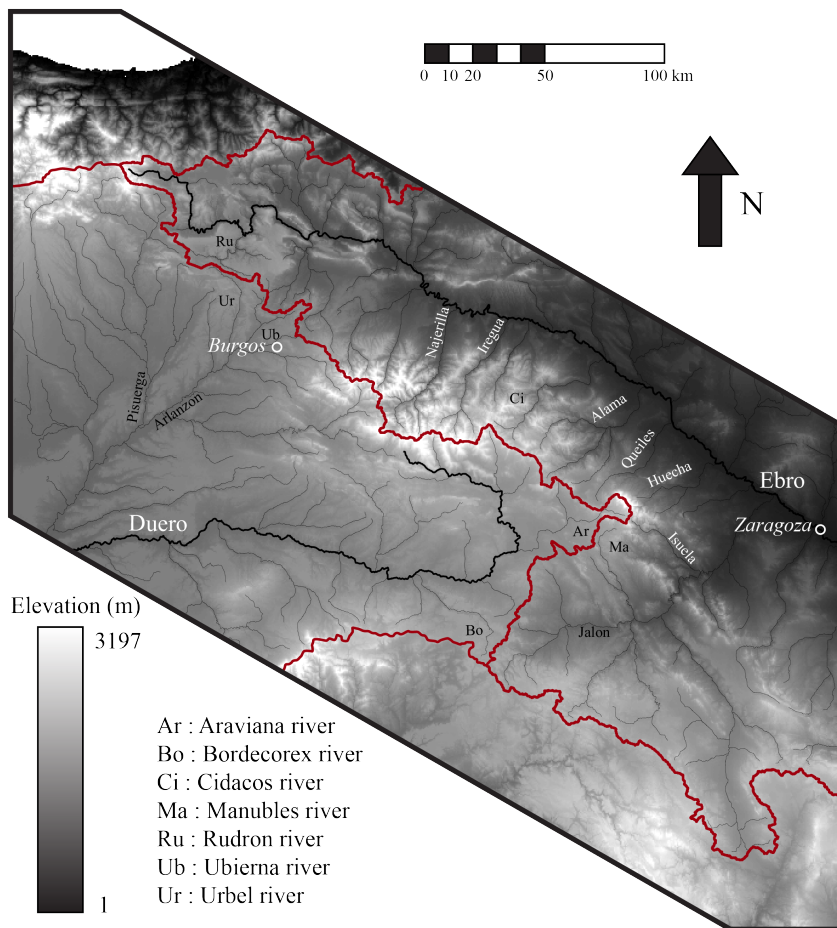


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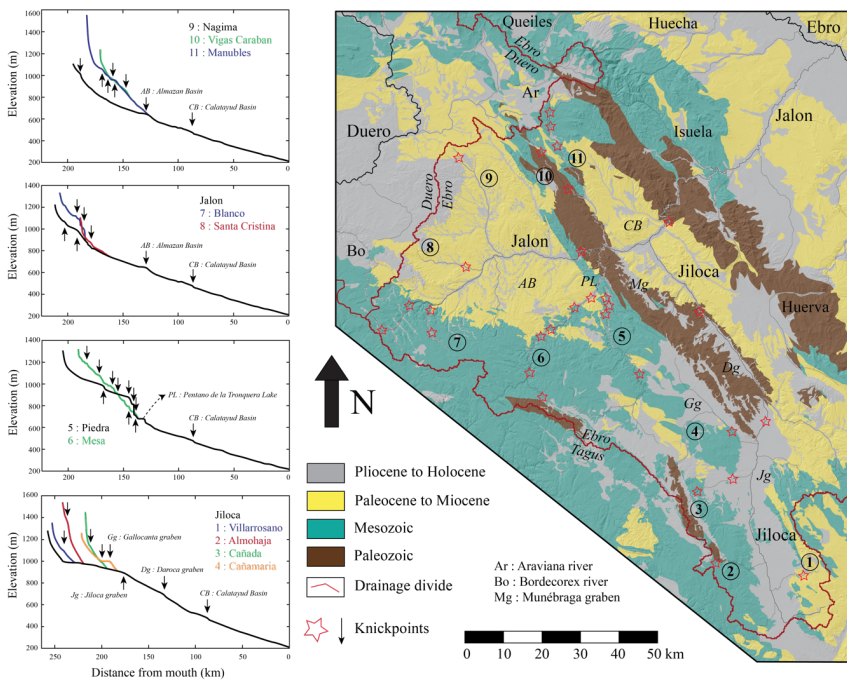


Figure 4

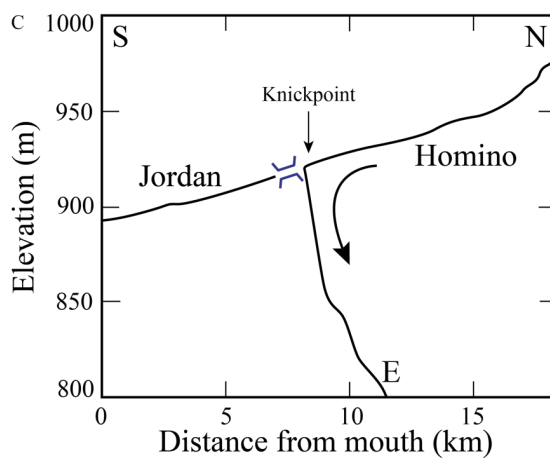
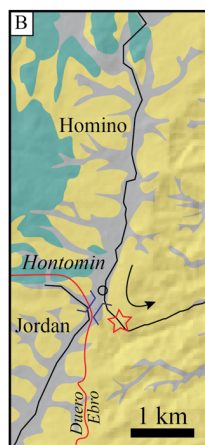
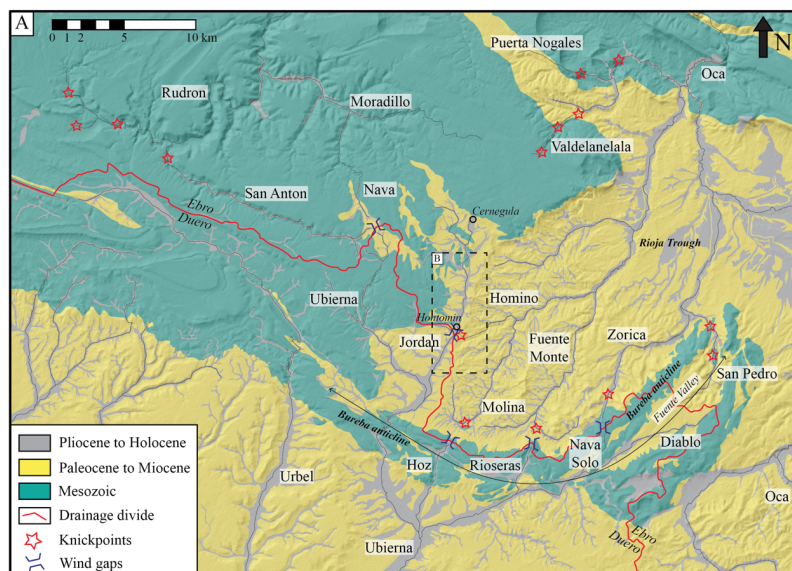


