To the Associated Editor of ESurf

Dear V. Vanacker

We are pleased to submit the revised version of our manuscript “Drainage reorganization and divide migration induced by the excavation of the Ebro basin (NE Spain)”.

We want to thank you and the two reviewers for very useful and constructive comments that greatly helped us to clarify and improve our manuscript. We have significantly reorganized and shortened the manuscript (594 lines against 663), without changing the scientific results and the conclusion.

In the following we respond to the comments point-by-point, beginning by your comments.

Sincerely yours,

Stéphane Bonnet on behalf of the co-authors

Associated Editor

We have now received two reviews on your manuscript. They provide useful suggestions for the improvement of your final document.
The most important points are :
- Reviewer#1 and #2 asks for a careful revision of the terminology used in the paper, and more specifically to the use of the terms “endorheic”, “unfilling”, etc.

We modified the ms accordingly (see details in the response to reviews). Both reviewers asks for clarification of the use of expressions such as “almost still endorheic” or “quasi-endorheic configuration”. They are right, we agree that these expressions were misleading. We used these expressions because as already pointed out by Anton et al. for example (ref in the ms), the upstream part of the Duero basin, upstream its main knickzone, is an area where there is a limited incision. This is an area where the endorheic topography is partially preserved. That is why we use the expression: “almost still endorheic”. We agree with the reviewer that this expression could be misleading and we use consequently the term “relict of the endorheic stage” in the revised ms. All the occurrences of these misleading expressions have been changed in the ms.

“unfilling” has been replaced by erosion.

- Reviewer#1 is concerned about repeated text. The latter concerns – for example -the sentences on lines 36-42 and 85-91 that are repeated.

We’ve worked on the ms to avoid repeated text at the end of the abstract (lines 36-42) and introduction (lines 85-91). These sentences were not needed at the end of the introduction and have consequently been deleted in the revised ms.

- The organization of the paper needs further attention, and the revised paper needs better separation of methods, results and discussion. This is particularly so for section 3 on “morphometric analyses”. It is not very clear if section 3.1 is based on own research, a literature review, or a combination of both. As suggested by Reviewer#1, try to highlight your own research findings, and discuss them in the context of the literature and the theory (in section 4).

We agree and we reorganized the ms in order to better distinguish between results and interpretations.

We substantially reorganized the section 3 and sub-sections. We have simplified the section 3 (dedicated to results) by creating two new sub-sections, 3.1 and 3.2 where we now present all the evidence for captures in the two studied area, the Iberian Range (3.1) and the Rioja trough (3.2). In the previous ms, some evidence of captures published in the literature were presented first in the section 2 (dedicated to the setting) and then again in the former section 3.1. These sentences (lines 186-195 and 213-223 in the former ms) have been moved and merged with the former section 3.1, in the new sections 3.1 and 3.2 (these changes are highlighted by colors in the revised ms with track changes). Now, section 2 focuses only on the geological setting.

We rewrote the section dedicated to captures (new sections 3.1 and 3.2) by introducing first the evidence of captures from the literature and then by presenting new evidence based on our analysis. We made the choice to present literature and our results in the same sub-sections (instead of presenting all the literature in a sub-section "geomorphological setting" in the setting in section 2 for example) because when we present our results we frequently compared them with the previous work. So we think better, because easier to understand, to have the literature and then our results in the same sub-section.

Finally, we have also added a new sub-section 3.3 where we present the map that shows the paleo-position of the Ebro-Duero divide deduced from all the evidence of captures.

Also, section 4 (discussion) contains new analyses on the stream power, that would rather belong in section 3

We agree. We have moved the section on the stream power analysis to the result section (in the sub-section 3.3) because the calculation is based on the map presented in the result section. Now there isn't any new analyses and results in the section 4 (discussion)

- The theoretical background of the chi analyses is based on Perron and Royden (2013), and Mudd et al. (2014). You can refer to the literature to avoid repetition, and resume section 3.2.1.

Done. The Chi-analysis is now in a new dedicated sub-section 3.4. As suggested by reviewers we have significantly shorten the presentation of the theoretical background and kept only necessary information.

- Reviewer#2 suggests rewording parts of the introduction, discussion/conclusion to highlight the importance of your study, and its wider implications.

Done. We have modified the introduction, discussion and conclusion in that way. We particularly rephrased the conclusion, to better highlight our main findings (see also response to review #1).

The two reviews give more detailed comments that need to be addressed in your rebuttal.

Review#1

The authors explore a number of captures, most prominently the Homino River one. This one is well known to geomorphologists, and documented not only by Mikes 2010, but also for example in the report accompanying the corresponding chart of the Geological Map of Spain, published by the IGME. I also recall public panels on display for the random visitor in the Hontomin village, explaining the fluvial captures. I'm sure further bibliographical research will bring even more appropriate references.

The capture in the vicinity of the Homino River is indeed an outstanding example of the many captures that occurred near the Duero-Ebro divide. We decided to show this nice and clear example on figure 7, with some others that exist in the same area. Mikes (2010) already did substantial work in this area and we referred to his publication several times in the submitted ms. Despite our in-depth literature research, we have not found so many publications describing the fluvial captures in our study area (our reference list can attest that we have not only looked at “main-stream” journals). In the first, we were not aware of the report accompanying the Geological Map of Montorio, published by the IGME (1997). In the revised version we have added the reference to this work (Pineda, 1997).

I counted 5 mentions of the Duero basins as being "almost still endorheic". The expressions used are inappropriate and misleading. The entire Duero Basin is exorheic today. Perhaps the authors mean that the top of the sedimentary infill is relatively well preserved, and incision is small/recent relative to the Ebro. This needs clarification because it seems to be central point of the article.

We actually used this expression because of the good preservation of the sedimentary infill formed during the endorheism upstream the major knickzone on the Duero profile, because this area have not been incised. The endorheic topography is relatively well-preserved here because the base-level in this area is the top of the knickzone as already recognized by Anton et al. (ref in the ms). We agree that the expression that we used was possibly misleading so we changed it by “relict of the endorheic stage” in the revised ms. We clarifed this in the main text (cf also our response to associate editor’s comments). For example the following sentence (lines 25-26 in the submitted ms):

“The Ebro basin is highly excavated, whereas the Duero basin is well preserved and may be considered as almost still endorheic.”

has been rephrased (lines 23-24 in the revised ms):

“The Ebro basin is highly excavated, whereas relicts of the endorheic stage are very well preserved in the Duero basin”

647-650: The logics behind this reasoning are obscure. Again, what is a “quasiendorheic configuration”? And how does the Ebro piracy effect on it? In terms of drainage area, the Duero is still larger than the Ebro basin, so area is not the problem.

The Ebro piracy led to important river captures at the expense of the Duero Basin. The Duero basin then recorded a loss of drainage area through time. This is not a question of absolute size of the Duero drainage basin but a question of decrease of its drainage area. We propose that the decrease of its area, estimated here to be of ~12% on the basis of existing markers, resulted in a decrease of its incision capacity. It is the reason why we consider that the Ebro piracy is responsible for the preservation of large relicts of the endorheic configuration in the Duero Basin.

We rephrased the sentences (now lines 557-561):

"*We propose that the reduction of the Duero drainage area caused by captures and incision in the Ebro basin, is responsible for a significant decrease of the incision capacity in the Duero basin. We infer that the ongoing drainage network growth in the Ebro basin may be responsible for the current preservation of large morphological relicts of the-endorheic stage in the Duero basin.*"

Some formal aspects need attention: two entire paragraphs of the abstract are copied as such in the main text, f.e., the last par. in the Introduction.

Done. These sentences have been deleted from the introduction (see letter to Editor)

Instead of the latter, I would expect an explanation of what is to come later in the paper, what question is addressed and what strategy they follow.

Done. We rephrased the last part of the introduction (lines 73-79):

"Following a presentation of the geological context, we first compile evidence of fluvial captures along the Ebro-Duero divide, based on previous studies and our own investigations, and we map the location of knickpoints and relict portions of the drainage network. We use all these observations to reconstruct a paleo-divide position and to estimate the impact of divide migration in terms of drainage area and stream power. We complement this dataset by providing a map of χ across divide (Willett et al., 2014) to highlight potential disequilibrium state between rivers of the Ebro and Duero catchments. "

Also the first half of the conclusions are not conclusions.

We agree. The conclusion has been rephrased:

Submitted ms (lines 655-659):
"The Ebro and Duero basins both recorded a long endorheic stage during Oligocene and Miocene times. Since the Late Miocene, the Ebro basin is opened to the Mediterranean Sea and record important unfilling. This results in important incision driven by a very active drainage network. By contrast, the Duero basin is opened to the Atlantic Ocean since the Late Miocene – Early Pliocene and record only limited incision."

First part of the conclusion in the revised ms (lines 576-579):
"In this paper we present a morphometric analysis of the landscape along the divide between the Ebro and Duero drainage basins located in the northern part of the Iberian Peninsula. This area show numerous evidence of river captures by the Ebro drainage network resulting in a long-lasting migration of their divide, toward the Duero basin..."

Lines 415-454 are really redundant because that derivation is shown in many earlier papers, and is not relevant to the paper.

Done, we significantly reduced the theoretical background (see tracks in the revised ms)

I would highlight Perron & Royden, ESPL, 2013, as the original authors.

We agree. We already referred to this paper in the submitted ms

Point “3.2.2” should in my view be the "Results", which seem poor relative to the Discussion.

We merged sub-sections 3.2.1 (Chi-methodology, significantly reduced) and 3.2.2 (results from Chi analysis) of the submitted ms in a new single sub-section dedicated to the Chi analysis (now 3.4). We also presented some results in the section 3.1 of the former ms (regional map of knickpoints and captures, reconstruction of the paleo-divide position) but actually these findings were not enough separated from literature (see comments in review#2). This has been improved in the revised ms (new sub-sections 3.1, 3.2 and 3.3).

Overall, the ms. at its present stage focuses more on interpretation/speculation than on its new objective results. I don’t report here any further on formal issues.

Review#2

GENERAL COMMENTS This study examines watershed migration as a result of capture between 2 of the largest Iberian drainages – the Ebro and the Duero. I think that the paper adds valuable insights into drivers of migration divide, but that these are currently somewhat lost in the manuscript. I suggest that the paper could be fronted and ended with a stronger abstract, introduction and discussion/conclusions that frame the wider implications of the study.
We reorganized the ms accordingly to better highlight our main findings.

This would include emphasizing why this study is important in terms of wider implications (eg type of capture Bishop 1995; implications for landscape Mather et al 2002,), ? I would argue that the key highlights need to be drawn out more clearly e.g. demonstrating the role of lithology as a limiter to incision (seen on smaller scale in other captures eg Shepherd 1982, Mather 2000). Where this occurs within the basin will impact on how far any sea-level generated wave of incision can propagate up a basin and thus has wide ranging significance to other studies. This occurs in both the mid Duero and lower Ebro in the coastal ranges. I am not suggesting a major re-write here – more a subtle re-wording of the text to incorporate such points and widen the impact of the study.

We agree that providing evidence of lithology as a limiter to incision would be an interesting topic however we do not think that we provide enough evidence of this mechanism to highlight it in this paper. On the opposite, the role of divide migration in reducing the incision capacity of a river is a phenomenon that, to our knowledge, has never been documented before and we consequently rather preferred to focus our paper on this new topic.

SPECIFIC COMMENTS /
Line 40, 76, 659 – what does ‘almost still endoheric” mean? – you mean it retains the landscape signature? clarify
Corrected (see responses to associate editor an reviewer#1)

Line 41 – how does the Ebro enable enhoherism of the Duero? I don’t understand
Rephrased (lines 31-35): “*Fluvial captures have strong impact on drainage areas, fluxes, and so on their respective incision capacity. We conclude that drainage reorganization driven by*

the capture of the Duero rivers by the Ebro drainage system explains the first-order preservation of endorheic stage remnants in the Duero basin, due to drainage area loss, independently from tectonics and climate."

