Origin of the high elevated Pyrenean peneplain

Julien Babault, Jean van den Driessche, Stéphane Bonnet, Sébastien Castelltort, Alain Crave

TECTONICS, VOL. 24, TC2010, doi:10.1029/2004TC001697, 2005

Origin of the highly elevated Pyrenean peneplain

Julien Babault, Jean Van Den Driessche, and Stéphane Bonnet

Géosciences Rennes, UMR CNRS 6118, Université de Rennes 1, Rennes, France

Sébastien Castelltort

Department of Earth Sciences, Eidgenossische Technische Hochschule-Zentrum, Zurich, Switzerland

Alain Crave

Géosciences Rennes, UMR CNRS 6118, Université de Rennes 1, Rennes, France

Received 9 June 2004; revised 5 December 2004; accepted 13 December 2004; published 19 April 2005.

[1] Peneplanation of mountain ranges is generally considered the result of long-term erosional processes that smooth relief and lower elevation near sea level. Therefore peneplain remnants at high elevation in mountain ranges are used to infer posttectonic surface uplift. Such an interpretation has been proposed for the Pyrenees where high-elevation, low-relief erosional surfaces rose up to more than 2000 m. Because the Pyrenean foreland basins are filled with very thick continental deposits, which have buried the early jagged landscape, we challenge this hypothesis by pointing out that relief applanation does not necessarily require elevation lowering. We propose an alternative interpretation in which piedmont aggradation of detrital sediment that comes from erosion of the high chain induces the rise of the base level of the range, therefore reducing strongly the erosive efficiency of the drainage system and resulting in the progressive smoothing of the relief. Such a process allows a high-elevation, low-relief erosional surface to develop at the scale of the range. In the Pyrenees, occurrence of high-elevation, low-relief erosional surface remnants does not imply a posttectonic uplift, but is instead due to the dissection of the initial Miocene high-elevation, low-relief surface by the recent drainage system, the erosive activity of which has been enhanced by global climate change from the late Pliocene onward. **Citation:** Babault, J., J. Van Den Driessche, S. Bonnet, S. Castelltort, and A. Crave (2005), Origin of the highly elevated Pyrenean peneplain, *Tectonics*, *24*, TC2010, doi:10.1029/2004TC001697.

1. Introduction

[2] Following the definition of *Davis* [1889], *Bates and Jackson* [1980] define the term "peneplain" as "a low, nearly featureless, gently undulating land surface of considerable area, which presumably has been produced by the processes of long-continued subaerial erosion, almost to base level in the penultimate stage of a humid, fluvial geomorphic cycle." They specify that "peneplain" also denotes "such a surface uplifted to form a plateau and subjected to dissection." This later definition derives from numerous works which have interpreted the occurrence of highly elevated, more or less flat, erosional surfaces in mountain ranges throughout the world as remnants of originally low peneplains, later uplifted and now dissected by the recent drainage network [*de Sitter*, 1952; *Keefer*, 1970; *Blackstone*, 1975; *Scott*, 1975; *Tweto*, 1975]. In this interpretation, peneplanation is thus viewed as a lowering of mean surface elevation and concomitant relief subduing. On the other hand, the occurrence of planation surfaces at high elevation in mountain belts is one of the criteria used to infer their surface uplift and is at the heart of the current debate between the late Cenozoic uplift of modern mountain belts through the world and global climate change [e.g., *England and Molnar*, 1990; *Molnar and England*, 1990; *Zhang et al.*, 2001].

[3] A striking feature of the Pyrenees morphology is the presence of highly elevated, low-relief, erosional surfaces which have been extensively described since the beginning of the last century by numerous geomorphologists and geologists [*Penck*, 1894; *Mengel*, 1910; *Sorres*, 1913; *Panzer*, 1926; *Astre*, 1927; *Nussbaum*, 1931; *Boissevain*, 1934; *Pannekoek*, 1935; *Birot*, 1937; *Goron*, 1941; *de Sitter*, 1952; *Calvet*, 1994]. Late Miocene overlying continental deposits provide an upper age limit for these surfaces [*Birot*, 1937; *Roca*, 1996]. Following previous works [*Boissevain*, 1934; *Birot*, 1937; *Goron*, 1941] *de Sitter* [1952] wrote that "admirably preserved posttectonic erosional leveling surfaces witness to the original low altitude of the folded chain and to later elevation." In other words, in *de Sitter*'s [1952] view, the present-day morphology (and elevation) of the Pyrenees is unrelated to the Palaeogene alpine tectonics that led to crustal thickening in the Pyrenees. To explain the Pyrenean high-elevation, low-relief surfaces, he invoked a Pliocene upheaval contemporary with a phase of tangential compression, though he could not document it. Indeed, there is no evidence of tangential deformation during Pliocene times that could have produced the ~12 km of crustal thickening necessary to induce the 2000 m of Pliocene uplift invoked by *de Sitter* [1952] and more recent works [*Calvet*, 1985; *Brunet*, 1986; *Briais et al.*, 1990;