Figure 5

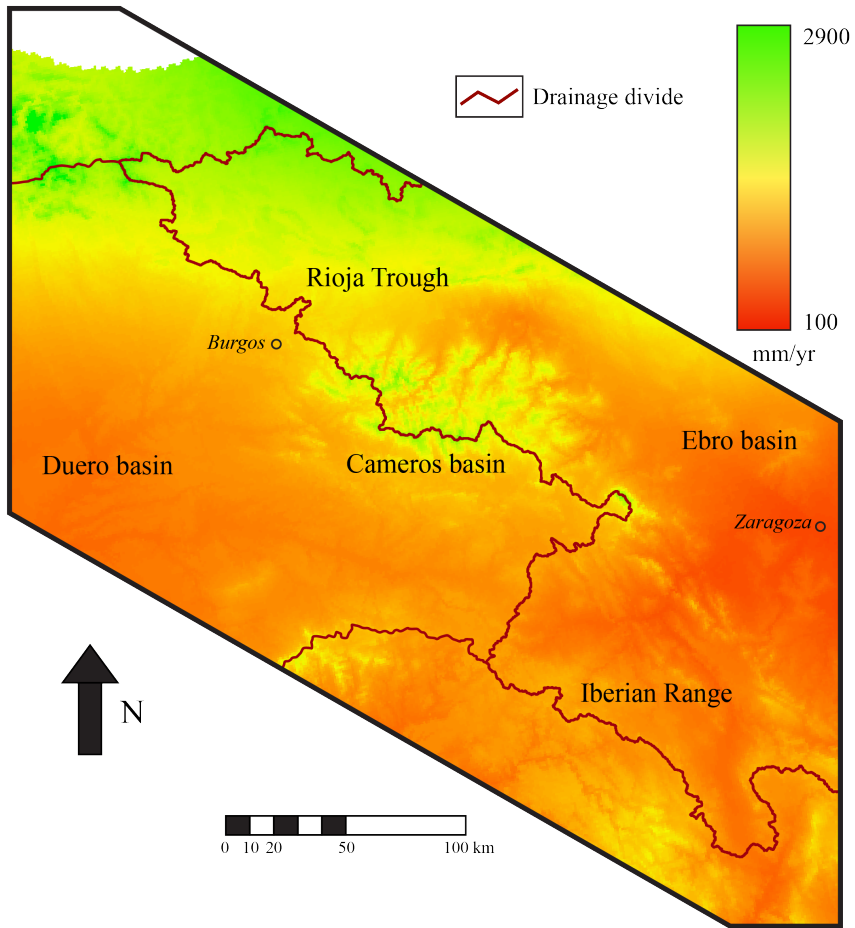


Figure 6

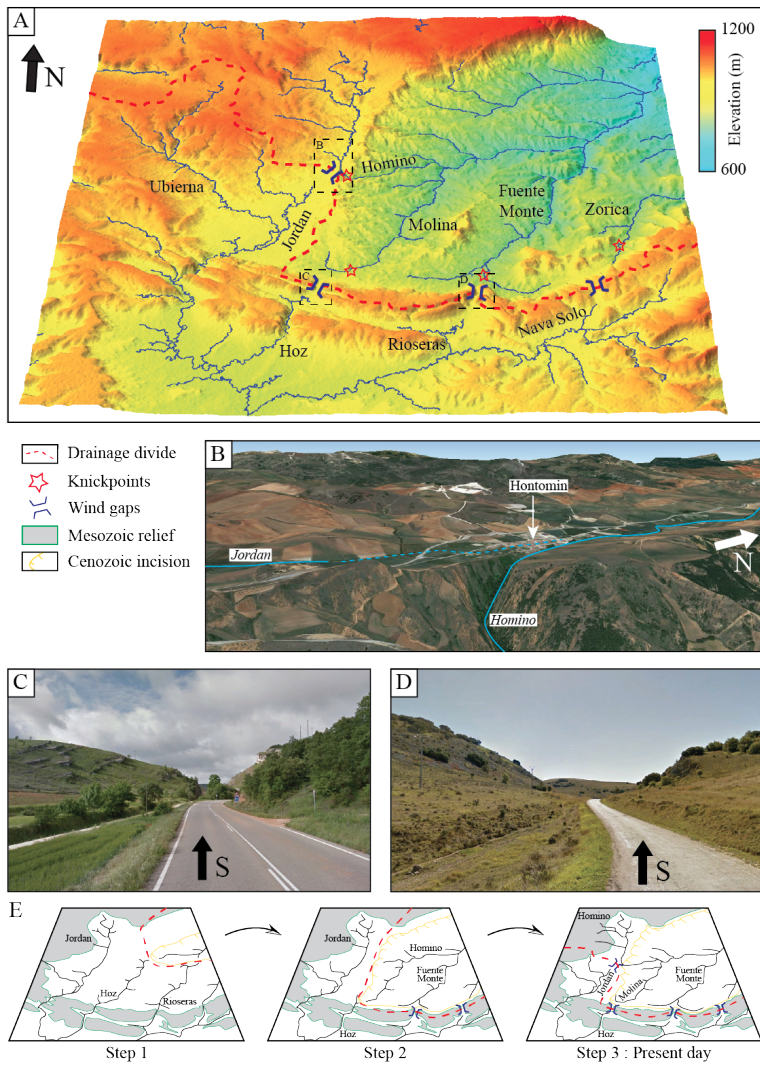


Figure 7



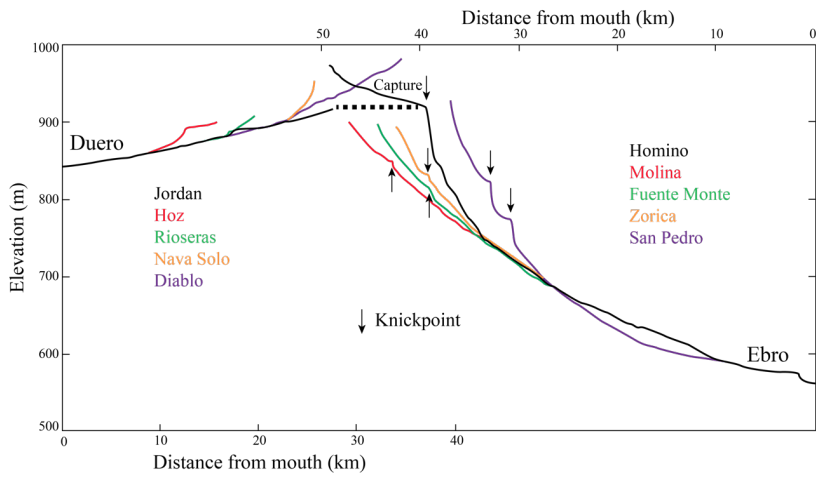


Figure 8

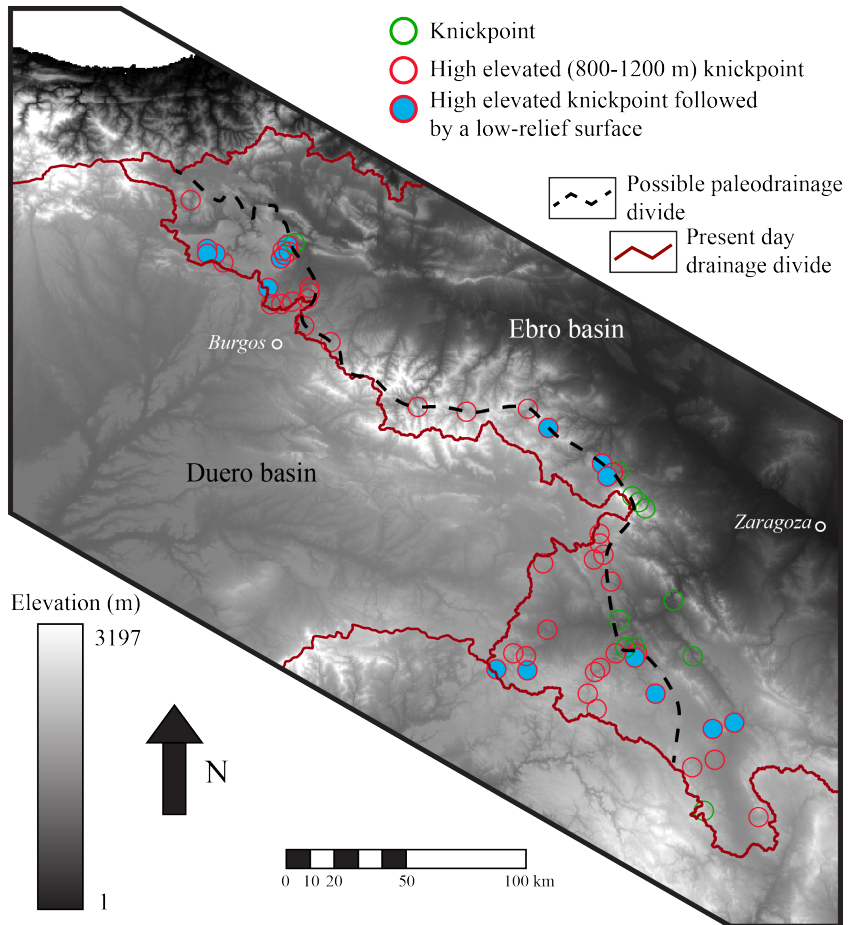


Figure 9

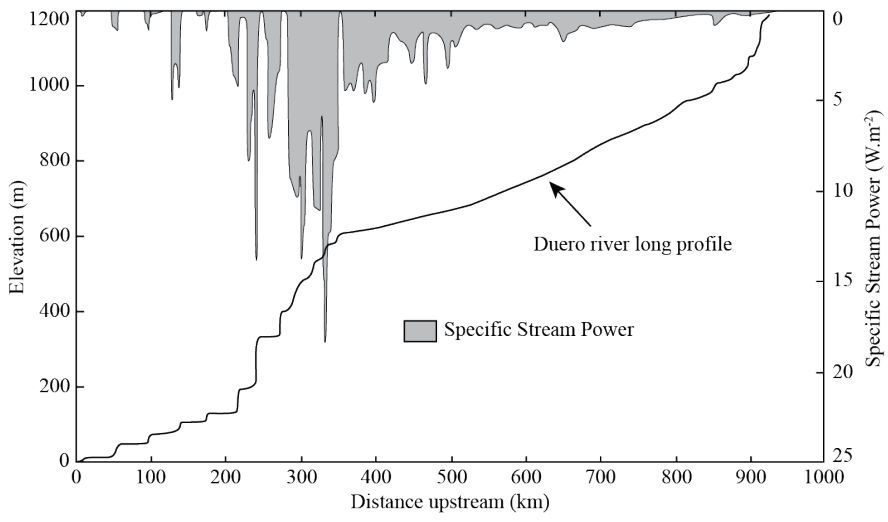


Figure 10

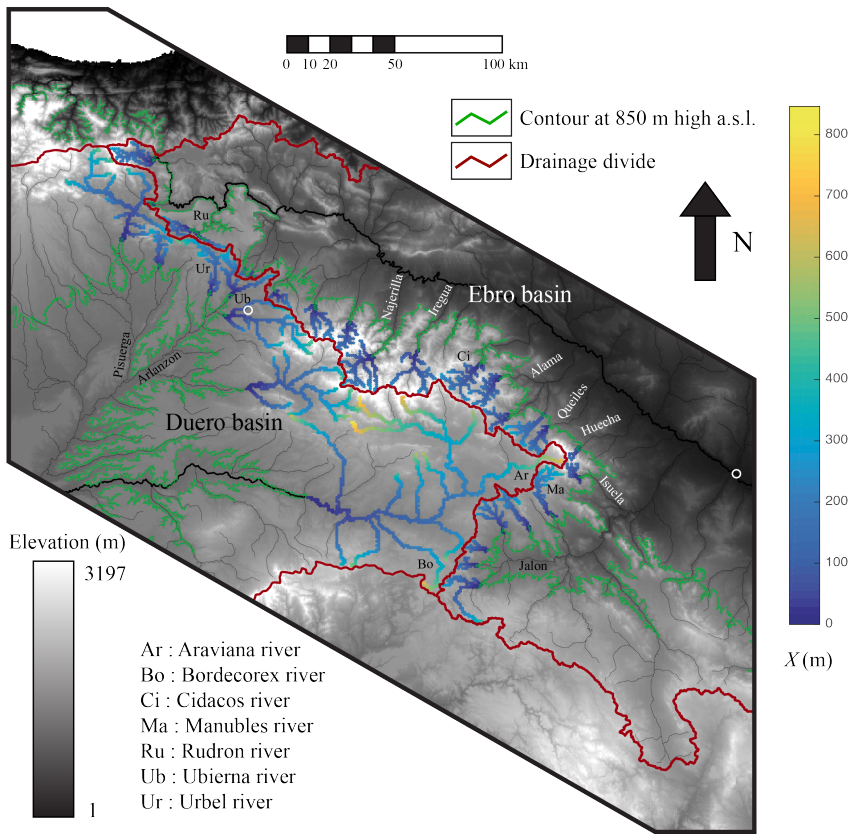


Figure 11

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

3  
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5  
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10  
11 **Abstract**

12  
13 Intracontinental endorheic basins are key elements of source-to-sink systems as they preserve  
14 sediments eroded from the surrounding catchments. Drainage reorganization in such a basin in  
15 response to changing boundary conditions has strong implications on the sediment routing  
16 system and on landscape evolution. The Ebro and Duero basins represent two foreland basins,  
17 which developed in response to the growth of surrounding compressional orogens, the Pyrenees  
18 and the Cantabrian mountains to the north, the Iberian Ranges to the south, and the Catalan  
19 Coastal Range to the east. They were once connected as endorheic basins in the early Oligocene.  
20 By the end of the Miocene, new post-orogenic conditions led to the current setting in which the  
21 Ebro and Duero basins are flowing in opposite directions, towards the Mediterranean Sea and  
22 the Atlantic Ocean. Although these two hydrographic basins recorded a similar history, they are  
23 characterized by very different morphologic features. The Ebro basin is highly excavated,  
24 whereas relicts of the endorheic stage are very well preserved in the Duero basin. The  
25 contrasting morphological preservation of the endorheic stage represents an ideal natural  
26 laboratory to study the drivers (internal / external) of post-orogenic drainage divide mobility,  
27 drainage network and landscape evolution. To that aim, we use field and map observations and  
28 we apply the  $\chi$ -analysis of river profiles along the divide between the Ebro and Duero drainage  
29 basins. We show here that the contrasting excavation of the Ebro and Duero basins drives a  
30 reorganization of their drainage network through a series of captures, which resulted in the  
31 southwestward migration of their main drainage divide. Fluvial captures have strong impact on  
32 drainage areas, fluxes, and so on their respective incision capacity. We conclude that drainage  
33 reorganization driven by the capture of the Duero rivers by the Ebro drainage system explains

34 the first-order preservation of endorheic stage remnants in the Duero basin, due to drainage area  
35 loss, independently from tectonics and climate.

36

## 37 **1. Introduction**

38

39 Landscapes subjected to contrasted erosion rates between adjacent drainage basins show a  
40 migration of their drainage divide toward the area of lower erosion rates (Bonnet, 2009; Willett  
41 et al., 2014). This is the case for mountain ranges characterized by gradients in precipitation  
42 rates due to orography, once landscapes are in a transient state and are not adjusted to  
43 precipitation differences (Bonnet, 2009). It also occurs when drainage reorganized in response  
44 to capture (Yanites et al., 2013; Willett et al., 2014). River capture actually drives a drop in the  
45 spatial position location of drainage divide (Prince et al. 2011) but also produces a wave of  
46 erosion in the captured reach (Yanites et al., 2013) that may impact divide position. Historically,  
47 migration of divides has been inferred by changes in the provenance of sediments stored in  
48 sedimentary basins (e.g. Kuhlemann et al., 2001). It is however a process that is generally very  
49 difficult to document in erosional landscapes. Recent developments have provided models and  
50 analytical approaches to identify divide migration in the landscape (Bonnet, 2009; Castellort  
51 et al., 2012; Willett et al., 2014; Whipple et al., 2017). Among them the recently-developed  $\chi$ -  
52 analysis of longitudinal profiles of rivers (Perron and Royden, 2012) is based on the recognition  
53 of disequilibrium along river profiles, disequilibrium being defined by the departure from an  
54 ideal equilibrium shape. The application of this method to both natural and numerically-  
55 simulated landscapes, has allowed to demonstrate contrasts in the equilibrium state of rivers  
56 across divide and then to infer their migration (Willett et al., 2014). The applicability of this  
57 method is however limited to settings where the response time of rivers is larger compared to  
58 the rate of divide migration, so they can actually show disequilibrium in their longitudinal  
59 profiles (Whipple et al., 2017).