Line 74, 578 – what is 'unfilling'?
This is not an established term - do you mean erosion? Incision?
Corrected (erosion)

Lines 87-88 is one reason why it is important to know this, but it is sandwiched admidst other information – a more explicit 'why this is important' for the study should be provided from the start (currently this is hidden in the text)
These lines are about one of the main conclusion of our study and have been removed from the end of the introduction.

Lines 320-1 Contrasts in sharpness could also be attributed to lithological differences - expand.
We add the following sentence (lines 275-276): "*However despite a similar bedrock we cannot ruled out some local influence of the lithology on the shape of these knickpoints*".
"

Line 597 – you mean the headwaters of the modern Ebro rather than the Duero (as this reads)? – confusing
Yes, it was a mistake, Ebro instead of Duero. Corrected

Lines 613-618 – so how does this compare to other captures – as these are headward these are incremental – overall drainage has time to adjust rather than mid-basin captures which tend to be more of a sudden impact eg smaller , well documented captures such as Sorbas Basin. Stokes et al 2002
This is an interesting question that we cannot really address; it would deserve to be investigated for example through a modelling approach
Some areas could be more succinct (do we really need to know about the Late Cretaceous climate in section 2.4?)
We think interesting to present the long-term climatic background because it allows us to propose that the difference in the landscape evolution of the Duero and Ebro is not related to climate

TECHNICAL COMMENTS

Line 71, 129, 189, 282, 284, 293, 520 onwards – use of 'evidences' should be evidence (it can only be singular!)
OK corrected
Line 72 since should be from
OK corrected
Line 99 on should be of
OK corrected
Line 107 'Since early stage collision, (not of)
OK corrected
Line 108 - ?carbonated alluvial sediments? – I do not understand
Changed: "clastic deposits"
Line 119 – as well as what process underlies. . ..
OK corrected

Line 122 – you mean upper Duero – there is much incision below this
Yes, corrected
Line 137 ‘in’ should be ‘of’
OK corrected
Line 156 should be ‘accommodated’ and Hercynian
OK corrected
Line 158 – this event – what event? Clarify
OK corrected
Line 161, 209 onwards ‘deformations’ should be deformation
OK corrected
Line 162 –‘ such as the. . ...’
OK corrected
Line 170 – . . ..periods of quiescence. . ..
OK corrected
Line 173 such as fluvial. . ...
OK corrected
Line 203 – took place should be ‘existed’
OK corrected
/ Line 207 – ‘detritic’ not needed
OK corrected
Line 228 – network should be networks
OK corrected
Line 230 associated with (not to)
OK corrected
Line 233 precipitation not precipitations
OK corrected
Line 260 tongues are. . .. . .
OK corrected
Line 300 - knickpoints do not ‘witness’ capture –they may provide evidence of migrating base-levels which may be associated with capture
OK corrected
Lines 304/5 require references to support these ages
We add reference to Gutierrez-Santolalla et al., 1996
Line 306 – ‘never been drained before’ – I think you mean never externally drained (it would have been drained ie had drainage)?
Yes corrected by adding “externally”
Line 322 – why ‘for instance’ ?
Mistake, changed (“Finally” instead of “for instance”)
Line 331 – of not in
OK corrected
Line 358, 371, 635 – why ‘remarkable’ do you mean marked?
OK corrected (deleted)
Line 389 – witnessed? Do you mean suggested by. . ..
OK corrected (suggested)
Line 391 –recorded = records
OK corrected
Line 398 with not to
OK corrected
Line 408 a lot = many
OK corrected

Line 487, little = small
OK corrected
Line 500, X value contrasts
OK corrected
Line 523 deduce not deduced
OK corrected
Line 525suggested rather than evidence
OK corrected
Line 526-7 implied by rather than well witnessed by
OK corrected
Line 533 – define long (temporal? Spatial?)
Long-term
Line 536 – trends in not trend of /
OK corrected
Line 550 precipitation not precipitations
OK corrected
Line 559 – alternations between (rather than alternance)
OK corrected
Line 560 glacier not glaciers
OK corrected
Line 574'the to first order' – does not make sense – reword
Deleted: to first order
Line 584 you mean 'climatic conditions similar to the. . ..'?
Yes. Corrected
Line 608 'The present drainage of the . . ..'
OK corrected
Line 637 helps with (not for)
Sentence deleted
Line 647 Then ? – not needed, remove
Sentence deleted
Line 655 – record (not recorded)
Sentence deleted
Line 658 'was open to the Atlantic Ocean from the. . ..''
OK corrected
Line 659 records not record
OK corrected

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

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Abstract

Intracontinental endorheic basins are key elements of source-to-sink systems as they preserve sediments eroded from the surrounding catchments. Drainage reorganization in such a basin in response to changing boundary conditions has strong implications on the sediment routing system and onlandscape evolution. The Ebro and Duero basins ~~in the north Iberian plate~~ represent two foreland basins, which developed in response to the growth ~~were filled in relation with the growing~~ of surrounding compressional orogens, the Pyrenees and the Cantabrian mountains to the north, the Iberian Ranges to the south, and the Catalan Coastal Range to the east. They were once connected as endorheic basins in the early Oligocene. By the end of the Miocene, new post-orogenic conditions led to the current setting in which the Ebro and Duero basins are flowing in opposite directions, towards the Mediterranean Sea and the Atlantic Ocean. ~~they were disconnected and started to flow into the Mediterranean Sea and the Atlantic Ocean, respectively, in a post-orogenic context~~. Although these two hydrographic basins recorded a similar history, they are characterized by very different morphologic features. The Ebro basin is highly excavated, whereas relicts of the endorheic stage are very well preserved in the Duero basin~~ is well preserved and may be considered as almost still endorheic~~.

~~These two bordering basins then show~~ The contrasting morphological preservation ~~states~~ of the~~ir~~ endorheic stage~~s and~~ represents an ideal natural laboratory to study ~~what factors~~the drivers (internal / external) ~~control~~ of post-orogenic drainage divide mobility, ~~and~~ drainage network and landscape evolution~~ in post-orogenic basins~~. To that aim, we use field and map observations and we apply the Chi-analysis of river profiles ~~across the divide~~ along the

~~boundary~~ divide between the Ebro and Duero drainage~~ basins in the Northern Iberian Peninsula to evaluate the migration of their divide~~.

We show here that the contrasting excavation of the Ebro and Duero basins drives a reorganization of their drainage network through a series of captures, which ~~and~~ resulted in the southwestward migration of their main drainage divide. Fluvial captures have strong impact on drainage areas, fluxes, and so on their respective incision capacity~~, especially for the captured basin~~. ~~Thus, we~~We conclude that drainage reorganization~~, and~~ drive by the capture of the Duero rivers by the Ebro ~~ones~~drainage system explains the first-order~~, independently from tectonics and climate, enable~~ preservation of endorhei~~csm~~ stage remnants the Duero basin due to drainage area loss, independently from tectonics and climate.

1. Introduction

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

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The applicability of this method is however limited to settings where the response time of rivers is larger compared to the rate of divide migration, so they can actually show disequilibrium in their longitudinal profiles (Whipple et al., 2017).

~~In this study, we use field observations and we apply the Chi-analysis of river profiles across divide along the boundary between the Ebro and Duero drainage basins in the Northern Iberian Peninsula to evaluate the migration of their divide.~~ The~~se two~~ Ebro and Duero drainage basins in the Northern Iberian Peninsula show geological and geomorphological ~~evidences~~evidence ~~indicating that they record~~of very contrasted erosional histories during the Neogene. They ~~went through~~initally recorded a long endorheic stage ~~since~~ from the Early Oligocene to the Late Miocene (REF ?). Since then, ~~before being~~both basins opened toward the Atlantic Ocean (Duero) or the Mediterranean Sea (Ebro)~~ during the Late Miocene, in a post-orogenic context~~. The Ebro basin's opening is reflected in the landscape by evidence of river incision ~~led to important unfilling and excavation~~ (Garcia-Castellanos et al., 2003), whereas ~~opening of~~ the Duero Basin ~~did not drive excavation of~~does not show significant erosion in its upstream part~~,~~ as a large relict of its endorheic morphology is preserved. ~~that can then be considered as almost still endorheic~~ (Antón et al., 2012). The Duero river long profile actually shows a pronounced knickpoint (knickzone) ~~in the downstream end of its longitudinal profile that lim~~defining~~its~~ an upstream domain of high mean elevation (~800 m) and low relief where the sediments deposited during the ~~ary filling of its~~ endorheic stage are ~~is~~ relatively well preserved. Then, these two ~~bordering~~ adjacent basins are ~~then~~ characterized by contrasting preservation ~~states~~ of their endorheic stages and represent an ideal natural laboratory to evaluate the mechanisms that caused differential post-orogenic incision at the origin of divide migration ~~study what factors control drainage divide mobility, and drainage network and landscape evolution in post-orogenic basins.~~. Following a presentation of the geological context, we first compile evidence of fluvial captures along the Ebro-Duero divide, based on previous studies and our own investigations, and we map the location of knickpoints and relict portions of the drainage network. We use all these observations to reconstruct a paleo-divide position and to estimate the impact of divide migration in terms of drainage area and stream power. We complement this dataset by providing a map of χ across divide (Willett et al., 2014) to highlight potential disequilibrium state between rivers of the Ebro and Duero catchments. ~~We show here that contrasting excavation between the Ebro and Duero basins drives a reorganization of their drainage network through a series of captures and resulted in the southwestward migration of their main drainage divide. Fluvial captures have strong~~

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~~impact on drainage areas, fluxes, and so on incision capacity, especially for the captured basin. Thus, we conclude that drainage reorganization, and capture of the Duero rivers by the Ebro ones, independently from tectonics and climate, enable endorheism in the Duero basin due to drainage area loss.~~

2. Geological setting

2.1 The Ebro and Duero basins

The Ebro and Duero basins represent two hydrographic basins ~~covering~~ located in the northern part of the Iberian Peninsula (Fig. 1). The bedrock of the Ebro and Duero drainage basins mainly consists ~~on~~ of Cenozoic deposits, and Mesozoic and Paleozoic rocks in their headwaters (Fig. 2). They ~~used to~~ formed once a unique foreland basin during the Cenozoic controlled by the flexural loading by the surrounding mountain belts~~, connected in the Rioja Trough (Mikes, 2010), due to flexural subsidence related to the orogenic growth of their surroundings~~: the Pyrenees and the Cantabrian mountains to the north (Pulgar et al., 1999), the Iberian and Central Ranges to the south (Guimerà et al., 2004; De Vicente et al., 2007), and the Catalan Coastal Range (CCR) to the east (López-Blanco et al., 2000 ; Salas et al., 2001), during collision between Iberia and Europe since the Late Cretaceous.