0278-7407/05/2004TC001697

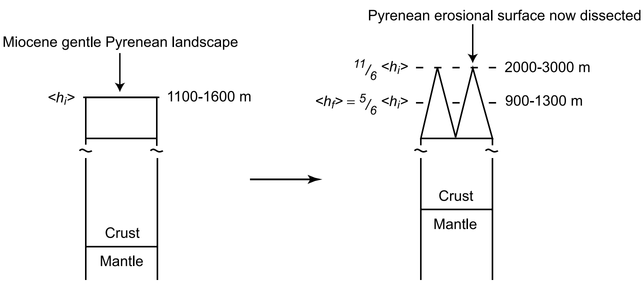


Figure 1. Effect of isostatically compensated erosion on the uplift of high-elevation, low-relief remnants. The h_i is the initial mean elevation of a gentle Pyrenean Miocene landscape, and h_f is the mean elevation of the resulting landscape after a post-Miocene dissection, that is, very heterogeneous erosion. Isostatically compensated erosion of *Molnar and England*'s model [1990] predicts a slight decrease of the final mean elevation by five sixths of the initial mean elevation h_i and a rock and Moho uplift equal to h_i. Deep incision by streams near to sea level results in a peak elevation of $11/6 \times h_i$, that is, higher than the initial mean elevation. The model implies an already highly elevated, gentle landscape and river incision almost at sea level, which is not the case in the Pyrenees where downstream the course of rivers flow 300 m and 500 m asl on the northern and the southern flank, respectively. The present elevation of the high-elevation, low-relief surfaces (ranging from 2000 m to 3000 m) would require an initial Miocene mean elevation of 900 m to 1300 m, that is, in the same order as the current elevation, implying an unrealistic lack of erosion since the Miocene.

Calvet, 1994]. Moreover, Pliocene normal faulting in the eastern Axial Zone of the Pyrenees [*Cabrera et al.*, 1988; *Briais et al.*, 1990; *Carozza and Baize*, 2004] implies local horizontal extension, not compression. An alternative explanation [*Brunet*, 1986] is to consider that the Palaeogene lithospheric root of the Pyrenees was removed from the Neogene, inducing Pliocene uplift. However, the tomographic study of *Souriau and Granet* [1995] shows evidence of a lithospheric root down to 100 km depth beneath the Pyrenees. In addition, *Vacher and Souriau* [2001] have recently shown that the Pyrenean relief is currently overcompensated at crustal level, requiring the presence of a dense crustal root that could be achieved by the transformation of lower crust into the eclogite facies.

[4] *England and Molnar* [1990] observe that the 2000 m uplift of the Pyrenees, as inferred by *de Sitter* [1952] from the remnants elevation of the applanation surface, is overestimated. As this Miocene surface is currently highly dissected, the mean elevation of the chain has necessarily decreased since this epoch, whereas the remnants elevation increased due to isostatic compensation. Following *Molnar and England*'s model [1990], the current remnants elevation, between 2000 m and 3000 m, would require a mean elevation of the Pyrenees of 1100 m to 1600 m before post-Miocene dissection. This is of the same order as the current mean elevation of the chain (1500 m) implying that no erosion occurred since the Miocene, which is unrealistic (Figure 1). Besides the fact that the Miocene elevation of the applanation surface would be already high, isostatically compensated erosion as described by the Molnar and England model could not account for the whole elevation of the high-elevation, low-relief surfaces in the Pyrenees, even less so that it requires deep valley incision near sea level which is not the present case.

[5] In summary, we believe that the interpretation that the high-elevation, low-relief surfaces of the Pyrenees indicate that the chain was lowered and peneplaned before the Pliocene and that this peneplain was later uplifted from the Pliocene onward is wrong. The fundamental reason underlying this misinterpretation is the mistake of equating the destruction of relief with a lowering of the earth's surface, which is just the same mistake as equating the generation of relief with surface uplift as stressed by *England and Molnar* [1990].