60

61 The Ebro and Duero drainage basins in the Northern Iberian Peninsula show geological and  
62 geomorphological evidence of very contrasted erosional histories during the Neogene. They  
63 initially recorded a long endorheic stage from the Early Oligocene to the Late Miocene (Riba  
64 et al., 1983; Garcia-Castellanos et al., 2003). Since then, both basins opened toward the Atlantic  
65 Ocean (Duero) or the Mediterranean Sea (Ebro). The Ebro basin's opening is reflected in the  
66 landscape by evidence of river incision (Garcia-Castellanos et al., 2003), whereas the Duero  
67 Basin does not show significant incision in its upstream part as a large relict of its endorheic

68 morphology is preserved (Antón et al., 2012). The Duero river long profile actually shows a  
69 pronounced knickpoint (knickzone) defining an upstream domain of high mean elevation (~800  
70 m) and low relief where the sediments deposited during the endorheic stage are relatively well  
71 preserved. Then, these two adjacent basins are characterized by differences in incision and in  
72 the preservation of their endorheic stages. They thus represent an ideal natural laboratory to  
73 evaluate divide migration in response to differential post-orogenic incision. Following a  
74 presentation of the geological context, we first compile evidence of fluvial captures along the  
75 Ebro-Duero divide, based on previous studies and our own investigations, and we map the  
76 location of knickpoints and relict portions of the drainage network. We use all these  
77 observations to reconstruct a paleo-divide position and to estimate the impact of divide  
78 migration in terms of drainage area and stream power. We complement this dataset by providing  
79 a map of  $\chi$  across divide (Willett et al., 2014) to highlight potential disequilibrium state between  
80 rivers of the Ebro and Duero catchments.

81

## 82 **2. Geological setting**

83

### 84 2.1 The Ebro and Duero basins

85

86 The Ebro and Duero basins represent two hydrographic basins located in the northern part of  
87 the Iberian Peninsula (Fig. 1). The bedrock of the Ebro and Duero drainage basins mainly  
88 consists of Cenozoic deposits, and Mesozoic and Paleozoic rocks in their headwaters (Fig. 2).  
89 They formed once a unique foreland basin during the Cenozoic controlled by the flexural  
90 loading by the surrounding mountain belts: the Pyrenees and the Cantabrian mountains to the  
91 north (Pulgar et al., 1999), the Iberian and Central Ranges to the south (Guimerà et al., 2004;  
92 De Vicente et al., 2007), and the Catalan Coastal Range (CCR) to the east (López-Blanco et al.,  
93 2000 ; Salas et al., 2001), during collision between Iberia and Europe since the Late Cretaceous.

94

95 From the Late Cretaceous, the Ebro and Duero basins were essentially filled by clastic deposits,  
96 and opened toward the Atlantic Ocean in the Bay of Biscay (Alonso-Zarza et al., 2002). During  
97 the Late Eocene – Early Oligocene, the uplift in the Western Pyrenees (Puigdefàbregas et al.,  
98 1992) led to the closure of the Ebro and Duero basins as attested by the Ebro basin  
99 continentalization dated at ~36 Ma (Costa et al., 2010). The center of these two basins became  
100 long-lived lakes filled with lacustrine, sandy, and evaporitic deposits from the Oligocene to the  
101 Miocene (Riba et al., 1983; Alonso-Zarza et al., 2002; Pérez-Rivarés et al., 2002, 2004; Garcia-

102 Castellanos et al, 2003; Garcia-Castellanos, 2006; Larrasoña et al., 2006; Vázquez-Urbez et  
103 al., 2013). The opening of the Ebro basin through the Catalan Coastal Range toward the  
104 Mediterranean Sea occurred during the Late Miocene, leading to kilometer-scale excavation  
105 throughout the basin (Fillon and Van der Beek, 2012; Fillon et al., 2013; Garcia-Castellanos  
106 and Larrasoña, 2015). The exact timing and processes driving the opening, as well as the  
107 role of the Messinian Salinity Crisis, have long been debated (Coney et al., 1996 (post-  
108 Messinian); Garcia-Castellanos et al., 2003 (13-8.5 Ma); Babault et al., 2006 (post-Messinian);  
109 Urgeles et al., 2010; Cameselle et al. (2014) (Serravallian-Tortonian); Garcia-Castellanos and  
110 Larrasoña, 2015 (12-7.5 Ma)). In contrast with the Ebro basin, incision in the upper Duero  
111 basin appears much less significant. The Duero basin is characterized by a low relief topography  
112 (Fig. 1) in its upstream part, at 700-800 m above sea level to the west, and at 1000-1100 m a.s.l.  
113 to the north, northeast, and to the east in the Almazan subbasin, close to the divide with the  
114 Ebro basin. The connection of the Duero River with the Atlantic Ocean occurred from the Late  
115 Miocene-Early Pliocene to the Late Pliocene-Early Pleistocene (Martín-Serrano, 1991). The  
116 current Ebro and Duero drainage networks are separated by a divide running from the  
117 Cantabrian belt to the NW, toward the SE in the Iberian Range (Figs. 1, 2, 3). In the following,  
118 we review the geological evolution of the different domains that constitute this drainage divide  
119 between the Ebro and Duero drainage basins.

120

## 121 2.2 The Iberian Range

122

123 The Iberian Range (Figs. 2, 4) is a double vergent fold-and-thrust belt resulting from Late  
124 Cretaceous inversion of Late Jurassic-Early Cretaceous rift basins during Iberia – Europe  
125 convergence (Salas et al., 2001; Guimerà et al., 2004; Martín-Chivelet et al., 2002). It is divided  
126 into two NW-SE directed branches, the Aragonese and the Castillian branches, separated by the  
127 Tertiary Almazan subbasin (Bond, 1996). The Almazan subbasin is connected to the Duero  
128 basin since the Early Miocene (Alonso-Zarza et al., 2002).

129 The Iberian Range is essentially made of marine carbonates and continental clastic sediments  
130 ranging from Late Permian to Albian, overlying a Hercynian basement. The Cameros subbasin  
131 to the NW represents a late Jurassic-Early Cretaceous trough almost exclusively filled by  
132 continental siliciclastic deposits (Martín-Chivelet et al., 2002 and references therein; Del Rio  
133 et al., 2009). Shortening in the Iberian Range occurred from the Late Cretaceous to the Early  
134 Miocene, along inherited Hercynian NW-SE structures (Gutiérrez-Elorza and Gracia, 1997;  
135 Guimerà et al., 2004; Gutiérrez-Elorza et al., 2002). The opening of the Calatayud basin in the



136 Aragonese branch occurred during the Early Miocene in response to right-lateral transpression  
137 on the southern margin of the Iberian Range (Daroca area) (Colomer and Santanach, 1988). It  
138 is followed during the Pliocene and the Pleistocene, by pulses of extension reactivating faults  
139 in the Calatayud basin, and the formation of grabens such as the Daroca, Munébraga,  
140 Gallocanta, and Jiloca grabens (Fig. 4; Colomer and Santanach, 1988; Gutiérrez-Elorza et al.,  
141 2002; Capote et al., 2002). This is also outlined by the occurrence of Late Pliocene to Early  
142 Pleistocene breccias and glaciais levels in the Daroca and Jiloca grabens (Gracia, 1992, 1993a;  
143 Gracia and Cuchi, 1993; Gutiérrez-Santolalla et al., 1996). These Neogene troughs are filled by  
144 continental deposits and pediments, up to the Quaternary (Fig. 4). The Neogene tectonic pulses  
145 in the Iberian are interrupted by periods of quiescence during which erosion surfaces developed  
146 (Gutiérrez-Elorza and Gracia, 1997).

147 Deformation and uplift of the Iberian Range and Cameros basin resulted in the development of  
148 a new drainage divide between the Duero and Ebro basins and in the isolation of the Almazan  
149 subbasin (Alonso-Zarza et al., 2002). In contrast, the connection between the Duero the Ebro  
150 basins has not been affected by significant deformation and uplift in the proto-Rioja trough  
151 (Mikes, 2010).

152

### 153 2.3 The Rioja trough and Bureba high

154

155 The Rioja trough (Figs. 2, 5) recorded important subsidence, especially during the Cenozoic (>  
156 5 km), related to compression and thrusting on its borders (Jurado and Riba, 1996). As thrusting  
157 initiated in the Pyrenean-Cantabrian belt and in the Iberian Range and Cameros basin, the Rioja  
158 trough became domain of important synorogenic sediment transfer between the Ebro and Duero  
159 basins. During the Paleocene, the Rioja trough was a marine depositional environment. With  
160 the increase of sediment fluxes that originated from the exhumation of surrounding mountain  
161 belts, sedimentation became essentially continental in the Eocene. Thrusting continued during  
162 the Oligocene resulting in the formation of an anticline connecting the Cantabrian domain and  
163 the Cameros inverted basin. This morphologic high (the Bureba anticline, Fig. 5) located in the  
164 center of the area is supposed to have triggered the disconnection between the Duero and Ebro  
165 basins (Mikes, 2010), as suggested by the repartition of alluvial fans on both sides of this  
166 structure (Muñoz-Jiménez and Casas-Sainz, 1997; Villena et al., 1996). During the Miocene,  
167 deformation ceased as evidenced by the deposition of undeformed middle Miocene to Holocene  
168 strata. The Bureba anticline is cored by Albian strata and topped by Santonian limestones and

169 Oligocene conglomerates controlling the location of the current main drainage divide between  
170 the Ebro and Duero river networks (Fig. 5).

171

#### 172 2.4 Climate evolution

173

174 Climate exerts a major control on valley incision, sediment discharge, and on the evolution of  
175 drainage networks (Willet, 1999; Garcia-Castellanos, 2006; Bonnet, 2009; Whipple, 2009;  
176 Whitfield and Harvey, 2012; Stange et al., 2014). The mean annual precipitation map for the  
177 North Iberian Peninsula (Hijmans et al., 2005) shows a similar pattern for both the Ebro and  
178 Duero basins as they record very low precipitation, associated with global subarid conditions,  
179 with the exception of the Cameros basin that record a slightly higher precipitation rate (Fig. 6).

180 There is a strong contrast to the north, toward the Mediterranean Sea and the most elevated  
181 areas in the Cantabrian and Pyrenean belts, where precipitation drastically increases.