~~Since early stage of collision~~From the Late Cretaceous, the Ebro and Duero basins were essentially filled by clastic deposits ~~siliciclastic and carbonated alluvial sediments~~, and opened toward the Atlantic Ocean in the Bay of Biscay (Alonso-Zarza et al., 2002). During the Late Eocene – Early Oligocene, the uplift in the Western Pyrenees (Puigdefàbregas et al., 1992) led to the closure of the Ebro and Duero basins as attested by the Ebro basin ~~and to~~ continentalization ~~in an endorheic setting~~dated at ~36 Ma (Costa et al., 2010). The center of these two basins became long-lived lakes filled with lacustrine, sandy, and evaporitic deposits from the Oligocene to the Miocene (Riba et al., 1983; Alonso-Zarza et al., 2002; Pérez-Rivarés et al., 2002, 2004; Garcia-Castellanos et al, 2003; Garcia-Castellanos, 2006; Larrasoaña et al., 2006; Vázquez-Urbez et al., 2013). The o~~O~~pening of the Ebro basin through the Catalan Coastal Range toward the Mediterranean Sea ~~to the East~~ occurred during the Late Miocene, leading to ~~important unfilling and~~kilometer-scale excavation ~~recorded~~ throughout the basin (Fillon and Van der Beek, 2012; Fillon et al., 2013; Garcia-Castellanos and

Larrasoaña, 2015). ~~However, its~~The exact timing and and processes driving the opening, as well as the role of~~its relation to~~ the Messinian Salinity Crisis, ~~as well as what processes is underlying this opening~~, ~~has~~ have long been debated (Coney et al., 1996 (post-Messinian); Garcia-Castellanos et al., 2003 (13-8.5 Ma);~~-~~Babault et al., 2006 (post-Messinian); Urgeles et al., 2010; Cameselle et al. (2014) (Serravallian-Tortonian); Garcia-Castellanos and Larrasoaña, 2015 (12-7.5 Ma)). ~~By contrast~~In contrast with the Ebro basin, incision in the upper Duero basin appears ~~very limited, although~~much less significant.~~-~~The Duero basin is characterized by a low relief topography (Fig. 1) in its upstream part, at 700-800 m above sea level to the west, and at 1000-1100 m a.s.l. to the north, northeast, and to the east in the Almazan subbasin, close to the divide with the Ebro basin.~~opening through the Iberian Massif toward the Atlantic Ocean to the west. occurred progressively from west to east by river capture and sediment colmatation of the basin~~The connection of the Duero River with the Atlantic Ocean occurred from the Late Miocene-Early Pliocene to the Late Pliocene-Early Pleistocene (Martín-Serrano, 1991). The current Ebro and Duero drainage networks are separated by a divide running from the Cantabrian belt to the NW, toward the SE in the Iberian Range (Figs. 1, 2, 3). In the following, we review the geological evolution of the different domains that constitute ~~today the~~this drainage divide between the Ebro and Duero drainage basins. ~~The current Ebro and Duero drainage networks are separated by a divide running from the Cantabrian belt to the NW, toward the SE in the Iberian Range (Figs. 1, 2, 3). The easternmost part of the Duero river is the Ebro tributaries that are the Jalon, Huecha, Queiles, Alama, Cidacos, Iregua, and Najerilla rivers, whereas the Arlanzon and Pisuerga rivers (Duero tributaries) are opposed to facing the Najerilla, Tiron, Oca, and Rudron rivers, and to the westernmost part of the Ebro river (Fig. 3). The Northeastern part of the Duero basin (the easternmost Duero river, the Arlanzon and Pisuerga rivers) mainly consists in broad flat valleys characterized by low incision depth, with low-gradient streams dominated by concave longitudinal profiles (Antón et al., 2012, 2014). By contrast, the western part of the Ebro basin is characterized by more incised valleys, especially in the Cantabrian and in the Cameros – Iberian Range domains, with more complex longitudinal profiles (knickpoints, remnants of high elevated surfaces).~~

2.2 ~~Geology and drainage divide in the~~ The Iberian Range

The Iberian Range (Figs. 2, 4) is a double vergent fold-and-thrust belt resulting from Late Cretaceous inversion of Late Jurassic-Early Cretaceous rift basins ~~rift-related Mesozoic basins~~

~~since the Late Cretaceous in response to~~during Iberia – Europe convergence (Salas et al., 2001; Guimerà et al., 2004; Martín-Chivelet et al., 2002). It is divided into two NW-SE ~~orientated~~ directed branches, the Aragonese and the Castillian branches, separated by the Tertiary Almazan subbasin ~~, which results from flexural subsidence due to thrusting in the Iberian Range~~ (Bond, 1996). The Almazan subbasin is connected to the Duero basin since the Early Miocene (Alonso-Zarza et al., 2002).

The Iberian Range is essentially made of marine carbonates ~~to~~ and continental clastic sediments ranging from ~~the~~ Late Permian to ~~the~~ Albian, ~~covering~~ overlying a Hercynian basement. The Cameros subbasin to the NW represents a~~n~~ late Jurassic-Early Cretaceous ~~highly subsiding~~ trough almost exclusively filled by continental siliciclastic deposits (Martín-Chivelet et al., 2002 and references therein; Del Rio et al., 2009). Shortening ~~is recorded up~~in the Iberian Range occurred from the Late Cretaceous to the Early Miocene, ~~and accomodated by hercynian~~along inherited Hercynian NW-SE structures (Gutiérrez-Elorza and Gracia, 1997; Guimerà et al., 2004; Gutiérrez-Elorza et al., 2002). ~~This event is responsible for the~~The opening of the Calatayud basin in the Aragonese branch occurred during the Early Miocene in response to right-lateral transpression on the ~~, as dextral and inverse deformations are recorded on its~~ southern margin of the Iberian Range (Daroca area) (Colomer and Santanach, 1988). It is followed during the Pliocene and the Pleistocene, by pulses of ~~extensive deformations leading to~~extension reactivating faults ~~fault reactivations~~ in the Calatayud basin, and ~~to~~ the formation of ~~new depressions~~grabens such as the Daroca, Munébrega, Gallocanta, and Jiloca grabens (Fig. 4; Colomer and Santanach, 1988; Gutiérrez-Elorza et al., 2002; Capote et al., 2002). This is also outlined by the occurrence of Late Pliocene to Early Pleistocene breccias and glacis levels ~~deposited~~ in the Daroca and Jiloca grabens ~~from the Late Pliocene to the Early Pleistocene~~ (Gracia, 1992, 1993a; Gracia and Cuchi, 1993; Gutiérrez-Santolalla et al., 1996). These Neogene troughs are filled by continental deposits and pediments, up to the Quaternary (Fig. 4). The Neogene tectonic ~~history of~~ pulses in the Iberian ~~Range is characterized by tectonic pulses intercalated with~~are interrupted by periods of quiescence ~~periods responsible for the formation of~~during which erosion surfaces ~~from the Early Miocene to the Late Pliocene – Early Pleistocene~~developed (Gutiérrez-Elorza and Gracia, 1997). ~~These surfaces are highly reworked and/or deformed due to subsequent tectonic activity, except for the youngest one, which appears only affected by surface processes as fluvial incision (Gutiérrez-Elorza and Gracia, 1997).~~

~~Uplift in~~ Deformation and uplift of the Iberian Range and Cameros basin resulted in the development of a new drainage divide between the Duero and Ebro basins and in the isolation of the Almazan subbasin (Alonso-Zarza et al., 2002). In contrast, the connection between the Duero the Ebro basins has not been affected by significant deformation and uplift in the proto-Rioja trough ~~separating the Duero from the Ebro, whereas they are still connected to the Northwest, especially through the proto-Rioja trough~~ (Mikes, 2010). ~~Compression in the Northwest Iberian Range continues and the inverted Cameros basin is deformed as a large anticline that plunges to the W-NW, finally connecting to the Cantabrian domain through the Rioja trough in the Late Oligocene. This disconnects the Ebro from the Duero basins, localizing the divide further East from its present-day location (Pineda, 1997; Mikeš, 2010). During the Early Miocene, the Almazan subbasin, initially connected to the Ebro, became connected to the Duero basin (Alonso-Zarza et al., 2002), whereas in the Iberian Range, the formation of the Calatayud basin separated the Ebro from the Almazan-Duero basin.~~

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

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2.3 G~~eology and drainage divide in the~~ The Rioja trough and ~~the~~ Bureba high

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

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

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2.4 Climate evolution

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

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

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

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

3. Morphometric evidence of divide mobility between the Duero and Ebro catchments ~~Morphometric analyses~~

The easternmost part of the Duero river is opposed to the Ebro tributaries that are the Jalon, Huecha, Queiles, Alama, Cidacos, Iregua, and Najerilla rivers, whereas the Arlanzon and Pisuerga rivers (Duero tributaries) are opposed to ~~facing~~ the Najerilla, Tiron, Oca, and Rudron rivers, and ~~to~~ the westernmost part of the Ebro river (Fig. 3). The n~~N~~ortheastern part of the Duero basin (the easternmost Duero river, the Arlanzon and Pisuerga rivers) mainly consists

~~in~~of broad flat valleys characterized by low incision depth, ~~with~~ low-gradient streams dominated by concave longitudinal profiles (Antón et al., 2012, 2014). By contrast, the western part of the Ebro basin is characterized by more incised valleys, especially in the Cantabrian and in the Cameros – Iberian Range domains, with more complex longitudinal profiles (knickpoints, remnants of high elevated surfaces). Previous studies (Gutiérrez-Santolalla et al., 1996; Pineda, 1997; Mikes, 2010) already ~~been~~ shown that the Jalon and Homino rivers, which belong to the Ebro basin, have recently captured parts of the Duero basin in the Iberian Range and in the Rioja trough, respectively~~ (Gutiérrez-Santolalla et al., 1996; Mikeš, 2010~~). Such evolution has been recorded by the occurrence of geomorphological markers as wind gaps and elbows of captures, as well as by the presence of knickpoints and/or remnants of high elevated surfaces in river long profiles. To highlight this dynamic evolution, we performed a morphometric analysis of rivers all around the divide separating the Ebro basin from the Duero basin, with particular attention given to the Aragonese branch of the Iberian Range (Fig. 4) and to the Rioja Trough (Fig. 5), where captures have already been described.

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

3.1 Fluvial captures and related knickpoints in the Iberian Range

~~River capture evidences~~evidence ~~from geological, morphological and morphometric analyses~~

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

~~3.1.1 Jalon river area~~

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

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

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

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

~~3.1.2~~ 3.2 Fluvial captures and related knickpoints in the ~~The~~ Rioja trough area

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In the Rioja trough area, the position of the Ebro-Duero divide is partly controlled by the Bureba anticline.~~The Bureba area~~ It consists ~~in~~ of folded Middle Cretaceous to Early Miocene series, covered by undeformed Middle Miocene to Holocene deposits (Fig. 5). The ~~main structural feature is the Bureba~~ anticline~~,~~ is orientated E-W to the west and NE-SW to the east~~, cored by Albian strata and topped by Santonian limestones and dolomites.~~ The western part of the Rioja trough to the west of the NE-SW directed branch of the Bureba anticline (Fig. 5), used to be drained toward the Duero basin since the Oligocene (Pineda, 1997; Mikes, 2010). The westward migration of the divide to its current location is thought to have occurred in several steps of captures as shown by the occurrence of remnants of escarpments during the Late Miocene - Pliocene (Mikeš, 2010). Once the eastern branch of the Bureba anticline has been incised, the Ebro tributaries captured the western part of the Rioja trough, up to the E-W branch of the Bureba anticline to the southwest, from the Late Miocene to the Pliocene. The western part of the anticline forms a topographic ridge that is incised by Jordan river (Fig. 5) in a place where the divide between the Ebro and Duero river networks is located to the north of the ridge. To the East of this location however, the topographic ridge formed by the Bureba antcline controls the current location of the main drainage divide ~~between the Ebro and Duero river networks~~ (Fig. 5). ~~This ridge is incised by four rivers that are from west to east, the Ubierna with the Jordan river, the Hoz,~~Here, the ridge exhibits several wind gaps, located on the northward prolongation of the Hoz, ~~the~~ Rioseras, and ~~the~~ Nava Solo rivers (Figs. 5, 7). Further east, the Diablo river does not incise the ridge and its headwater is located in the core of the eastern branch of the Bureba anticline, the Fuente Valley (Fig. 5). These ~~five~~ last streams are tributaries of the Ubierna river, which is a tributary of the Arlanzon river and so, of the Duero river. To the north, the Ebro river system is represented, from west to east, by the Homino river (a tributary of the Oca river) and its four tributaries, the Molina, the Fuente Monte, the Zorica, and the San Pedro rivers (Figs. 5, 7). All these streams are outlined by Late Pleistocene to Holocene alluvial series that are deposited at the bottom of their respective valleys. Valleys from the Duero side appears larger than those from the Ebro side, which are significantly more incised.