[6] We will argue here that, under certain conditions, the rise of the mountain range base level due to massive alluvial sedimentation in foreland basins can considerably reduce the erosive efficiency of the drainage network in the mountain range, resulting in the development of a highly elevated "peneplain" (Figure 2).

[7] We first describe and analyze the present-day characteristics of the morphology of the Pyrenees. In a second step we review the morphologic evolution of the chain since the Eocene with regard to its southern flank, which allows us to propose a model for the development of the high-elevation, low-relief erosional surfaces. We then discuss the timing of the dissection of the high-elevation, low-relief surfaces with particular attention to the capture of the Ebro River by the Mediterranean as it has been assumed to have strongly influenced the present morphology of the southern flank. Finally, we extend the model developed for the southern flank to the entire chain. Our conclusions support the view

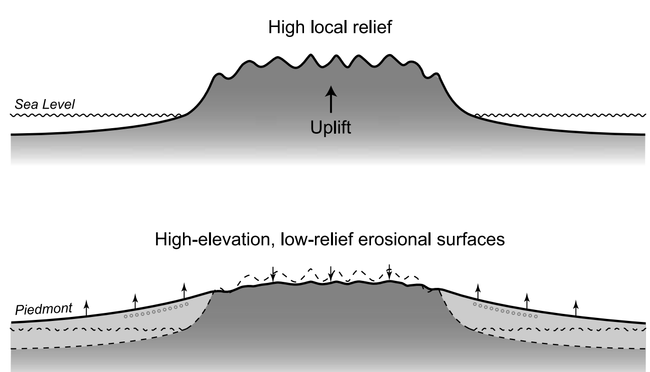


Figure 2. Sketch showing the effect of base level rise on the local relief of a mountain range. The change from marine sedimentation to continental sedimentation in foreland basins raises the initial base level of the chain that was corresponding to sea level. The base level rise reduces the local slopes and the erosive efficiency of the transverse rivers that drain the mountain range. By the end of tectonic uplift, the local relief is subdued almost as a peneplain but at an elevation well above sea level.