182 The paleoclimatic evolution from the Late Cretaceous to the Neogene is linked both with the  
183 effects of surrounding mountains uplift, and with the latitudinal variation drift of Iberia from  
184 30°N in the Cretaceous to ~40°N during Late Neogene times. The hot-humid tropical climate  
185 of the Late Cretaceous became drier and arid from the Paleocene to the Middle Miocene (López-  
186 Martínez et al., 1986), favouring the development of endorheic lakes (Garcia-Castellanos,  
187 2006). During the Middle-Late Miocene and Early Pliocene, the northern Iberia recorded more  
188 humid and seasonal conditions (Calvo et al., 1993; Alonso-Zarza and Calvo, 2000) with  
189 alternations of cold-wet and hot-dry periods (Bessais and Cravatte, 1988; Rivas-Carballo et al.,  
190 1994; Jiménez-Moreno et al., 2010). More humid and colder conditions took place in the Late  
191 Pliocene, characterized by dry glacial periods and humid interglacials (Suc and Popescu, 2005;  
192 Jiménez-Moreno et al., 2013). Climatic contrasts increased, triggering intense glaciers  
193 fluctuations in the surrounding mountain ranges during the Lower-Middle Pleistocene transition  
194 (1.4-0.8 Ma) (Moreno et al., 2012; Duval et al., 2015; Sancho et al., 2016), and throughout the  
195 Late Pleistocene period, which record glacial / interglacial oscillations, as evidenced by pollen  
196 identification (Suc and Popescu, 2005; Jiménez-Moreno et al., 2010, 2013; Barrón et al., 2016;  
197 García-Ruiz et al., 2016) and speleothem studies (Moreno et al., 2013; Bartolomé et al., 2015).  
198 Glaciers are considered as very efficient erosion tool in continental environment. They are  
199 likely to influence drainage divide migration (Brocklehurst and Whipple, 2002). There is large  
200 evidence of glaciers development especially for the Late Pleistocene in the Pyrenees (Delmas  
201 et al., 2009; Nivière et al., 2016; García-Ruiz et al., 2016), in the Cantabrian belt (Serrano et  
202 al., 2013, 2016; García-Ruiz et al., 2016), and in the Central Range (Palacios et al., 2011, 2012;

203 García-Ruiz et al., 2016). However, although numerous moraines have been mapped throughout  
204 the Iberian Range (Ortigosa, 1994; García-Ruiz et al., 1998; Pellicer and Echeverría, 2004),  
205 there is no evidence of U-shaped valleys and because of the lack of very high elevated massifs  
206 (>2500 m), the occurrence of active ice tongues are considered as limited, if not precluded  
207 (García-Ruiz et al., 2016).

208

### 209 **3. Evidence of divide mobility between the Duero and Ebro catchments**

210

211 The easternmost part of the Duero river is opposed to the Ebro tributaries that are the Jalon,  
212 Huecha, Queiles, Alama, Cidacos, Iregua, and Najerilla rivers, whereas the Arlanzon and  
213 Pisuerga rivers (Duero tributaries) are opposed to the Najerilla, Tiron, Oca, and Rudron rivers,  
214 and to the westernmost part of the Ebro river (Fig. 3). The northeastern part of the Duero basin  
215 (the easternmost Duero river, the Arlanzon and Pisuerga rivers) mainly consists of broad flat  
216 valleys characterized by low incision depth and low-gradient streams with concave longitudinal  
217 profiles (Antón et al., 2012, 2014). By contrast, the western part of the Ebro basin is  
218 characterized by more incised valleys, especially in the Cantabrian and in the Cameros – Iberian  
219 Range domains, with more complex longitudinal profiles (knickpoints, remnants of high  
220 elevated surfaces). Previous studies (Gutiérrez-Santolalla et al., 1996; Pineda, 1997; Mikes,  
221 2010) already shown that the Jalon and Homino rivers, which belong to the Ebro basin, have  
222 recently captured parts of the Duero basin in the Iberian Range and in the Rioja trough,  
223 respectively. Such evolution has been recorded by the occurrence of geomorphological markers  
224 as wind gaps and elbows of captures, as well as by the presence of knickpoints and/or remnants  
225 of high elevated surfaces in river long profiles. To highlight this dynamic evolution, we  
226 performed a morphometric analysis of rivers all around the divide separating the Ebro basin  
227 from the Duero basin, with particular attention given to the Aragonese branch of the Iberian  
228 Range (Fig. 4) and to the Rioja Trough (Fig. 5), where captures have already been described.

229 The studied basins were digitally mapped using high-resolution (~30 meters) digital elevation  
230 models (DEMs) from SRTM 1 Arc-Second Global elevation data available at the U.S.  
231 Geological Survey ([www.usgs.gov](http://www.usgs.gov)). The different DEMs were assembled using the ENVI  
232 software. We also used 1:50,000 geological maps from the Instituto Geológico y Minero de  
233 España ([www.igme.es](http://www.igme.es)). We used the TopoToolbox, a MATLAB-based software developed by  
234 Schwanghart and Scherler (2014), to extract the river network and longitudinal profiles and the  
235  $\chi$ -analysis Tool developed by Mudd et al. (2014).

236

### 237 3.1 Fluvial captures and related knickpoints in the Iberian Range

238

239 Neogene tectonics in the Iberian range controlled the uplift of topographic ranges and the  
240 formation of several basins whose connection with the Ebro or the Duero has occasionally  
241 changed through time. Nowadays, the western part of the Almazan subbasin (Figs. 2, 4) belongs  
242 to the Duero catchment, its eastern part being drained by the Ebro drainage network and  
243 especially by the Jalon river and its tributaries (Fig. 4). Gutiérrez-Santolalla et al. (1996)  
244 proposed that the Jalon river captured this domain after cutting into the Mesozoic and Neogene  
245 strata and the two Paleozoic ridges of the Aragonese branch of the Iberian Range. They used  
246 chronostratigraphic evidence to build a relative chronology of capture events in the Jalon area.  
247 First, the incision of the northern Paleozoic ridge and capture of the Calatayud basin by the  
248 Jalon river is attributed to a post-Messinian age. The Jiloca river, the easternmost main Jalon  
249 tributary, is then thought to capture the Daroca graben area to the east during the Late Pliocene  
250 – Early Pleistocene. This is followed from the Early to Late Pleistocene by the capture of the  
251 Jiloca graben to the southeast and finally by the capture of the Munébraga graben to the  
252 southwest, by the Jalon river (Gutiérrez-Santolalla et al., 1996), toward the easternmost part of  
253 the Almazan subbasin.

254 The Jalon river and tributaries show knickpoints in their longitudinal profiles (Fig. 4), at  
255 locations that are consistent with the events of captures proposed by Gutiérrez-Santolalla et al.  
256 (1996), suggesting that these captures are actually witnessed by knickpoints. The capture of the  
257 Jiloca graben corresponds to a major knickpoint in the Jiloca river profile that appears very  
258 smoothed, and that is followed by an upstream ~50 km long flat domain preserved at ~1000 m  
259 high above sea level. This imparts a convex shape to the Jiloca profile (Fig. 4). Due to the short  
260 period of time between the formation of the Jiloca graben (the earliest glacial deposits are  
261 attributed to the Middle Pliocene) and its capture (Early Pleistocene; Gutiérrez-Santolalla et al.,  
262 1996), we suggest this upstream domain was a short-lived endorheic domain that has never  
263 been externally drained before being captured by the Ebro network. In the northwestern part of  
264 the Jiloca graben, the Cañamaria river, a tributary of the Jiloca river, heads to the northwest,  
265 reaching the Gallocanta basin, also considered as a former graben (Gracia, 1993b; Gracia et al.,  
266 1999; Gutiérrez-Elorza et al., 2002). The upstream part of its river long profile is characterized  
267 by a sharper knickpoint at the entrance of the basin, and is followed by a ~15 km long flat  
268 domain (Fig. 4). Similarly to the Jiloca graben, the Gallocanta basin appears to be a short-lived  
269 endorheic domain that has been more recently captured by the Jiloca river network.

270 According to Gutiérrez-Santolalla et al. (1996), the Jalon river reached the southern Paleozoic  
271 ridge of the Aragonese branch, to the southwest of the Calatayud basin, captured the Munébrega  
272 graben and the Almazan subbasin (also characterized by a pronounced knickpoint) during the  
273 Pleistocene-Holocene, slightly after the capture of the Jiloca graben by the Jiloca river. This is  
274 coherent with morphological analysis of longitudinal profiles, as the major knickpoint related  
275 to the capture of the Jiloca graben appears very smoothed, whereas knickpoints observed in the  
276 west are sharper, suggesting they are younger. However we cannot ruled out some local  
277 influence of the lithology on the shape of these knickpoints.

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

284

### 285 3.2 Fluvial captures and related knickpoints in the Rioja trough area

286

287 In the Rioja trough area, the position of the Ebro-Duero divide is partly controlled by the Bureba  
288 anticline. It consists of folded Middle Cretaceous to Early Miocene series, covered by  
289 undeformed Middle Miocene to Holocene deposits (Fig. 5). The anticline is orientated E-W to  
290 the west and NE-SW to the east. The western part of the Rioja trough to the west of the NE-SW  
291 directed branch of the Bureba anticline (Fig. 5), used to be drained toward the Duero basin since  
292 the Oligocene (Pineda, 1997; Mikes, 2010). The westward migration of the divide to its current  
293 location is thought to have occurred in several steps of captures as shown by the occurrence of  
294 remnants of escarpments during the Late Miocene - Pliocene (Mikes, 2010). Once the eastern  
295 branch of the Bureba anticline has been incised, the Ebro tributaries captured the western part  
296 of the Rioja trough, up to the E-W branch of the Bureba anticline to the southwest, from the  
297 Late Miocene to the Pliocene. The western part of the anticline forms a topographic ridge that  
298 is incised by Jordan river (Fig. 5) in a place where the divide between the Ebro and Duero river  
299 networks is located to the north of the ridge. To the East of this location however, the  
300 topographic ridge formed by the Bureba antcline controls the current location of the main  
301 drainage divide (Fig. 5). Here, the ridge exhibits several wind gaps, located on the northward  
302 prolongation of the Hoz, Rioseras, and Nava Solo rivers (Figs. 5, 7). Further east, the Diablo  
303 river does not incise the ridge and its headwater is located in the core of the eastern branch of

304 the Bureba anticline, the Fuente Valley (Fig. 5). These last streams are tributaries of the Ubierna  
305 river, which is a tributary of the Arlanzon river and so, of the Duero river. To the north, the Ebro  
306 river system is represented, from west to east, by the Homino river (a tributary of the Oca river)  
307 and its four tributaries, the Molina, the Fuente Monte, the Zorica, and the San Pedro rivers (Figs.  
308 5, 7). All these streams are outlined by Late Pleistocene to Holocene alluvial series that are  
309 deposited at the bottom of their respective valleys. Valleys from the Duero side appears larger  
310 than those from the Ebro side, which are significantly more incised.

311 The Jordan river's headwater is located north of the ridge formed by the Bureba anticline. We  
312 can continuously follow its valley deposits northward along a broadly gentle slope, up to the  
313 locality of Coraegula (Fig. 5). However, the current course of the Jordan river is cut ~8 km  
314 south, in the vicinity of Hontomin, by the Homino (Ebro) river (Figs. 5B, C, 7). This fluvial  
315 capture is characterized by a well-defined and highly incised elbow of capture, already  
316 described by Pineda (1997) and Mikes (2010). The longitudinal profile of the Homino river  
317 shows a sharp knickpoint located on Hontomin (Fig. 7C). Finally, there is a small wind gap on  
318 the divide between the two opposite rivers (Figs. 5, 7).

319 To the southeast, the headwater of the Hoz river is located to the south of a wind gap cut into  
320 the Bureba ridge (Fig. 7C). To the north, in the exact prolongation of the Hoz river, the Molina  
321 river shows a bend similar to the elbow of capture previously described for the Homino river  
322 (Fig. 7) and there is a minor knickpoint located on this elbow, according to the extracted river  
323 long profile. Thus, it is likely that the Molina river used to represent the former upper reach of  
324 the Hoz river, in a period when the Ebro-Duero divide was located northward, before being  
325 captured by the Ebro network.

326 To the east, the Rioseras and the Nava Solo rivers have also their headwater located to the South  
327 of wind gaps in the Bureba ridge (Fig. 7). Similarly, in their exact prolongations, the Fuente  
328 Monte and the Zorica rivers show important elbows of capture with minor knickpoints. They  
329 may also represent former upper reaches of Duero streams that have been captured by the Ebro  
330 network (Figs. 5, 7, 8).