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

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

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

Further east, the headwater of the Diablo river is located on the depression represented by the core of the eastern branch of the Bureba anticline, the Fuente valley. In its prolongation to the northeast, the San Pedro river incises the northeastern termination of the anticline from the north before entering the valley, leading to a ~~remarkable~~ southward retreat of the divide (Fig. 5). Capture is again evidenced by important incision contrast between Ebro and Duero systems, and by sharp knickpoints on the upper reach of the San Pedro river long profile when crossing the Santonian dolomites (Fig. 8). According to this whole set of observations, and in agreement with previous findings of Pineda (1997) and Mikes (2010), we propose that the western part of the Rioja trough, in the Bureba area has been recently captured by the Ebro drainage network leading to a sequence of ~~significant~~ southwestward retreat of the main drainage divide, toward the Duero basin (Fig. 7E).

~~3.1.3 Other capture features along the Ebro/Duero drainage divide~~

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

~~Both the Ebro river and several tributaries show high elevated ~10-20 km long flat domains at ~800 – 1200 m a.s.l. and major knickpoints in the upper reach of their long profiles as the Rudron, Queiles, and Alama rivers, as well as the Homino river and its tributaries: the Puerta~~

~~Nogales and Valdelanelala rivers (Figs. 5, 8; Fig. S1). All these domains may not be related to surface uplift as they are not clearly associated to active tectonic features.~~

~~It has been shown that the occurrence of high elevated, low-relief surfaces, may result from drainage reorganization leading to isolation and starvation of a drainage area, rather than remnants of ancient erosional conditions or uplift (Yang et al., 2015). The Duero basin is characterized by a high mean elevation (~1000 m) and by a very limited incision in the vicinity of the Ebro/Duero drainage divide. A sudden divide migration toward the Duero basin is then expected to isolate such high elevated and relatively preserved surfaces.~~

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

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

We used all observations that support divide migration in the Iberian Range and Rioja trough to estimate a paleo-position of the drainage divide between the Duero and Ebro drainage basins (Fig. 9). For this purpose, we considered the location of major knickpoint along the rivers where fluvial captures are defined. Both the Ebro river and several tributaries show high elevated ~10-20 km long flat domains at ~800 – 1200 m a.s.l. and major knickpoints in the upper reach of their long profiles as the Rudron, Queiles, and Alama rivers, as well as the Homino river and its tributaries: the Puerta Nogales and Valdelanelala rivers (Figs. 5, 8; Fig. S1). All these flat domains may not be related to surface uplift as they are not clearly associated ~~to~~with active tectonic features.

~~It has been shown that the occurrence of high elevated, low-relief surfaces, may result from drainage reorganization leading to isolation and starvation of a drainage area, rather than remnants of ancient erosional conditions or uplift (Yang et al., 2015).~~ The Duero basin ~~is~~being characterized by a high mean elevation (~1000 m) and by a very limited incision in the vicinity of the Ebro/Duero drainage divide~~. A~~, a sudden divide migration toward the Duero basin is then expected to isolate such high elevated and relatively preserved surfaces. We suggest these flat domains have been recently captured by Ebro tributaries, and represent remnants of Duero drainage areas, ~~isolated~~ integrated into the Ebro catchment from ~~due to important~~ divide retreat toward the Duero basin.

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

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

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3.~~2~~4 ~~Chi (*X*)~~ *X* map

~~3.2.1 Background~~

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

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

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

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

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

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

~~The comparison between equations (1) and (3) show that ks may vary according to the uplift rate and by consequent spatial variations in ks can potentially be used to infer spatial variations in U (Kirby and Whipple, 2012). In a region where spatial variations in U are not expected, variations in ks may also reflect disequilibrium along the river, on the form of a knickpoint for example (Whipple and Tucker, 1999).~~

The comparison of the shape of longitudinal profiles of rivers across divide is a way that has been proposed recently to infer disequilibrium between rivers and the potential migration of their divide (Willett et al., 2014). Although the slope-area analysis of channel profiles (e.g. Whipple and Tucker, 1999; Kirby and Whipple, 2012) is potentially a powerful tool to evidence differences in the equilibrium state of rivers across divide, and then to infer their migration (Willett et al., 2014), this method is limited and even biased by the quality of the topographic data. Indeed, both a low-resolution of the DEM and corrections brought to the DEM (filling or carving), lead to substantial uncertainties that are automatically transferred to the slope~~, k_s and θ~~ -area data. To avoid slope measurements, Perron and Royden (2012) proposed a procedure based on a coordinate transformation allowing linearizing river profiles. ~~by using the elevation of each point along the profile (x) instead of the slope in the stream power equation.~~

Considering ~~steady-state with~~ constant uplift rate (U) and erodibility (K) in time and space~~,~~ ~~Equation (3) may be solved as follows~~ the χ-transformed profile of a river is defined by the following equation (Perron and Royden, 2012; Mudd et al., 2014):

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

with

$$\chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx \qquad (2)$$

w~~W~~here z (x) is the elevation of the channel, x is the longitudinal distance, -z_b is the elevation at the river's base level (distance x_b), A is the drainage area, A_0 is a reference ~~scaling~~ drainage area, and exponents m and n are empirical constants. ~~chi is an integral function of the drainage area along the channel network.~~

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When using the χ variable instead of the distance for plotting the elevation z along channel, (χ-plot),~~ »~~ ~~(elevation versus *X* diagram) of~~ the longitudinal profile of a steady-state channel is shown as a straight line (Perron and Royden, 2012). ~~This implies that~~Any channel~~s~~ pulled away from this line ~~are~~ is in disequilibrium and ~~are~~ is then expected to attempt to reach equilibrium. Mapping χ~~chi~~ on several watersheds and comparing χ~~chi~~ across drainage divides is then a potential way to high disequilibrium between rivers across divide and to elucidate ~~the basins dynamics and~~divide migration and drainage reorganization~~s~~ through captures (Willett et al., 2014).

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We used the Chi Analysis Tool developed by Mudd et al. (2014) to select the best m/n ratio by iteration (Perron and Royden, 2012) and to calculate ~~chi~~ χ for rivers throughout the ~~connection~~ divide between the Ebro and Duero basins from a similar base level at 850 m a.s.l. The best mean m/n ratio for all our streams is 0.425, which falls in the typical range of values observed for rivers (~0.4 – 0.6; e.g.) ~~characteristic of simple settings with uniform substrate, uplift rate and climate (~~Kirby and Whipple, ~~2001,~~ 2012~~; Wobus et al., 2006~~). The resulting map (Fig. ~~10~~11) shows ~~X~~ χ values calculated on different opposite streams in the vicinity of the Ebro/Duero drainage divide. Similar values on both sides of the divide suggest the two opposite streams are at equilibrium, whereas strong contrasted ~~X~~ χ values imply disequilibrium leading to divide migration, continuously or through fluvial capture, toward the high χ values ~~stream~~ (Willett et al., 2014).

~~3.2.2 Application to the divide between the Ebro and Duero basins~~

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The map of ~~X~~ χ values actually shows significant contrasting values across the Ebro/Duero divide. We comment here these contrasts along the divide from the SE to the NW of the area considered (Fig. ~~10~~11).

There is a strong contrast in χ~~X~~ values between the headwater of the Jalon river (Fig. ~~10~~11), characterized by low values (~300 m), and the closest part from the divide of the Bordecorex river (Fig. 4), a tributary of the Duero river (~500 m). Such a disequilibrium implies divide migration toward the Duero basin, predicting the capture of the uppermost reach of the Bordecorex river by the Jalon river. To the north, tributaries of the Jalon river show slightly lower χ~~X~~ values than the tributaries of the Duero river. This suggests a relative ~~equilibrium~~ stable situation although ~~little~~ small captures may occur toward the Duero basin. A higher contrast is observed around the easternmost part of the Duero basin, which is surrounded by the Ebro basin. The Araviana river (tributary of the Duero river) seems to be taken in a bottleneck between the Manubles river to the south and the Queiles river to the north (Fig. 4), which both show lower χ~~X~~ values (Fig. ~~10~~11). Toward the E~~e~~ast, there is a strongest χ~~X~~ values contrast between headwaters of the Araviana river (>700 m) and of the Isuela (Jalon tributary) and Huecha rivers (<100 m). This domain appears clearly in disequilibrium and is expected to be captured by the Ebro drainage network. Such high χ~~X~~ values differences appear also to the northwest (Fig. ~~10~~11), in the southern part of the Cameros basin where the Duero river and its tributaries' headwaters show χ~~X~~ values >500-700 m, whereas the facing rivers (Alama, Cidacos, Iregua, and Najerilla) are all characterized by low χ~~X~~ values <100 m. This predicts important disequilibrium and divide migration and fluvial captures toward the south. Northwestward, χ~~X~~ values between Duero and Ebro network are more similar indicating that the divide is relatively more stable here, up to the westernmost part of the Ebro basin (Fig. ~~10~~11). However, there are some slight localized χ~~X~~ values contrast~~s~~ (~200 / ~450 m) as observed between the Tiron and the Arlanzon rivers, between the Rudron and the

Ubierna and Urbel rivers, and between the Ebro and the Pisuerga rivers (Fig. ~~10~~11). These suggest minor local captures toward the Duero basin.

To sum up, χ~~X~~ values calculated in the vicinity of the drainage divide between the Ebro and Duero river networks show a general disequilibrium (Fig. ~~10~~11) as the Ebro network is characterized by low χ~~X~~ values (up to ~200-300 m) compared to those for the Duero network (up to ~450-700 m). In complement with all the ~~evidences~~evidence of divide displacements induced by captures described previously this allows predicting a general divide migration toward the Duero basin through headwater retreat~~ and river captures~~, in favor of the Ebro tributaries, especially around the Almazan subbasin, which is expected to be entirely captured by the Ebro basin.

4. Discussion

4.1 Long term trend of divide migration

The oldest capture evidence in our study area corresponds to the incision of the northern part of the Iberian Range by the Jalon river and by the capture of the Calatayud basin, attributed to the post-Messinian (Gutiérrez-Santolalla et al. 1996). We propose~~show~~, ~~by using~~ based on morphological evidence (Fig. 4) and in agreement with stratigraphic data (Gutiérrez-Santolalla et al. 1996), that the Jalon river system captured the Jiloca graben to the east since the Early Pleistocene, before progressively capturing the Almazan subbasin toward the west in the Holocene (Gutiérrez-Santolalla et al. 1996). From χ~~X~~ analysis (Fig. 11~~0~~), we deduce~~d~~ that the eastern part of the Duero basin, the Almazan subbasin, is being actively captured by Ebro tributaries that drained the Iberian Range and the Cameros basin. Despite low contrasts in χ~~X~~ values, local captures are also ~~evidenced~~ suggested in the vicinity of the Ebro / Duero drainage divide toward the northwest. Capture is ~~also well~~further ~~witnessed~~ implied by the occurrence of numerous high elevated (~1000 m) knickpoints and low-relief surfaces (Figs. 5, 8, 9, ~~10~~11).

Thus, there is a good correlation between χ~~X~~ predictions and morphological and stratigraphic data implying ~~for a~~ long-lasting ~~continuity for~~ captures and divide migration during Pliocene, Pleistocene, and Holocene times in favor of the Ebro basin.~~ during Pliocene, Pleistocene, and Holocene times~~.