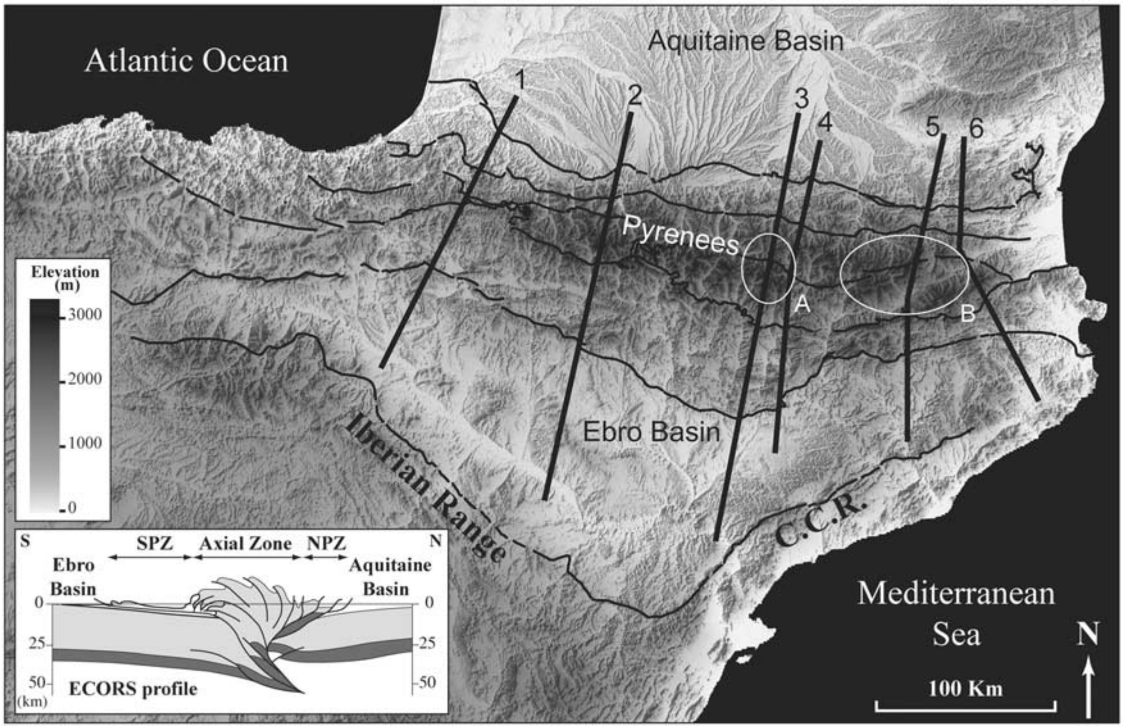


Figure 3. Digital elevation model (DEM) of the Pyrenees (from SRTM90 data), the Coastal Catalan Ranges (CCR), and the Iberian Range. The Pyrenees are flanked by the Aquitaine basin to the north and the Ebro basin to the south. The main faults are also represented. The topographic profiles of Figure 5 are distributed all over the Pyrenees and encompass parts of the Aquitaine and Ebro basins. Insert shows *Roure et al.*'s [1989] interpretation of the ECORS profile. NPZ is north Pyrenean zone; SPZ, south Pyrenean zone. Encircled areas are the two most extensive high-elevation, low-relief surfaces: A, Encantats massif; B, Aston, Andorra, and around the Cerdanya and Capcir basins (eastern Pyrenees).

that global climate exerts strong control on mountain morphology.

2. Geomorphology of the Pyrenees

2.1. General Characteristics

[8] The Pyrenees are a linear mountain range, around 450 km in length, orientated approximately east-west (Figure 3). Its width ranges from 100 km in both the eastern and western parts to 160 km in the central part. The mean elevation in the Axial Zone is about 2000 m in an area 200 km long and 20 km wide (Figure 4a). Elevation of the peaks is around 3000 m, with Pico de Aneto in Aragón (central Spanish Pyrenees) being the highest summit with an altitude of 3404 m. The Pyrenees are flanked by two low-elevation (300–500 m) foreland basins, the Aquitaine plain to the north and the Ebro basin to the south. The transverse

Figure 4. Analysis of the local relief of the Pyrenees derived from SRTM90 DEM data. Local relief is calculated by moving a 5 km wide circular search window over the DEM. At each point, the maximum range of elevation values within the window is determined and plotted at the center of the circle. The same method is used to perform the mean elevation by moving a 30 km wide window. (a) The mean elevation value is indicated and represented by lines superimposed on the local relief. The drainage divide between the northern and the southern flank is also reported. The map shows low values of local relief corresponding to low mean elevation and higher values of local relief corresponding to high mean elevation, except in the Encantats and the eastern Pyrenees. The low relief of Cerdanya and Capcir corresponds in part to Neogene and Quaternary depositional flat surfaces of extensional basins lying at 1000 m asl. (b) Rough contours of high-elevation, low-relief erosional surface remnants, such as described in the literature, superimposed on the local relief. Dissection of the initial erosional surface by the recent drainage system has resulted in small high-elevation, low-relief surface remnants of hundreds of square meters to several square kilometers which cannot be represented on the map, explaining the misfit between the contour lines and the local relief data. (c) The local slope map shows that high-elevation, low-relief surface remnants appear as small areas with a local slope less than 11°. See color version of this figure at back of this issue.

profiles (Figure 5) show a slight asymmetry: the southern flank is globally wider and has a lower slope than the northern flank. This asymmetry matches well the known structural asymmetry between the so-called north and south Pyrenean zones [e.g., *Mattauer*, 1968; *Choukroune et al.*, 1989]. The north Pyrenean zone is characterized by steeply dipping crustal thrusts which makes it narrow, whereas the south Pyrenean zone is recognized for its thin-skinned tectonics style that makes it very wide with shallow deformation (Figure 3). This structural and hence morphological asymmetry can eventually be related, at lithospheric scale, to the subduction of the Spanish lithosphere beneath