331 Further east, the headwater of the Diablo river is located on the depression represented by the  
332 core of the eastern branch of the Bureba anticline, the Fuente valley. In its prolongation to the  
333 northeast, the San Pedro river incises the northeastern termination of the anticline from the  
334 north before entering the valley, leading to a southward retreat of the divide (Fig. 5). Capture is  
335 again evidenced by important incision contrast between Ebro and Duero systems, and by sharp  
336 knickpoints on the upper reach of the San Pedro river long profile when crossing the Santonian  
337 dolomites (Fig. 8). According to this whole set of observations, and in agreement with previous

338 findings of Pineda (1997) and Mikes (2010), we propose that the western part of the Rioja  
339 trough, in the Bureba area has been recently captured by the Ebro drainage network leading to  
340 a sequence of southwestward retreat of the main drainage divide, toward the Duero basin (Fig.  
341 7E).

342

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

353

### 354 3.3 Past position of the Ebro-Duero divide and implication for stream-power of the Duero River

355

356 We used all observations that support divide migration in the Iberian Range and Rioja trough  
357 to estimate a paleo-position of the drainage divide between the Duero and Ebro drainage basins  
358 (Fig. 9). For this purpose, we considered the location of major knickpoint along the rivers where  
359 fluvial captures are defined. Both the Ebro river and several tributaries show high elevated ~10-  
360 20 km long flat domains at ~800 – 1200 m a.s.l. and major knickpoints in the upper reach of  
361 their long profiles as the Rudron, Queiles, and Alama rivers, as well as the Homino river and  
362 its tributaries: the Puerta Nogales and Valdelanelala rivers (Figs. 5, 8; Fig. S1). All these flat  
363 domains may not be related to surface uplift as they are not clearly associated with active  
364 tectonic features. The Duero basin being characterized by a high mean elevation (~1000 m) and  
365 by a very limited incision in the vicinity of the Ebro/Duero drainage divide, a sudden divide  
366 migration toward the Duero basin is then expected to isolate such high elevated and relatively  
367 preserved surfaces. We suggest these flat domains have been recently captured by Ebro  
368 tributaries, and represent remnants of Duero drainage areas, integrated into the Ebro catchment  
369 from divide retreat toward the Duero basin. Overall, we consider a paleodrainage divide  
370 delimited by these high-elevated knickpoints and flat domains, except for the Jiloca graben area  
371 to the southeast, characterized by the occurrence of short-lived endorheic domains (Fig. 9).

372 Incision in the Ebro basin leads to the capture of new drainage areas, whereas the Duero basin  
373 recorded important loss of its own surface. The present day drainage area of the Cenozoic Duero  
374 basin, upstream of the major knickzone observed to the west in the Iberian Massif is ~63000  
375 km<sup>2</sup>. We used the paleo-divide position shown in Figure 9 to define a « recent » captured area  
376 that used to belong to the Duero basin. This area represents ~7700 km<sup>2</sup>, which corresponds to  
377 ~12% of the present-day Cenozoic Duero basin drainage area. Such a reduction of the drainage  
378 area could have strong implications on the evolution of the Duero basin, as important lowering  
379 of water and sediment fluxes, and so of incision throughout the basin. To better resolve the  
380 impact of such drainage area reduction on incision capacity, we perform a stream power analysis  
381 of the Duero river. We consider the specific stream power,  $\omega$ , defined as  $\omega = \rho g Q S / W$ , where  
382  $\rho$  is water density,  $g$  is gravitational acceleration,  $Q$  is discharge,  $S$  is local river gradient, and  
383  $W$  is river width (see the Supplement for details of the calculation). We calculate  $\omega$  for the  
384 present-day Duero river, and for a restored ancient Duero river that drained this 12% of lost  
385 area. We plot the difference (ancient – present day) between the two curves in Figure 10, with  
386 the Duero river long profile. Calculated difference in specific stream power values are relatively  
387 low (< 2 W m<sup>-2</sup>) for the upstream part of the basin, but increase to ~5 W m<sup>-2</sup> when approaching  
388 the major knickzone at a distance of ~350 km from the river mouth. The knickzone is  
389 characterized by peak values exceeding 10 W m<sup>-2</sup>, which rapidly decrease to ~0 W m<sup>-2</sup> at the  
390 base of the knickzone (~200 km) and up to the river mouth (Fig. 10). Some alternating peak  
391 and null values are observed in the lower reach of the river and may be related to the occurrence  
392 of numerous dams along the river. Overall, the specific stream power calculated for the ancient  
393 Duero river show higher values than for the present day from the base of the knickzone to the  
394 uppermost reach of the river (Fig. 10). This implies a general decrease of the Duero river's  
395 incision capacity between this ancient state to the present day, magnified on the knickzone.

396

#### 397 3.4 $\chi$ map

398

399 The comparison of the shape of longitudinal profiles of rivers across divide is a way that has  
400 been proposed recently to infer disequilibrium between rivers and the potential migration of  
401 their divide (Willett et al., 2014). The  $\chi$ -analysis of river profiles (Perron and Royden, 2012) is  
402 a powerful tool to evidence differences in the equilibrium state of rivers across divide, and then  
403 to infer their migration (Willett et al., 2014). This method is based on a coordinate  
404 transformation allowing linearizing river profiles (Perron and Royden, 2012). Considering



405 constant uplift rate (U) and erodibility (K) in time and space the  $\chi$ -transformed profile of a river  
406 is defined by the following equation (Perron and Royden, 2012; Mudd et al., 2014):

407

$$408 \quad z(x) = z_b(x_b) + \left(\frac{U}{KA_0^m}\right)^{1/n} \chi$$

409

410 with

$$411 \quad \chi = \int_{x_b}^x \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx$$

412 where  $z(x)$  is the elevation of the channel,  $x$  is the longitudinal distance,  $z_b$  is the elevation at  
413 the river's base level (distance  $x_b$ ),  $A$  is the drainage area,  $A_0$  is a reference drainage area, and  
414 exponents  $m$  and  $n$  are empirical constants.

415

416 When using the  $\chi$  variable instead of the distance for plotting the elevation  $z$  along channel, ( $\chi$ -  
417 plot), the longitudinal profile of a steady-state channel is shown as a straight line (Perron and  
418 Royden, 2012). Any channel pulled away from this line is in disequilibrium and is then expected  
419 to attempt to reach equilibrium. Mapping  $\chi$  on several watersheds and comparing  $\chi$  across  
420 drainage divides is then a potential way to high disequilibrium between rivers across divide and  
421 to elucidate divide migration and drainage reorganization through captures (Willett et al., 2014).  
422 We used the  $\chi$ -analysis Tool developed by Mudd et al. (2014) to select the best  $m/n$  ratio by  
423 iteration (Perron and Royden, 2012) and to calculate  $\chi$  for rivers throughout the divide between  
424 the Ebro and Duero basins from a similar base level at 850 m a.s.l. The best mean  $m/n$  ratio for  
425 all our streams is 0.425, which falls in the typical range of values observed for rivers (~0.4 –  
426 0.6: e.g. Kirby and Whipple, 2012). The resulting map (Fig. 11) shows  $\chi$  values calculated on  
427 different opposite streams in the vicinity of the Ebro/Duero drainage divide. Similar values on  
428 both sides of the divide suggest the two opposite streams are at equilibrium, whereas strong  
429 contrasted  $\chi$  values imply disequilibrium leading to divide migration, continuously or through  
430 fluvial capture, toward the high  $\chi$  values (Willett et al., 2014). The map of  $\chi$  values actually  
431 shows significant contrasting values across the Ebro/Duero divide. We comment here these  
432 contrasts along the divide from the SE to the NW of the area considered (Fig. 11).

433 There is a strong contrast in  $\chi$  values between the headwater of the Jalon river (Fig. 11),  
434 characterized by low values (~300 m), and the closest part from the divide of the Bordecorex  
435 river (Fig. 4), a tributary of the Duero river (~500 m). Such a disequilibrium implies divide  
436 migration toward the Duero basin, predicting the capture of the uppermost reach of the

437 Bordecorex river by the Jalon river. To the north, tributaries of the Jalon river show slightly  
438 lower  $\chi$  values than the tributaries of the Duero river. This suggests a relative stable situation  
439 although small captures may occur toward the Duero basin. A higher contrast is observed  
440 around the easternmost part of the Duero basin, which is surrounded by the Ebro basin. The  
441 Araviana river (tributary of the Duero river) seems to be taken in a bottleneck between the  
442 Manubles river to the south and the Queiles river to the north (Fig. 4), which both show lower  
443  $\chi$  values (Fig. 11). Toward the east, there is a strongest  $\chi$  values contrast between headwaters  
444 of the Araviana river ( $>700$  m) and of the Isuela (Jalon tributary) and Huecha rivers ( $<100$  m).  
445 This domain appears clearly in disequilibrium and is expected to be captured by the Ebro  
446 drainage network. Such high  $\chi$  values differences appear also to the northwest (Fig. 11), in the  
447 southern part of the Cameros basin where the Duero river and its tributaries' headwaters show  
448  $\chi$  values  $>500-700$  m, whereas the facing rivers (Alama, Cidacos, Iregua, and Najerilla) are all  
449 characterized by low  $\chi$  values  $<100$  m. This predicts important disequilibrium and divide  
450 migration and fluvial captures toward the south. Northwestward,  $\chi$  values between Duero and  
451 Ebro network are more similar indicating that the divide is relatively more stable here, up to the  
452 westernmost part of the Ebro basin (Fig. 11). However, there are some slight localized  $\chi$  value  
453 contrasts ( $\sim 200 / \sim 450$  m) as observed between the Tiron and the Arlanzon rivers, between the  
454 Rudron and the Ubierna and Urbel rivers, and between the Ebro and the Pisuerga rivers (Fig.  
455 11). It suggests minor local captures toward the Duero basin.

456

457 To sum up,  $\chi$  values calculated in the vicinity of the drainage divide between the Ebro and  
458 Duero river networks show a general disequilibrium (Fig. 11) as the Ebro network is  
459 characterized by low  $\chi$  values (up to  $\sim 200-300$  m) compared to those for the Duero network  
460 (up to  $\sim 450-700$  m). In complement with all the evidence of divide displacements induced by  
461 captures described previously this allows predicting a general divide migration toward the  
462 Duero basin through headwater retreat, in favor of the Ebro tributaries, especially around the  
463 Almazan subbasin, which is expected to be entirely captured by the Ebro basin.

464

#### 465 **4. Discussion**

466

##### 467 4.1 Long term trend of divide migration

468

469 The oldest capture evidence in our study area corresponds to the incision of the northern part  
470 of the Iberian Range by the Jalon river and by the capture of the Calatayud basin, attributed to  
471 the post-Messinian (Gutiérrez-Santolalla et al. 1996). We propose, based on morphological  
472 evidence (Fig. 4) and in agreement with stratigraphic data (Gutiérrez-Santolalla et al. 1996),  
473 that the Jalon river system captured the Jiloca graben to the east since the Early Pleistocene,  
474 before progressively capturing the Almazan subbasin toward the west in the Holocene  
475 (Gutiérrez-Santolalla et al. 1996). From  $\chi$ -analysis (Fig. 11), we deduce that the eastern part of  
476 the Duero basin, the Almazan subbasin, is being actively captured by Ebro tributaries that  
477 drained the Iberian Range and the Cameros basin. Despite low contrasts in  $\chi$  values, local  
478 captures are also suggested in the vicinity of the Ebro / Duero drainage divide toward the  
479 northwest. Capture is further implied by the occurrence of numerous high elevated (~1000 m)  
480 knickpoints and low-relief surfaces (Figs. 5, 8, 9, 11).

481 Thus, there is a good correlation between  $\chi$  evidence and morphological and stratigraphic data  
482 implying long-lasting captures and divide migration during Pliocene, Pleistocene, and  
483 Holocene times in favor of the Ebro basin.