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

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

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

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

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

Our stream power analysis along the Duero river (Fig. 10) shows that the difference in drainage area of the Duero inferred from our paleo-divide map (Fig. 9) induces a noticeable decrease ~~The remarkable difference~~ of stream power values of the Duero in the vicinity of the knickzone~~ (Fig. 11)~~. This stream power is a minimum estimate because calculation does not take into account possible captures and divide migration in other areas along the Duero basin divide, nor the full history of the divide migration through time and the related ongoing decrease in water discharge as documented in laboratory-scale landscape experiments (Bonnet, 2009). Some contrasts of incision are also observed in the Iberian Range along the southern border of the Duero, and in the Cantabrian domain to the North. Both show more important incision than in the Duero basin, suggesting potential river captures and divide migration at the expense of the Duero basin, increasing the total of lost drainage area~~, especially in domains where precipitation rates are higher than inside the basin (Fig. 6)~~. Even if it gives minimal estimate, our stream power analysis suggests that drainage area reduction may have limited~~s~~ the erosion in the Duero basin~~ as it helps ~~. This provides an explanation for the preservation of the lithologic barrier to the west, along the main knickzone of the Duero considered as an intermediate, local base level (Antón et al., 2012).We~~ then~~ propose that the reduction of the Duero drainage area ~~of the Duero basin that we document here, partly due to divide migration induced~~caused by captures and incision in the Ebro basin, is responsible for a significant decrease of the incision capacity in the Duero basin. ~~Then, active exorheism~~We infer that the ongoing exorheic stage of~~in~~ the Ebro basin ~~is likely~~may be responsible for the current preservation of large morphological relicts of the~~ -quasi ~~endorheic stage in ~~morphology of ~~the Duero basin.

~~and from the widespread excavation resulting from the opening of the Ebro basin toward the Mediterranean Sea since the Late Miocene.~~

The opening of the Ebro basin toward the Mediterranean Sea resulted in a drastic base level ~~down ~~drop. ~~We suggest this~~This results in the establishment of an upstream-migrating incision wave that propagates to every tributary of the ~~Duero ~~Ebro network, responsible for knickpoints migration (Schumm et al., 1987; Whipple and Tucker, 1999; Yanites et al., 2013) and for drainage reorganization and divide migration. The χ~~Chi~~ analysis that we performed along the current Ebro-Duero divide (Fig. ~~10~~11) highlights areas where geomorphic disequilibrium ~~still stands today~~is still ongoing, which suggests that they are areas where divide is ~~still ~~currently mobile. The modelling study performed by Garcia-Castellanos and Larrasoaña (2015) suggests that the re-opening of the Ebro basin occurred between 12.0 and 7.5 Ma. This indicates that the growth of the drainage network of the Ebro basin and the establishment of new steady-state conditions is a long-lived phenomenon, which is still not achieved today.

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

~~To better resolve the impact of such drainage area reduction on incision capacity, we perform a stream power analysis of the Duero river. We consider the specific stream power, ω, defined as $\omega = \rho\ g\ Q\ S\ /\ W$, where ρ is water density, g is gravitational acceleration, Q is discharge, S is local river gradient, and W is river width (see the Supplement for details of the calculation). We calculate ω for the present-day Duero river, and for a restored ancient Duero river that drained this 12% of lost area. We plot the difference (ancient – present day) between the two curves in Figure 11, with the Duero river long profile. Calculated difference in specific stream power values are relatively low (< 2 W m^{-2}) for the upstream part of the basin, but increase to ~5 W m^{-2} when approaching the major knickzone at a distance of ~350 km from the river mouth. The knickzone is characterized by peak values exceeding 10 W m^{-2}, which rapidly decrease to ~0 W m^{-2} at the base of the knickzone (~200 km) and up to the river mouth (Fig. 11). Some alternating peak and null values are observed in the lower reach of the river and may be related to the occurrence of numerous dams along the river.~~

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~~Overall, the specific stream power calculated for the ancient Duero river show higher values than for the present day from the base of the knickzone to the uppermost reach of the river (Fig. 11). This implies a general decrease of the Duero river's incision capacity between this ancient state to the present day~~.

Comment [S6]:

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

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

Conclusion

In this paper we present a morphometric analysis of the landscape along the divide between the Ebro and Duero drainage basins located in the northern part of the Iberian Peninsula. This area shows numerous evidence of river captures by the Ebro drainage network resulting in a long-lasting migration of their divide toward the Duero basin. Although these two~~Ebro and Duero~~ basins ~~both~~ record~~ed~~ a similar geological history, with a long endorheic stage during Oligocene and Miocene times, they show a very contrasted incision and preservation state of their original endorheic morphology. Since the Late Miocene, the Ebro basin was~~is~~ opened to the Mediterranean Sea and record important ~~unfilling~~erosion. On the opposite, the Duero was opened to the Atlantic Ocean since the Late Miocene – Early Pliocene but its longitudinal profile exhibits a pronounced knickpoint, which delimits an upstream domain of low relief and limited incision, likely representing a relict of its endorheic topography. We propose that this contrast of incision is the main driver of the drainage reorganization and migration of divide that we document. ~~This results in important incision driven by a very active drainage network. By contrast, the Duero basin is opened to the Atlantic Ocean since the Late Miocene – Early Pliocene and record only limited incision. Its upper part is considered as still almost endorheic.Such contrast in river-driven incision leads to important drainage reorganization between the two basins as shown by numerous occurrences of river captures by the Ebro basin network, and divide migration toward the Duero basin~~. The morphological analysis of rivers across the divide highlights areas where geomorphic disequilibrium is still ongoing, which

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suggests that the Ebro-Duero divide is currently mobile. The quantification of the decrease of the d~~D~~rainage area of the Duero based on the reconstruction of a paleo-position of the Ebro-Duero divide~~lost~~ shows that it results ~~then~~ in ~~the~~ a significant lowering of the ~~incision capacity~~stream power of the Duero ~~basin~~river, particularly along its knickzone. We suggest that divide migration induces a decrease of the incision capacity of the Duero river, thus favoring ~~its almost~~ the preservation of large relicts of the ~~its~~ endorheic ~~stage configuration~~ morphology in the upstream part of this basin.

Author contributions

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

Competing interests.

The authors declare that they have no conflict of interest.

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Figure captions:

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

Figure 2: Simplified geological map of the study area.

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

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

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

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

Figure 7: A) 3D topographic map of the Bureba sector showing important incision in the Ebro basin contrasting with the well-preserved Duero basin, and river capture ~~evidences~~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) ~~Remarkable~~ W~~w~~ind gaps located on the Bureba anticline. Pictures have been taken from the north of this structure toward the south. E) Possible three steps evolution of the southwestward divide retreat through multiple river captures witnessed in the area.

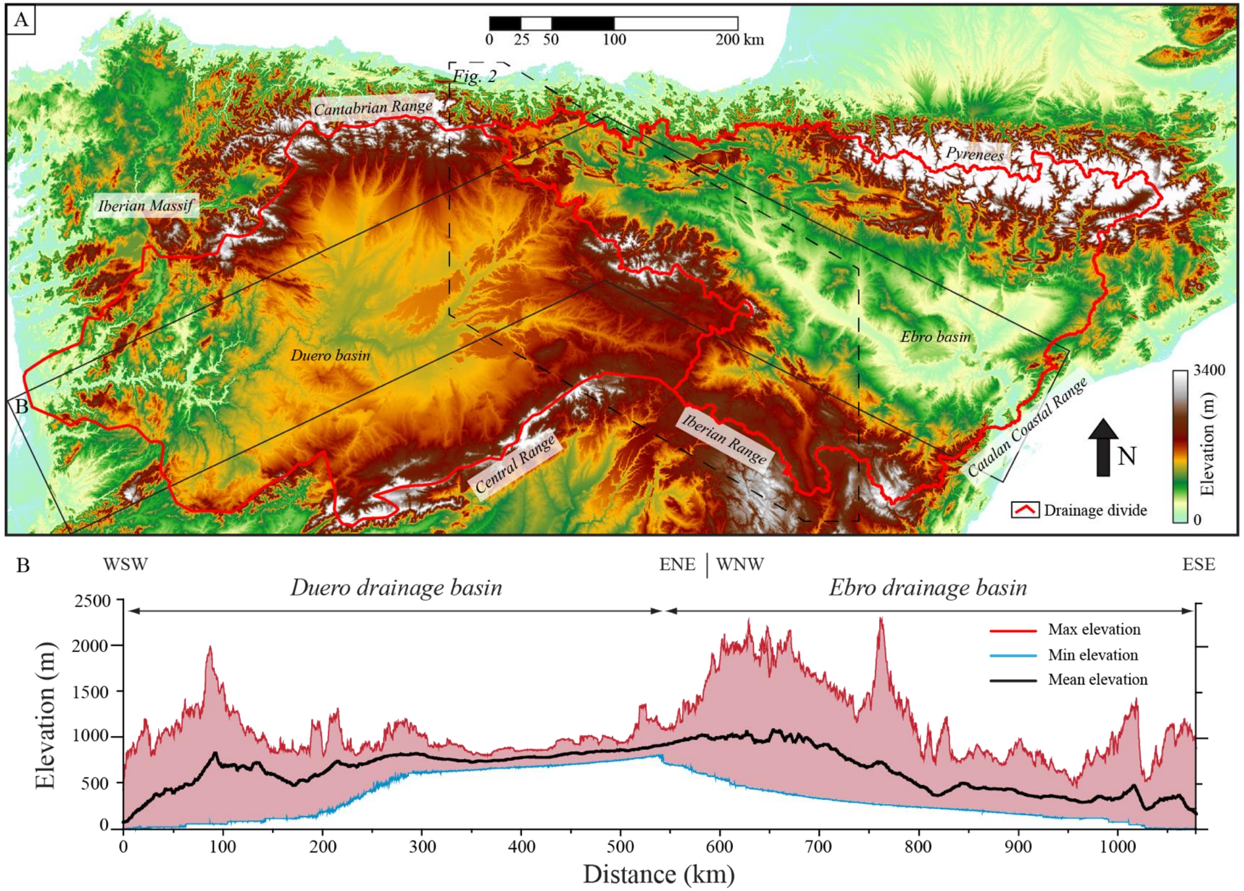
Figure 8: River long profiles for all the streams described in the Bureba area showing remarkable ~~evidences~~evidence of river capture. Colors are given to rivers that are linked in these capture processes.

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

Figure 10~~1~~: The Duero river long profile (black line) is compared to the difference between the specific stream power calculated for the possible ancient and for the present-day Duero river, in grey. Positive values suggest a diminution of the incision capacity of the Duero river, through time. Details on calculation are available in the Supplement (Section S1).