484  
485 The pursuit of such a long-term capture trend may be driven by tectonic and/or climatic forcing  
486 (Willett, 1999; Montgomery et al., 2001; Sobel et al., 2003; Sobel and Strecker, 2003; Bonnet,  
487 2009; Whipple, 2009; Castellort et al., 2012; Kirby and Whipple, 2012; Goren et al., 2015; Van  
488 der Beek et al., 2016). However, such long-term trend in drainage reorganization may also occur  
489 in tectonically quiescent domains, independently of external forcing (Prince et al., 2011). Here,  
490 the Iberian Range and the Cameros basin recorded extension pulses from the Late Miocene to  
491 the Early Pleistocene, responsible for the formation of several grabens as previously described  
492 (Gutiérrez-Santolalla et al., 1996; Capote et al., 2002). Extension events are also recorded  
493 during the Holocene, nevertheless, the youngest erosion surface of Late Pliocene-Early  
494 Pleistocene age observed in our study area shows no tectonic-related deformation and  
495 reworking, suggesting that tectonic activity is reduced here (Gutiérrez-Elorza and Gracia,  
496 1997). This is also consistent with the relative scarcity of seismic activity observed in our study  
497 area, compared, for instance, to the Pyrenees, or to the Betics (Herraiz et al., 2000; Lacan and  
498 Ortuño, 2012). We consequently propose that local tectonic activity is not the main driver of  
499 the capture histories documented here, as most capture events postdate the cessation of tectonic  
500 activity, and occur during periods of quiescence (Gutiérrez-Santolalla et al., 1996).

501

502 The Cameros Massif is characterized by relatively high mean annual precipitation up to ~1000  
503 mm/an (Fig. 6) with high elevation (~1400-2200 m) in comparison with the surrounding areas.  
504 This contrasts with the adjacent Ebro and Duero basins where low precipitation rates, of ~400-  
505 500 mm/an (Hijmans et al., 2005), illustrate subarid climate conditions. The Cameros area is  
506 the only place in our study area where a contrast in precipitation pattern (Fig. 6) would  
507 potentially drive a migration of the divide toward the drier, Duero area. Given that the same  
508 pattern is observed everywhere, even where there isn't any precipitation difference, we suggest  
509 that the present day climatic condition is unlikely to control the general pattern of current  
510 drainage reorganization between the Ebro and Duero basins. During the Pliocene and the  
511 Pleistocene, the climatic record in the northern Iberia Peninsula is characterized by alternations  
512 between similar subarid conditions and intense glaciation. Paleoclimate proxies do not allow to  
513 highlight past precipitation differences along the divide that could explain past drainage  
514 reorganization. Moreover, there is no clear evidence of important glacier development and  
515 related erosion in our study area, especially for the Cameros basin and the Iberian Range  
516 (Ortigosa, 1994; García-Ruiz et al., 1998, 2016; Pellicer and Echeverría, 2004). This indicates  
517 that drainage evolution between the Ebro and Duero basins is unlikely to be related to climatic  
518 evolution.

519

520 4.2 Excavation of the Ebro basin as the main factor controlling divide migration and limiting  
521 incision of the Duero river

522

523 A striking morphological feature for river capture in our study area is the important contrast in  
524 the incision pattern (e.g. Fig. 1B) from one side of the divide to the other. This suggests that the  
525 incision capacity of the river network is the main driver for capture and divide migration. Both  
526 tectonic and climatic forcing does not appear to control drainage reorganization between the  
527 Ebro and Duero basins.

528 The opening of the Ebro basin toward the Mediterranean Sea during the Late Miocene led to  
529 widespread excavation (García-Castellanos et al., 2003, García-Castellanos and Larrasoña,  
530 2015), favored by more humid and seasonal climatic conditions (Calvo et al., 1993; Alonso-  
531 Zarza and Calvo, 2000). By contrast, incision related to the opening of the Duero basin toward  
532 the Atlantic Ocean is concentrated to the west in the Iberian Massif, characterized by a  
533 largescale knickzone (150 km long and 500 m high) in the Duero river long profile (Fig. 1B).  
534 This contrasts with the limited eastward propagation of incision in the Cenozoic part of the  
535 basin (Antón et al., 2012, 2014), despite climatic conditions similar to the Ebro basin. An

536 explanation resides in the fact that the resistant Iberian Massif basement rocks may have  
537 controlled and limited incision and drainage reorganization in the Cenozoic Duero basin (Antón  
538 et al., 2012). The Duero profile upstream of this major knickzone may be considered as a high  
539 elevated local base level for its tributaries there. Difference between the Ebro and Duero base-  
540 levels implies a major contrast in fluvial dynamics. We suggest the systematic and long-term  
541 trend of divide migration toward the Duero basin and fluvial capture in favor of the Ebro basin  
542 is driven by the differential incision behavior, controlled by base-level difference.

543 Our stream power analysis along the Duero river (Fig. 10) shows that the difference in drainage  
544 area of the Duero inferred from our paleo-divide map (Fig. 9) induces a noticeable decrease of  
545 stream power values of the Duero in the vicinity of the knickzone. This stream power is a  
546 minimum estimate because calculation does not take into account possible captures and divide  
547 migration in other areas along the Duero basin divide, nor the full history of the divide migration  
548 through time and the related ongoing decrease in water discharge as documented in laboratory-  
549 scale landscape experiments (Bonnet, 2009). Some contrasts of incision are also observed in  
550 the Iberian Range along the southern border of the Duero, and in the Cantabrian domain to the  
551 North. Both show more important incision than in the Duero basin, suggesting potential river  
552 captures and divide migration at the expense of the Duero basin, increasing the total of lost  
553 drainage area. Even if it gives minimal estimate, our stream power analysis suggests that  
554 drainage area reduction may have limited the erosion in the Duero basin. This provides an  
555 explanation for the preservation of the lithologic barrier to the west, along the main knickzone  
556 of the Duero considered as an intermediate, local base level (Antón et al., 2012). We propose  
557 that the reduction of the Duero drainage area caused by captures and incision in the Ebro basin,  
558 is responsible for a significant decrease of the incision capacity in the Duero basin. We infer  
559 that the ongoing drainage network growth in the Ebro basin may be responsible for the current  
560 preservation of large morphological relicts of the endorheic stage in the Duero basin.

561 The opening of the Ebro basin toward the Mediterranean Sea resulted in a drastic base level  
562 drop. This results in the establishment of an upstream-migrating incision wave that propagates  
563 to every tributary of the Ebro network, responsible for knickpoints migration (Schumm et al.,  
564 1987; Whipple and Tucker, 1999; Yanites et al., 2013) and for drainage reorganization and  
565 divide migration. The  $\chi$ -analysis that we performed along the current Ebro-Duero divide (Fig.  
566 11) highlights areas where geomorphic disequilibrium is still ongoing, which suggests that they  
567 are areas where divide is currently mobile. The modelling study performed by Garcia-  
568 Castellanos and Larrasoña (2015) suggests that the re-opening of the Ebro basin occurred  
569 between 12.0 and 7.5 Ma. This indicates that the growth of the drainage network of the Ebro

570 basin and the establishment of new steady-state conditions is a long-lived phenomenon, which  
571 is still not achieved today.

572

### 573 **Conclusion**

574

575 In this paper we present a morphometric analysis of the landscape along the divide between the  
576 Ebro and Duero drainage basins located in the northern part of the Iberian Peninsula. This area  
577 shows numerous evidence of river captures by the Ebro drainage network resulting in a long-  
578 lasting migration of their divide, toward the Duero basin. Although these two basins record a  
579 similar geological history, with a long endorheic stage during Oligocene and Miocene times,  
580 they show a very contrasted incision and preservation state of their original endorheic  
581 morphology. Since the Late Miocene, the Ebro basin was opened to the Mediterranean Sea and  
582 record important erosion. On the opposite, the Duero was opened to the Atlantic Ocean since  
583 the Late Miocene – Early Pliocene but its longitudinal profile exhibits a pronounced knickpoint,  
584 which delimits an upstream domain of low relief and limited incision, likely representing a  
585 relict of its endorheic topography. We propose that this contrast of incision is the main driver  
586 of the migration of divide that we document. The morphological analysis of rivers across the  
587 divide highlights areas where geomorphic disequilibrium is still ongoing, which suggests that  
588 the Ebro-Duero divide is currently mobile. The quantification of the decrease of the drainage  
589 area of the Duero based on the reconstruction of a paleo-position of the Ebro-Duero divide  
590 shows that the divide migration results in a significant lowering of the stream power of the  
591 Duero river, particularly along its knickzone. We suggest that divide migration induces a  
592 decrease of the incision capacity of the Duero river, thus favoring the preservation of large  
593 relicts of the endorheic morphology in the upstream part of this basin.

594

595

### 596 **Author contributions**

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

599

600

### 601 **Competing interests.**

602 The authors declare that they have no conflict of interest.

603

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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 in 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 (data from Hijmans et al., 2005).

Figure 7: A) 3D view of the DEM of the Bureba sector showing important contrast of incision between the Ebro and Duero basins across their divide (red dashed line) and river capture evidence (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) Wind gaps cut into the Bureba anticline (see location on Fig. 7A). 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 evidence of river capture. Colors are given to rivers that are linked in these capture processes.

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: Duero river long profile (black line) and difference in the specific stream power of the river (grey) calculated by considering the paleo and present-day position of its divide. Positive values suggest a significant diminution of the incision capacity of the Duero river, particularly along the knickzone of its longitudinal profile. Details on calculation are available in the Supplement (Section S1).

Figure 11: Topographic map with  $\chi$  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.

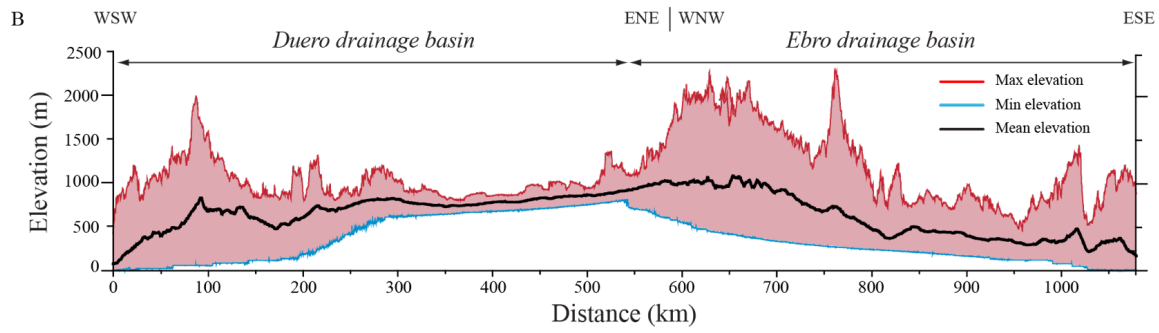
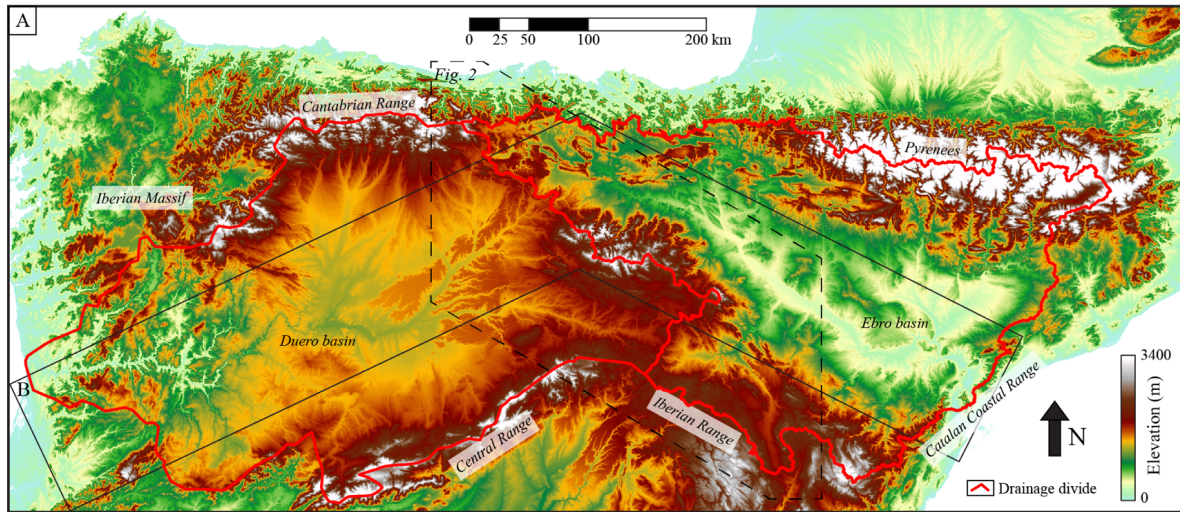