Figure 11~~0~~: Topographic map with *X* values calculated on different opposite streams in the vicinity of the Ebro/Duero drainage divide. This map shows significant contrasting values between the Ebro and Duero drainage networks.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50
100
200 km
Fig. 2
Cantabrian Range
Pyrenees
Iberian Massif
Duero basin
Ebro basin
B
Central Range
Iberian Range
Catalan Coastal Range
3400
Elevation (m)
0
N
Drainage divide
B
WSW
ENE
WNW
ESE
Duero drainage basin
Ebro drainage basin
Max elevation
Min elevation
Mean elevation
Elevation (m)
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800
900
1000
Distance (km)

Figure 1

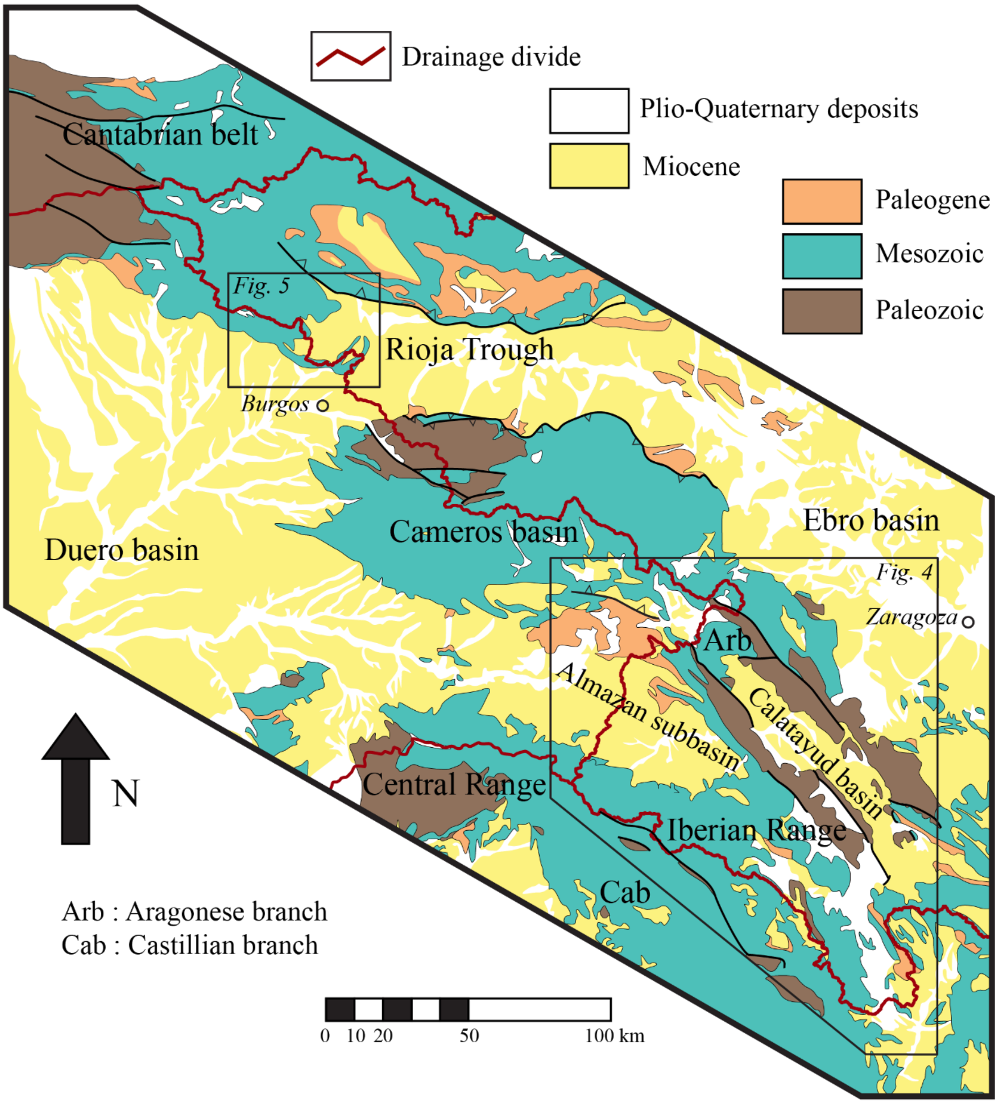
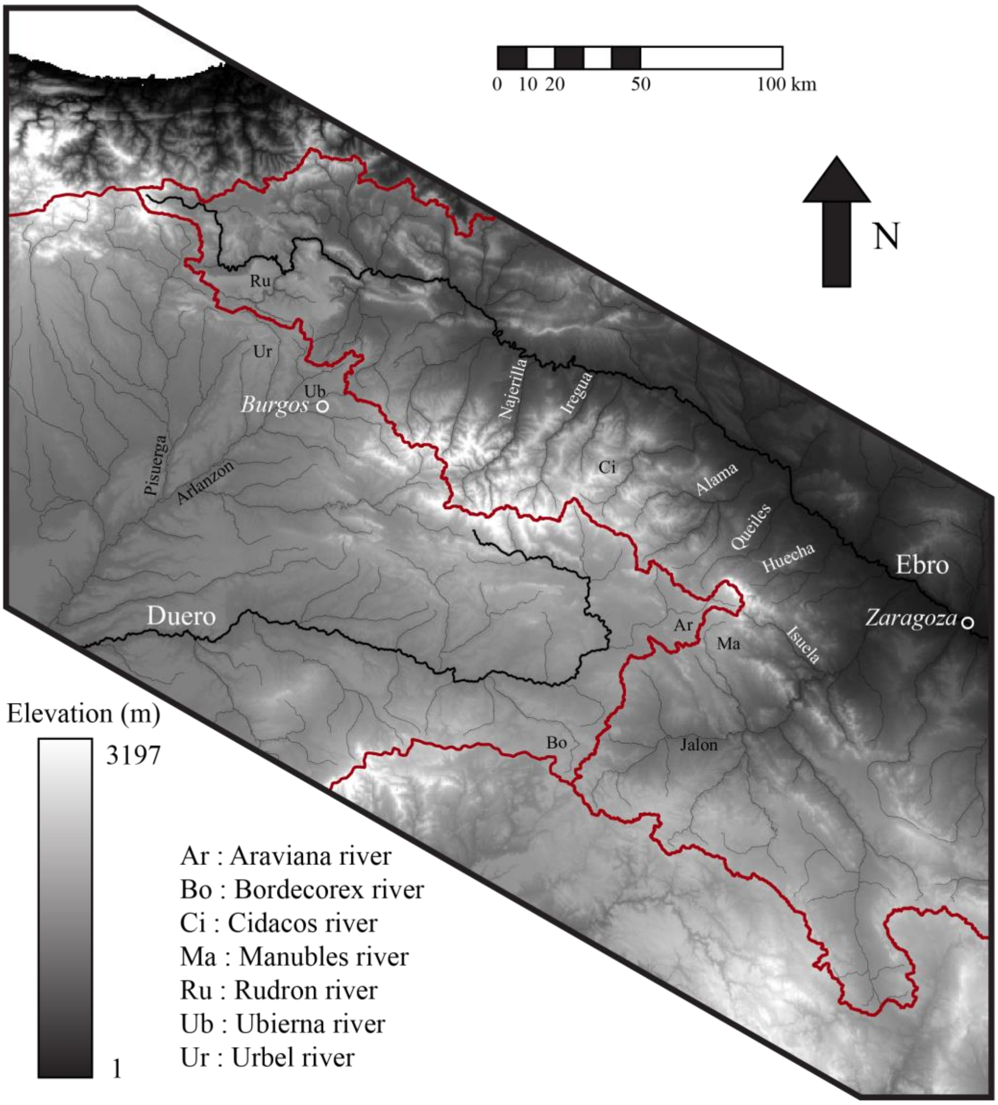

Drainage divide
Plio-Quaternary deposits
Miocene
Paleogene
Mesozoic
Paleozoic
Cantabrian belt
Fig. 5
Rioja Trough
Burgos
Cameros basin
Ebro basin
Duero basin
Fig. 4
Zaragoza
Arb
Almazan subbasin
Calatayud basin
Central Range
Iberian Range
Cab
N
Arb : Aragonese branch
Cab : Castillian branch
0 10 20 50 100 km

Figure 2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Arlanzon
Ci
Alama
Queiles
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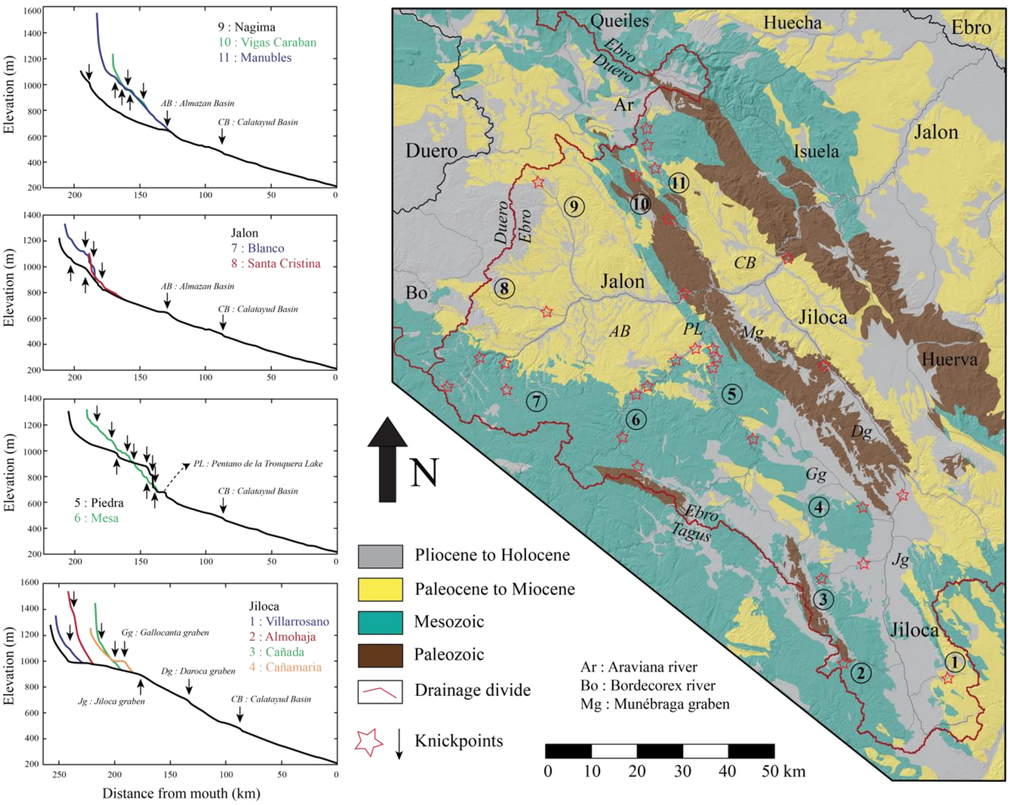
Ebro
Zaragoza
Duero
Ar
Ma
Isuela
Bo
Jalon
Elevation (m)
3197
1
Ar : Araviana river
Bo : Bordecorex river
Ci : Cidacos river
Ma : Manubles river
Ru : Rudron river
Ub : Ubierna river
Ur : Urbel river

Figure 3



Elevation (m)
9 : Nagima
10 : Vigas Caraban
11 : Manubles
AB : Almazan Basin
CB : Calatayud Basin
Jalon
7 : Blanco
8 : Santa Cristina
PL : Pentano de la Tronquera Lake
5 : Piedra
6 : Mesa
Jiloca
1 : Villarrosano
2 : Almohaja
3 : Cañada
4 : Cañamaria
Gg : Gallocanta graben
Dg : Daroca graben
Jg : Jiloca graben
Distance from mouth (km)
Queiles
Huecha
Ebro
Duero
Ar
Isuela
Jalon
Bo
CB
AB
PL
Mg
Jiloca
Huerva
Dg
Gg
Jg
Tagus
N
Pliocene to Holocene
Paleocene to Miocene
Mesozoic
Paleozoic
Drainage divide
Knickpoints
Ar : Araviana river
Bo : Bordecorex river
Mg : Munébraga graben
0 10 20 30 40 50 km

Figure 4

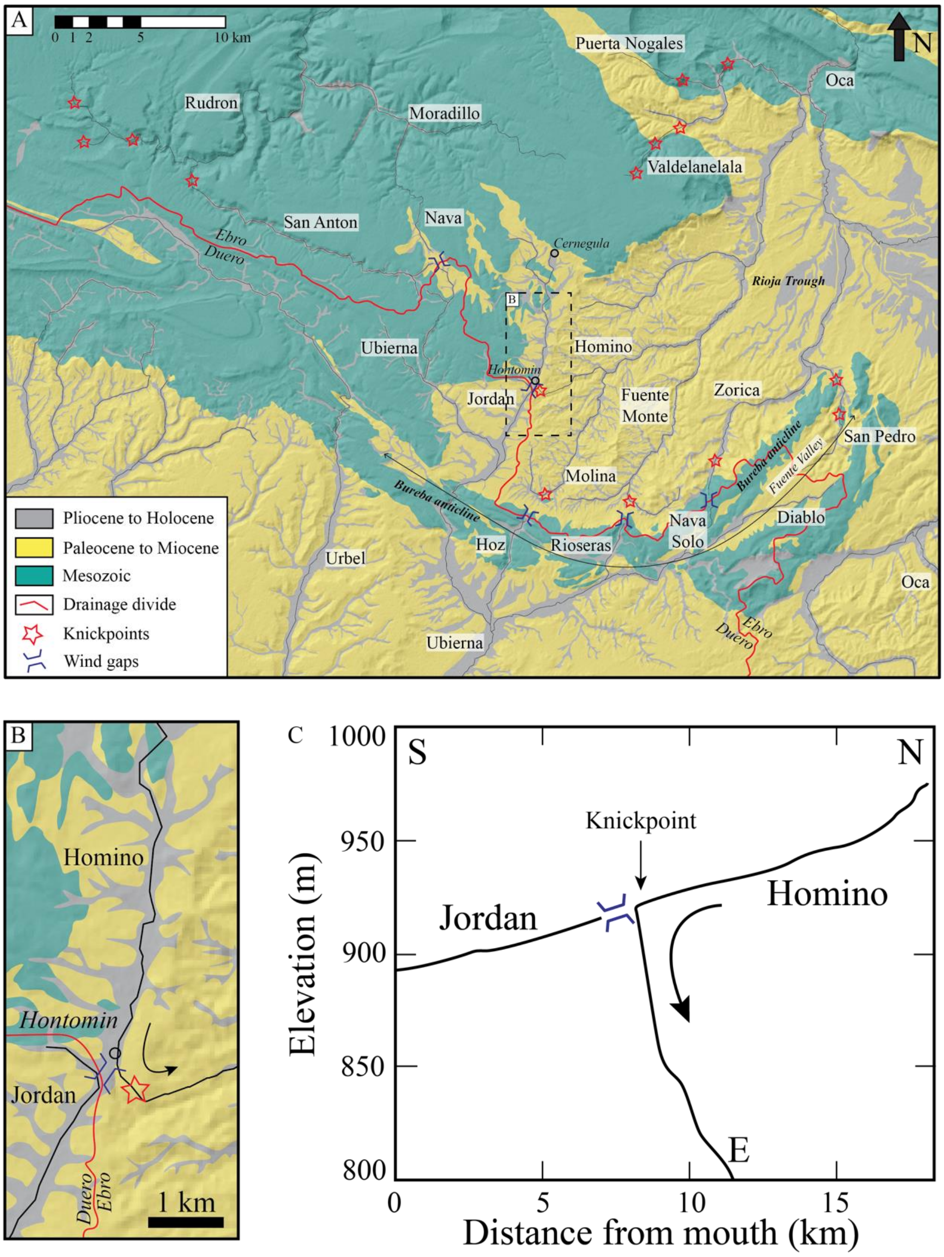

A
0 1 2 5 10 km
N
Puerta Nogales
Oca
Rudron
Moradillo
Valdelanelala
San Anton
Nava
Ebro
Duero
Cernegula
Rioja Trough
B
Ubierna
Homino
Hontomin
Jordan
Fuente Monte
Zorica
San Pedro
Bureba anticline
Fuente Valley
Molina
Nava Solo
Diablo
Hoz
Rioseras
Urbel
Oca
Ubierna
Pliocene to Holocene
Paleocene to Miocene
Mesozoic
Drainage divide
Knickpoints
Wind gaps
B
Homino
Hontomin
Jordan
Duero
Ebro
1 km
C
S
N
Knickpoint
Jordan
Homino
E
Elevation (m)
1000
950
900
850
800
0
5
10
15
Distance from mouth (km)

Figure 5

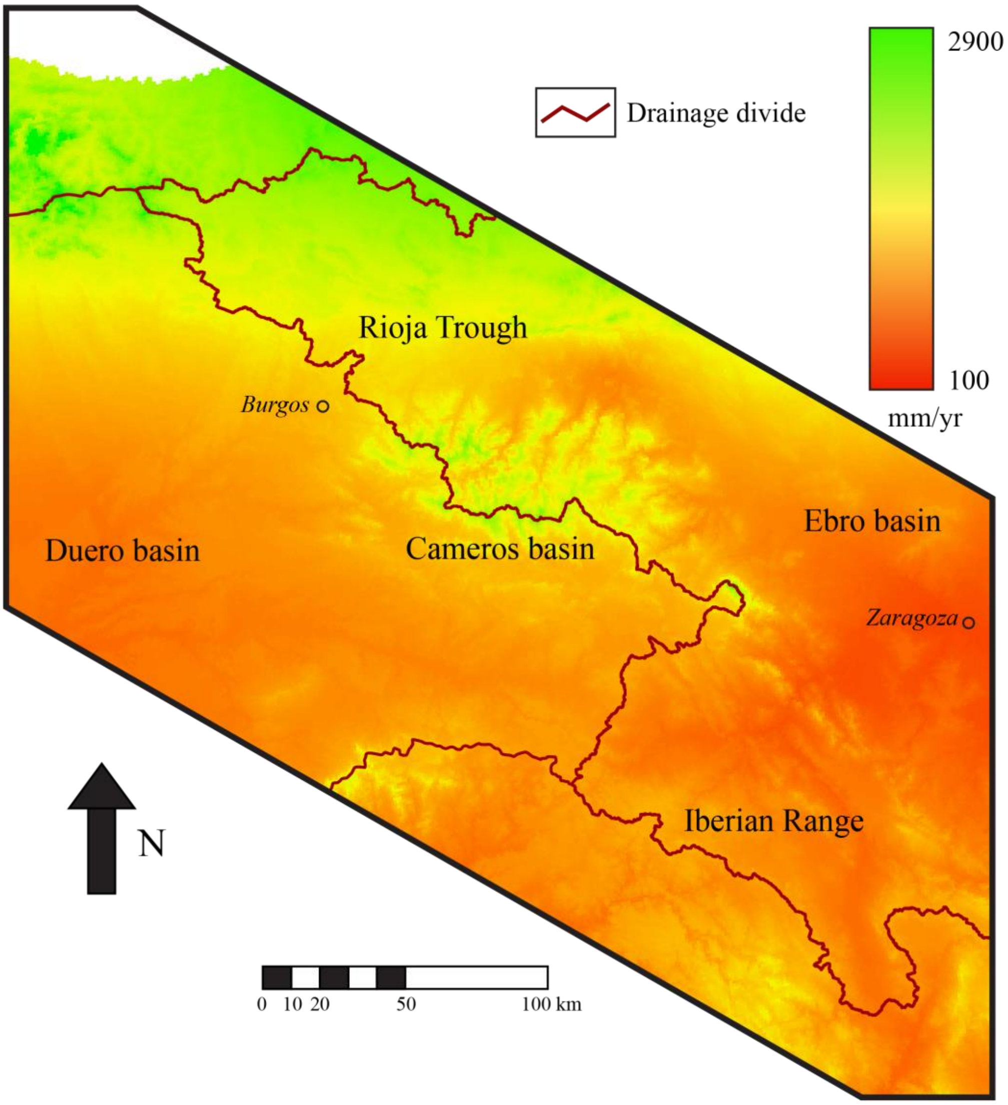

Drainage divide
2900
100
mm/yr
Rioja Trough
Burgos
Ebro basin
Duero basin
Cameros basin
Zaragoza
Iberian Range
N
0
10
20
50
100 km

Figure 6

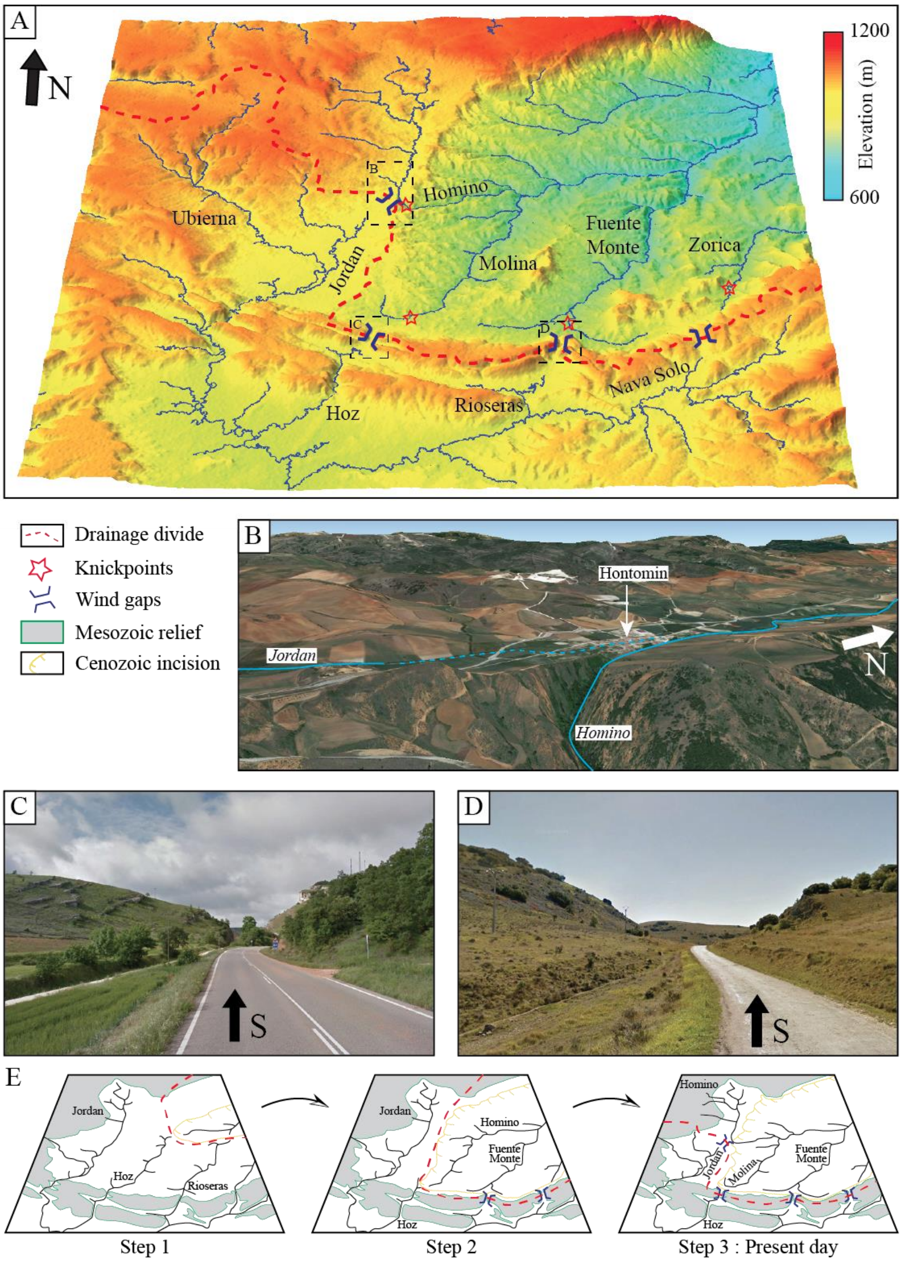

A
N
1200
Elevation (m)
600
Homino
Ubierna
Jordan
Fuente Monte
Zorica
Molina
Hoz
Rioseras
Nava Solo
B
C
D
Drainage divide
Knickpoints
Wind gaps
Mesozoic relief
Cenozoic incision
B
Hontomin
Jordan
Homino
N
C
S
D
S
E
Jordan
Hoz
Rioseras
Step 1
Jordan
Homino
Fuente Monte
Hoz
Step 2
Homino
Jordan
Molina
Fuente Monte
Hoz
Step 3 : Present day