Figure 1

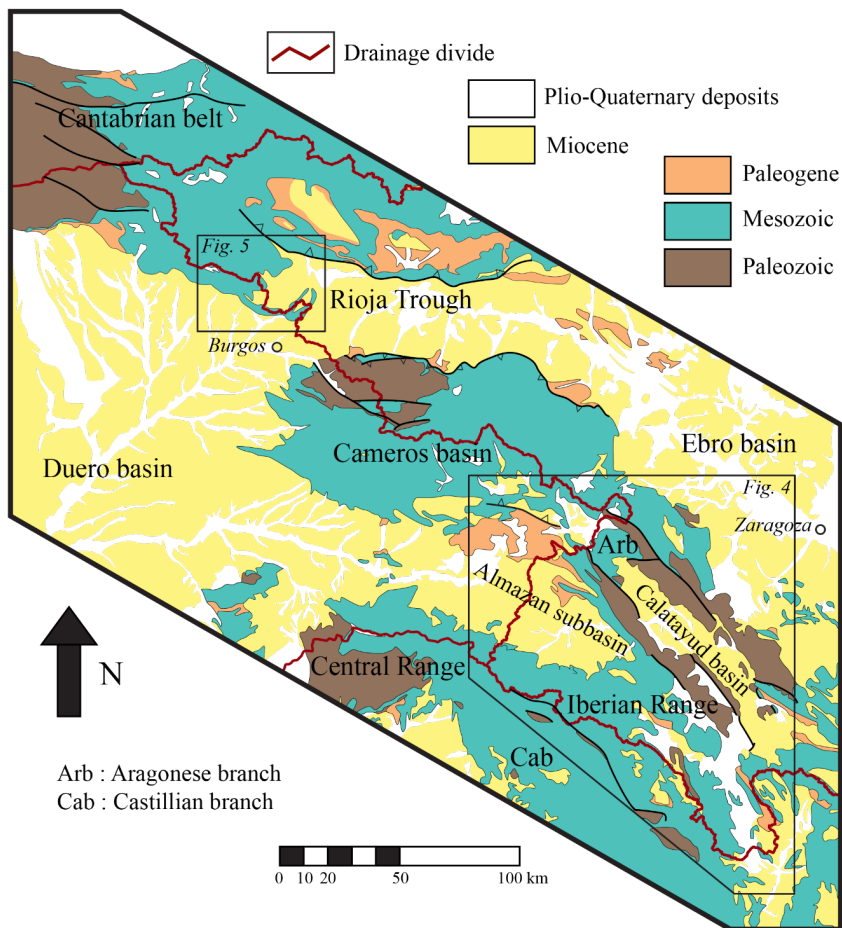


Figure 2

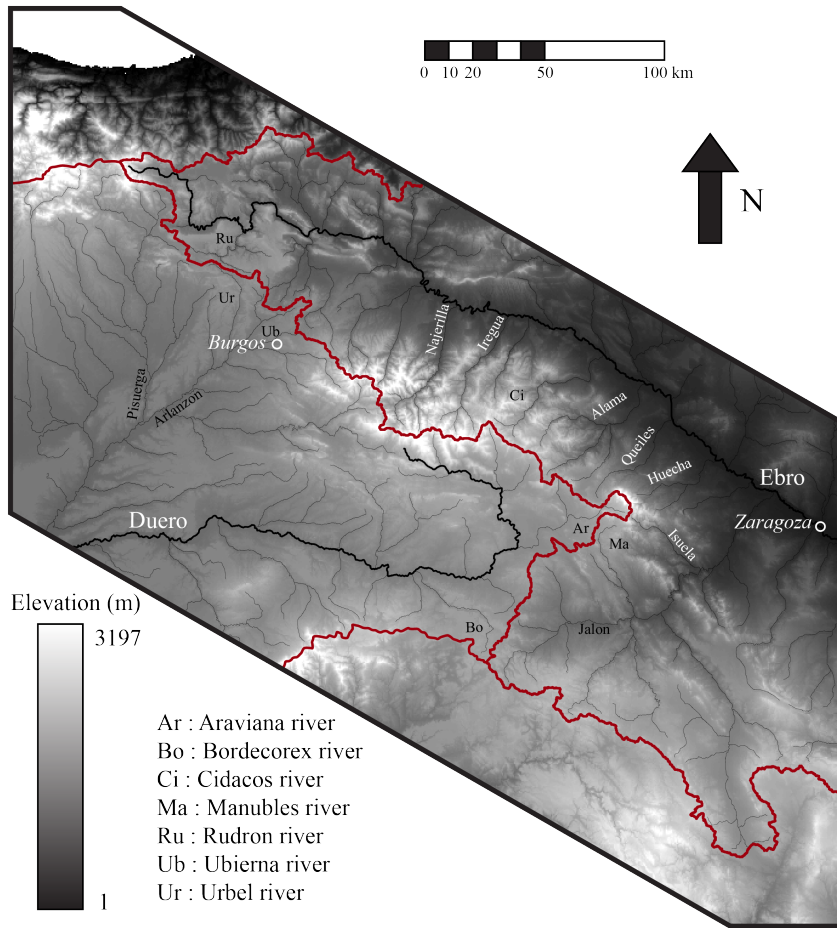


Figure 3

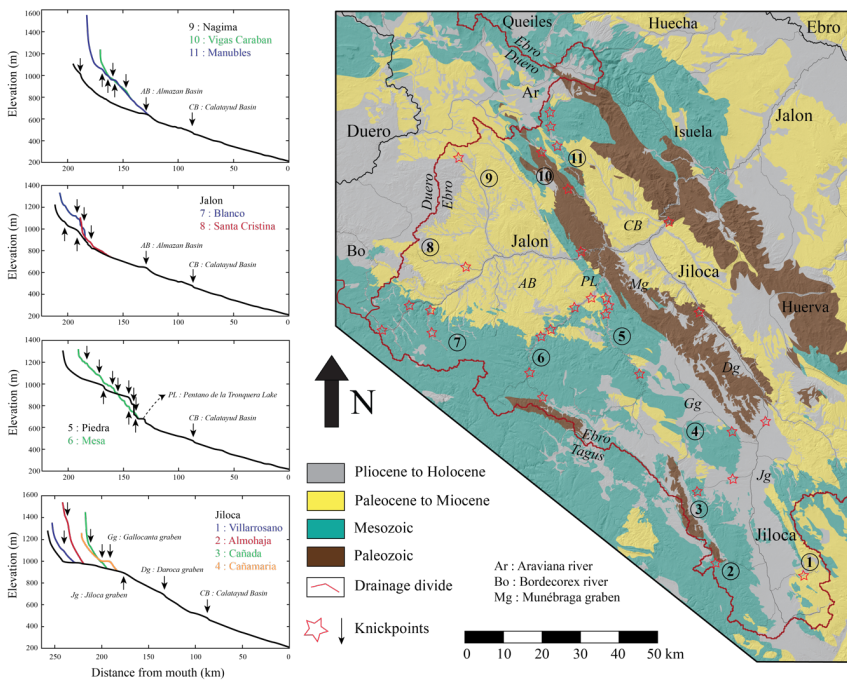


Figure 4



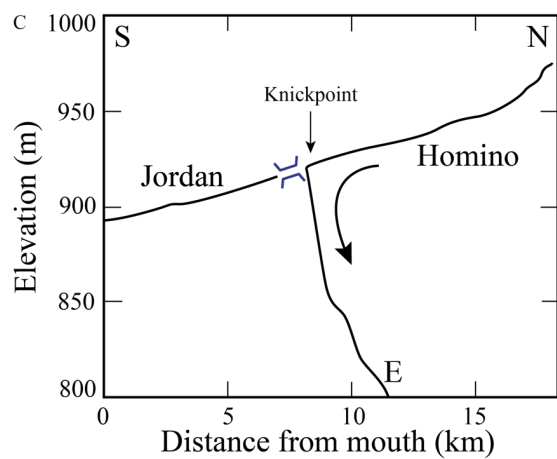
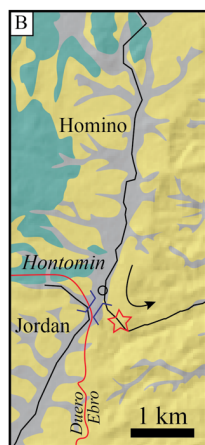
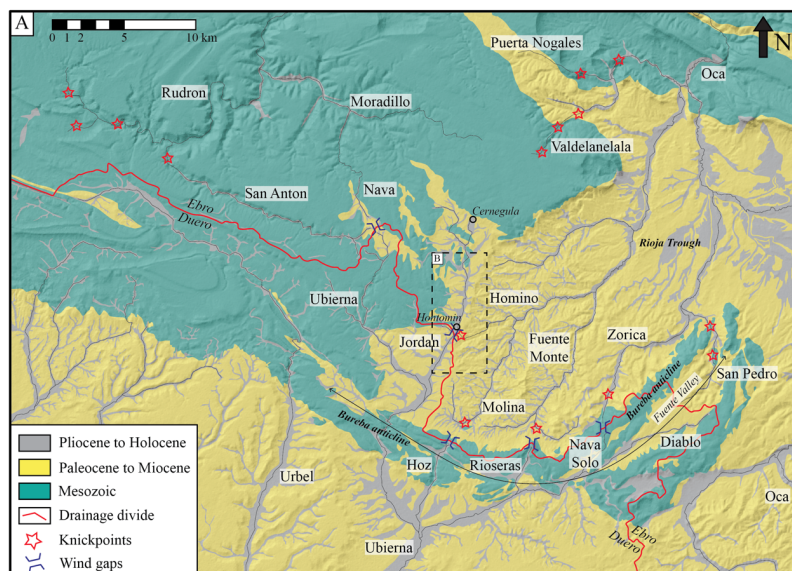