Figure 7

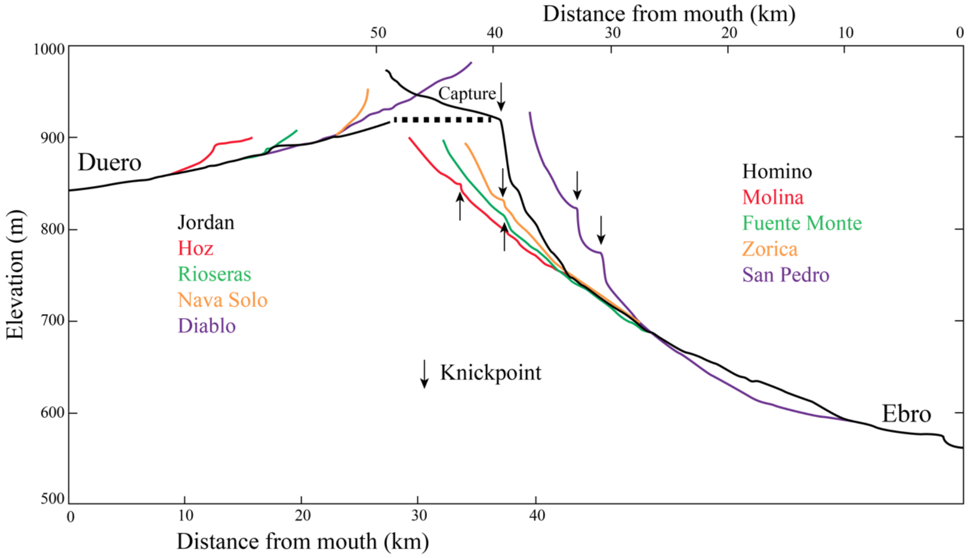

Distance from mouth (km)
50
40
30
20
10
0
1000
900
800
700
600
500
Elevation (m)
Duero
Capture
Jordan
Hoz
Rioseras
Nava Solo
Diablo
Homino
Molina
Fuente Monte
Zorica
San Pedro
Knickpoint
Ebro
0
10
20
30
40
Distance from mouth (km)

Figure 8

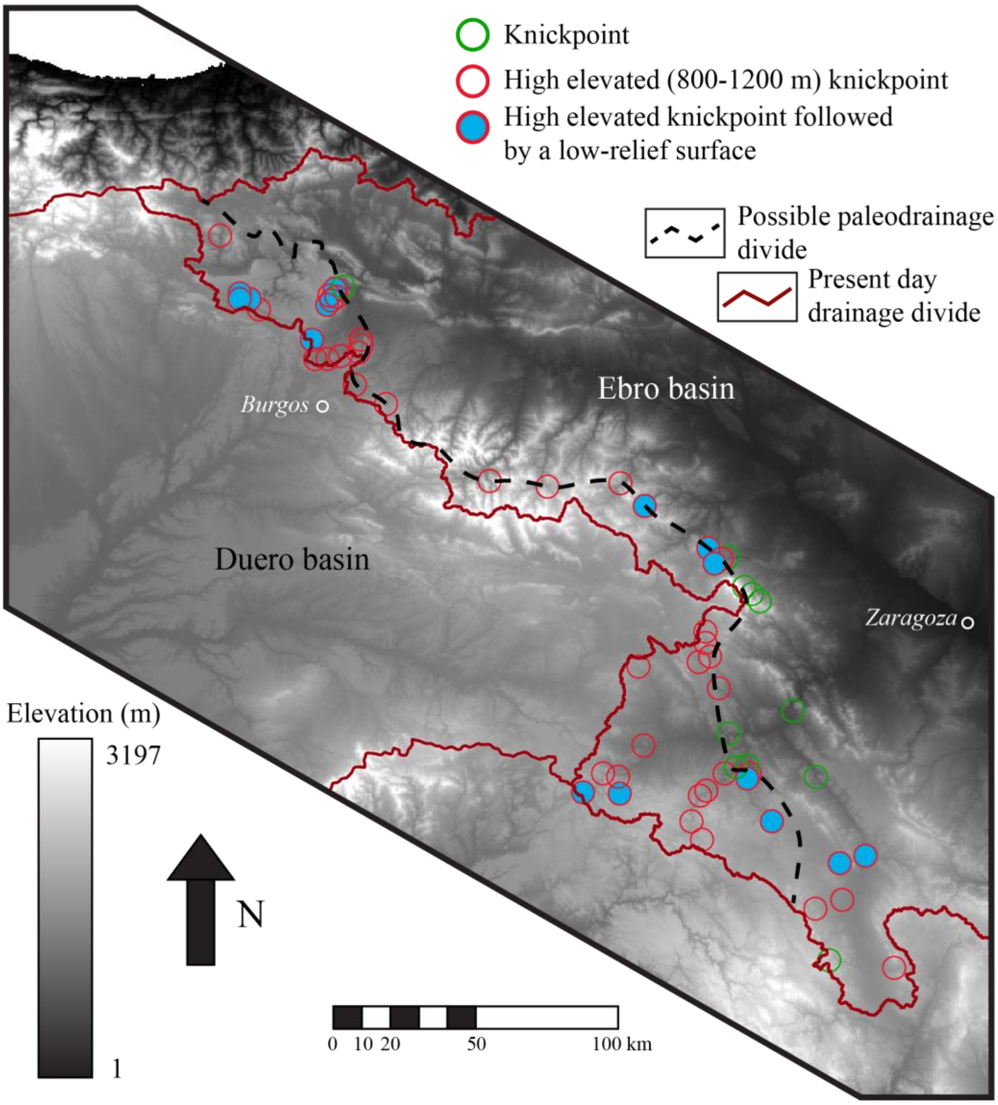

Knickpoint
High elevated (800-1200 m) knickpoint
High elevated knickpoint followed by a low-relief surface
Possible paleodrainage divide
Present day drainage divide
Ebro basin
Duero basin
Burgos
Zaragoza
Elevation (m)
3197
1
N
0
10
20
50
100 km

Figure 9

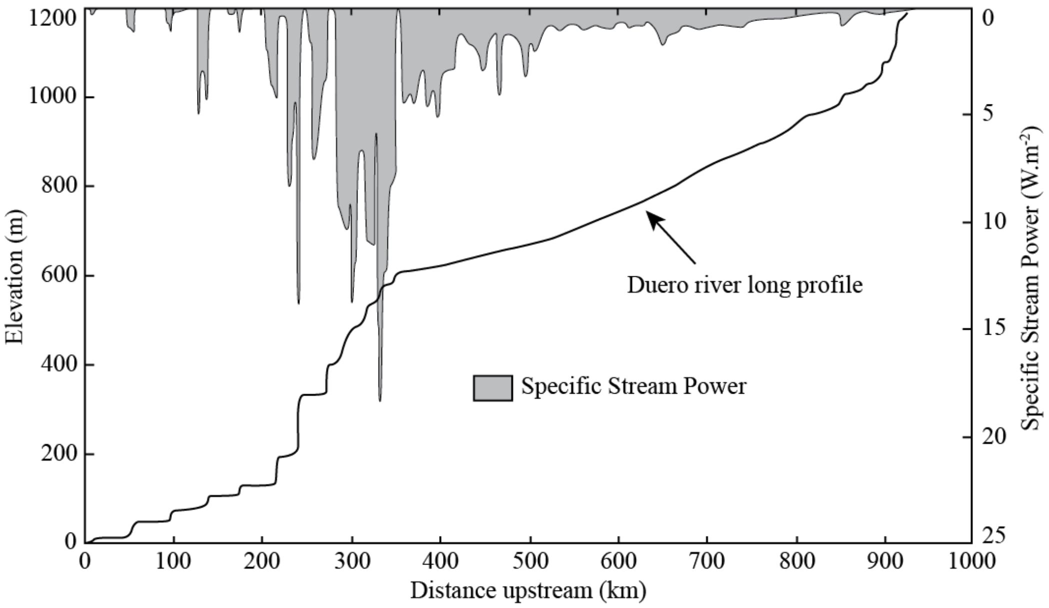

Elevation (m)
1200
1000
800
600
400
200
0
Specific Stream Power (W.m-2)
0
5
10
15
20
25
0
100
200
300
400
500
600
700
800
900
1000
Distance upstream (km)
Duero river long profile
Specific Stream Power

Figure 10

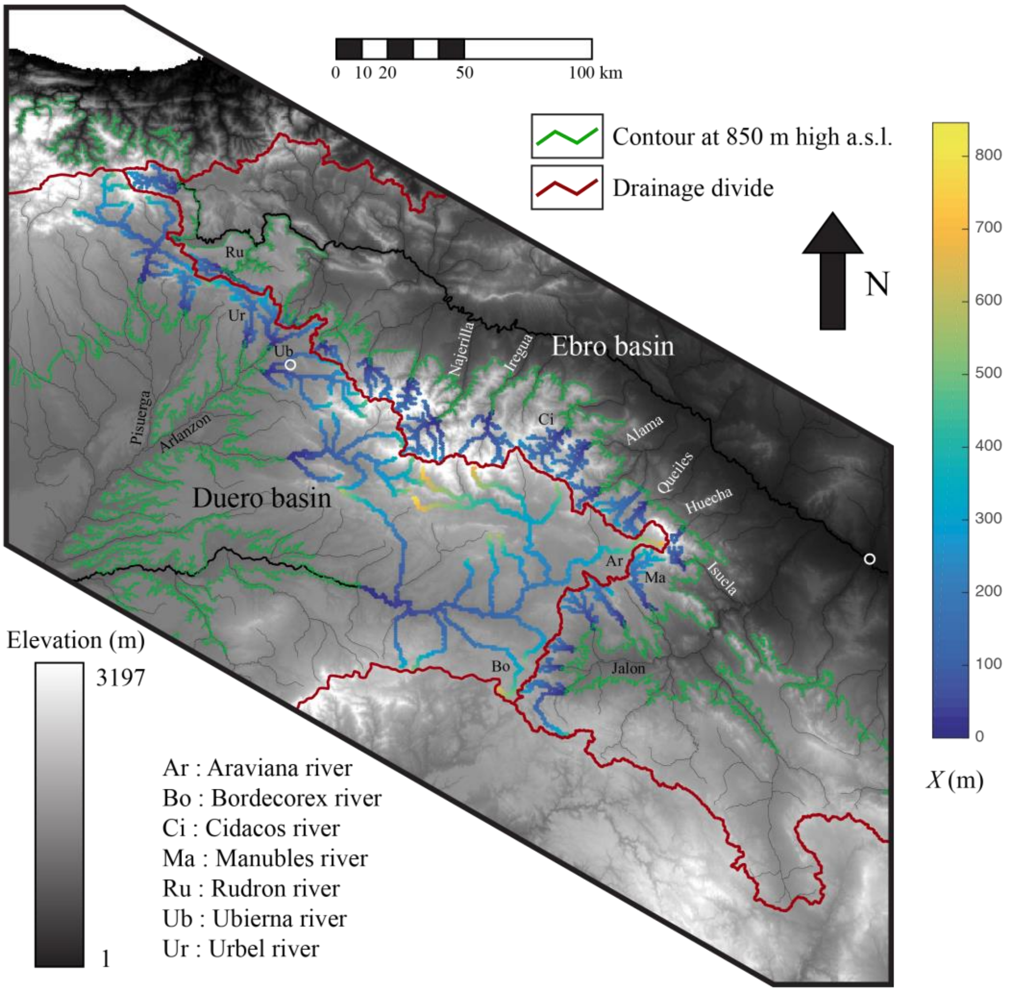

0 10 20 50 100 km
Contour at 850 m high a.s.l.
Drainage divide
N
Ebro basin
Duero basin
Ru
Ur
Ub
Pisuerga
Arlanzon
Najerilla
Iregua
Ci
Alama
Queiles
Huecha
Isuela
Ar
Ma
Bo
Jalon
Elevation (m)
3197
1
Ar : Araviana river
Bo : Bordecorex river
Ci : Cidacos river
Ma : Manubles river
Ru : Rudron river
Ub : Ubierna river
Ur : Urbel river
800
700
600
500
400
300
200
100
0
X (m)

Figure 11