Figure 5

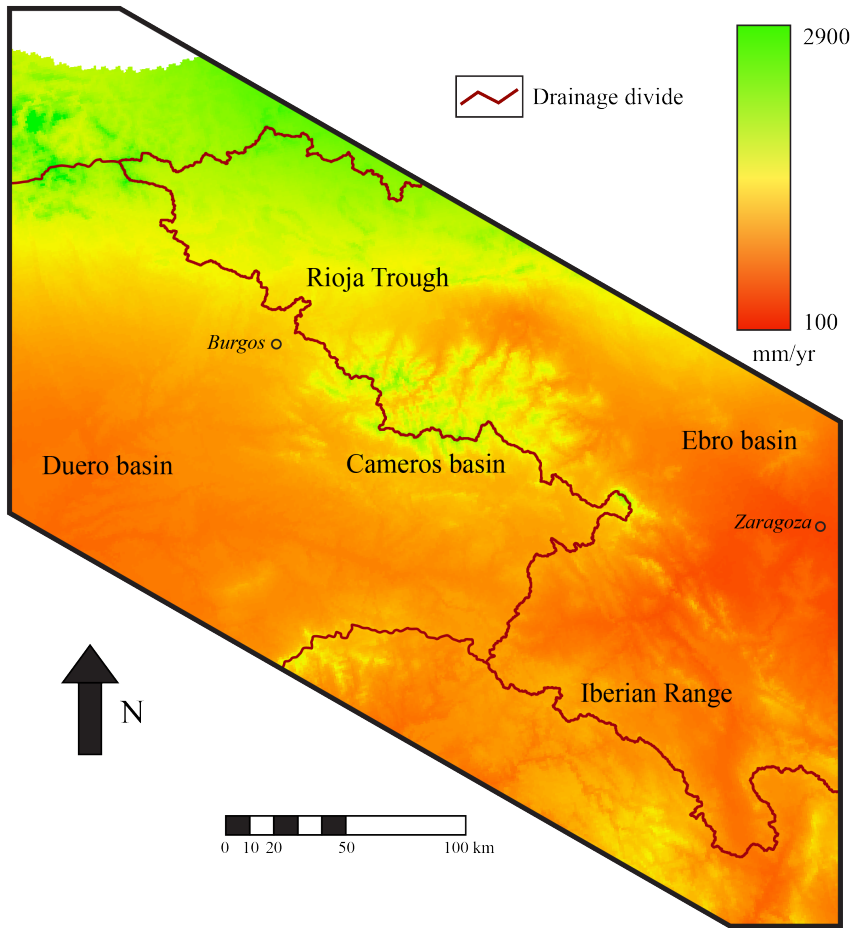


Figure 6

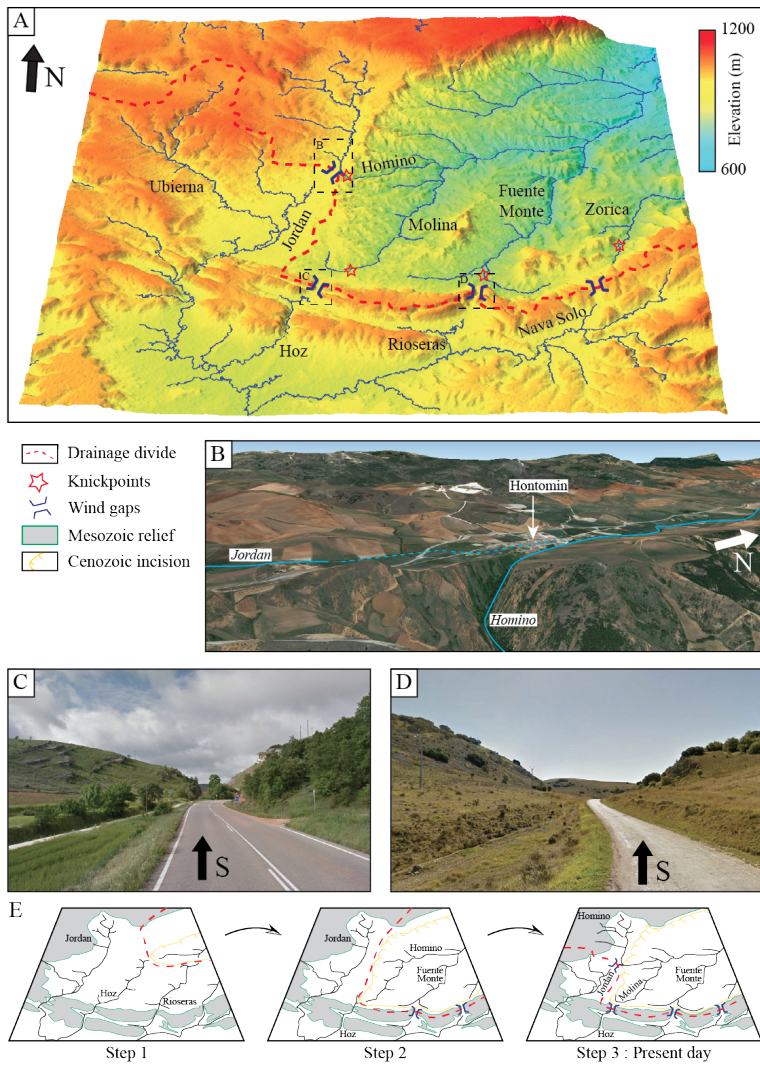


Figure 7

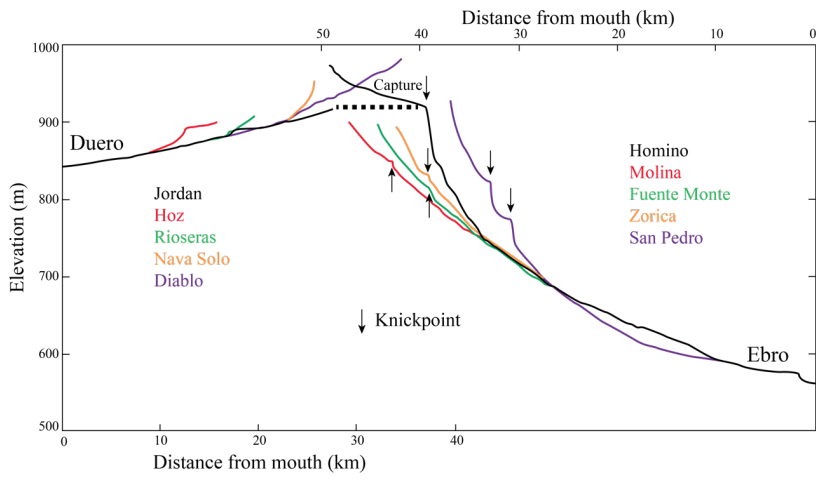


Figure 8

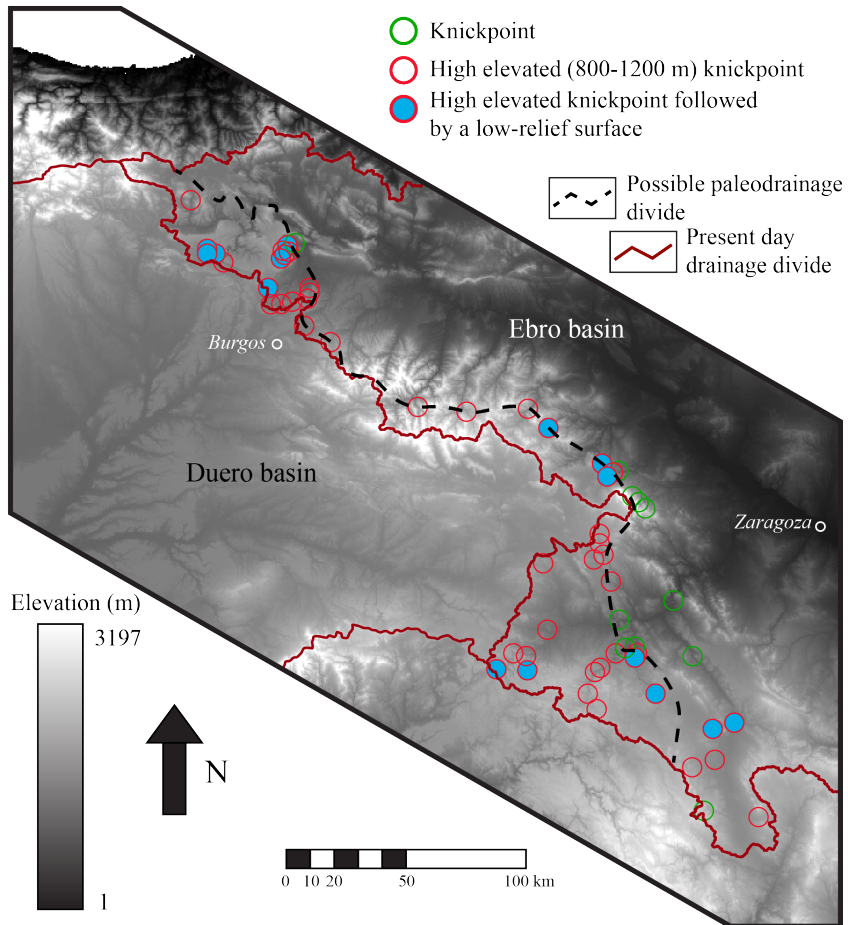


Figure 9

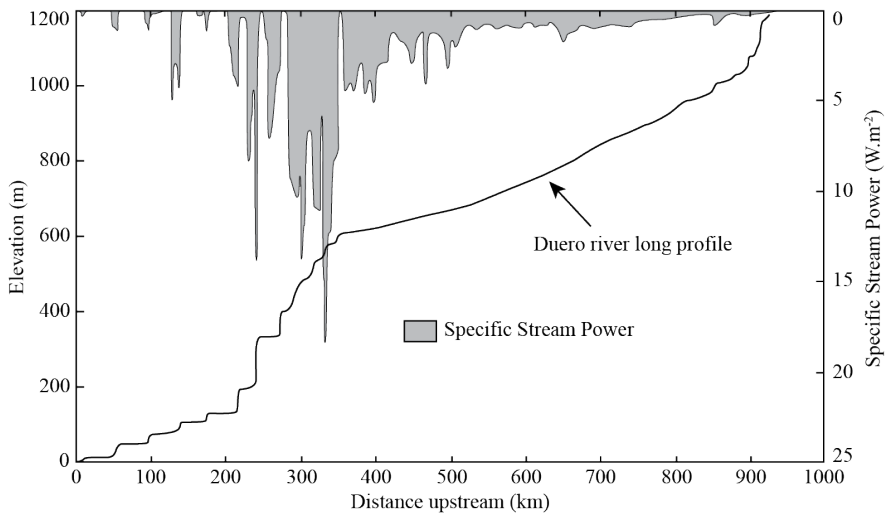


Figure 10

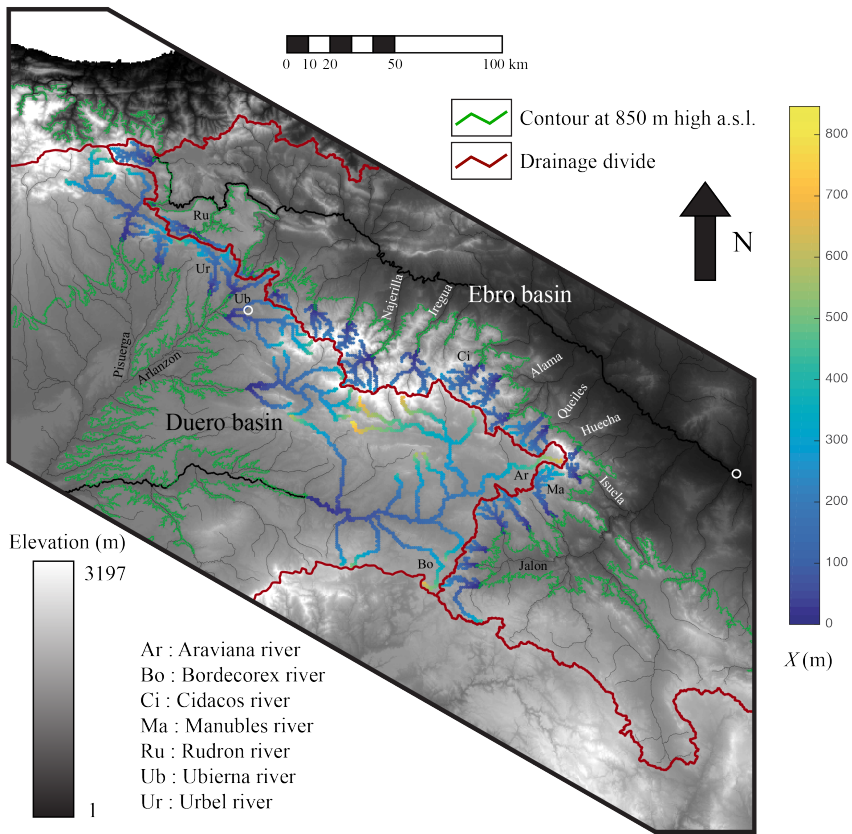


Figure 11