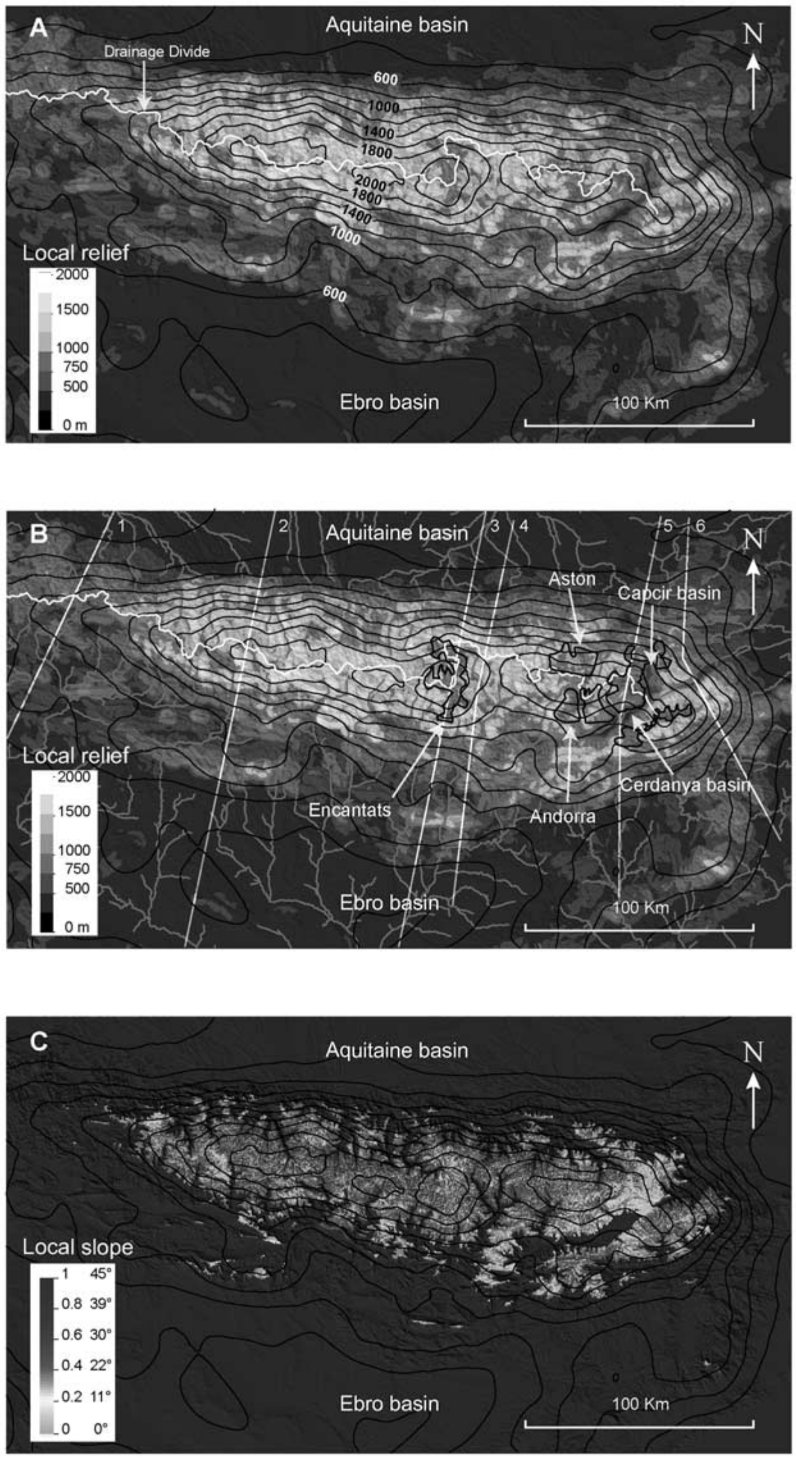


Figure 4

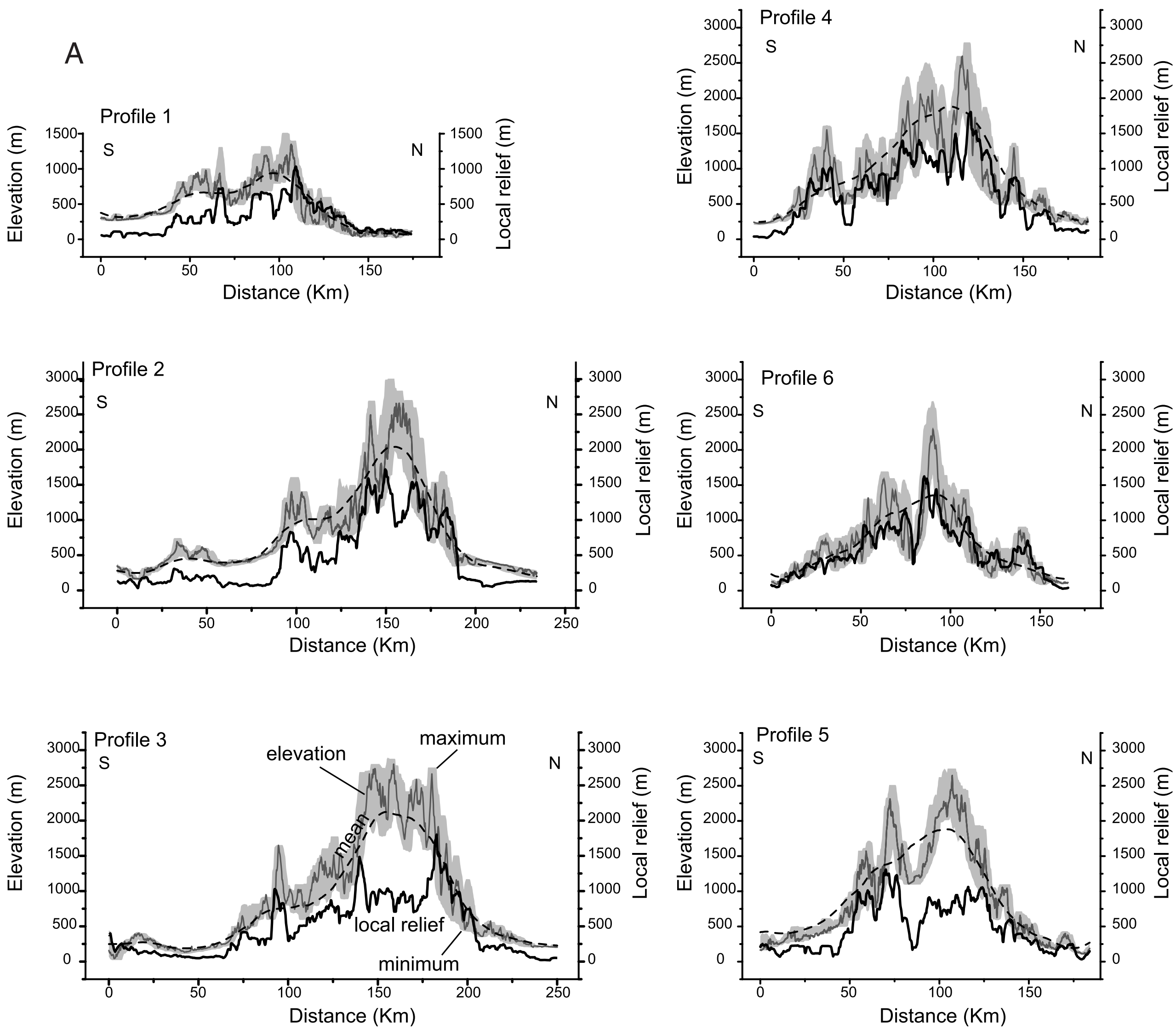


Figure 5. (a) Transverse topographic profiles across the Pyrenees (see location in Figure 3). On each profile are plotted the elevation, the maximum elevation, the minimum elevation, the mean elevation and the local relief. The local relief is computed over a 5 km moving window as in Figure 4. Profiles 1, 2, 4 and 6 show a gradual increase of the local relief with the mean elevation and vice versa. This configuration gives a bell-shaped geometry of the profiles. This is not the case for profiles 3 and 5 which cross the high-elevation, low-relief surfaces of the Encantats and the margin of the Cerdanya basin in the eastern Pyrenees. These profiles show a decrease of the local relief in the high chain. Each profile shows maximum and minimum elevations (shading). (b) Relationship between mean elevation and local relief. (left) Idealized sketch showing the relationship between mean elevation and local relief in mountain ranges including (or not including) a high plateau. (right) Where the transversal profiles cut across the high-elevation, low-relief surfaces, the local relief decreases as it does for high plateaus in mountain belts, arguing that the high-elevation, low-relief surfaces represent the remnants of an extensive smooth topography.

the European lithosphere [*Mattauer*, 1985; *Muñoz*, 1992; *Souriau and Granet*, 1995; *Teixell*, 1998].

2.2. Pyrenean Highly Elevated "Peneplain"

[9] A striking feature of the morphology of the Pyrenees is the occurrence of high-elevation, low-relief surfaces that have been previously interpreted as remnants of an uplifted peneplain surface [*Boissevain*, 1934; *Birot*, 1937; *Goron*, 1941; *de Sitter*, 1952; *Calvet*, 1985; *Brunet*, 1986; *Briais et al.*, 1990; *Calvet*, 1994]. By high-elevation flat surfaces, we mean a landscape with a smoothed morphology lying at about 2000 m above sea level (asl) (Figure 6), and which

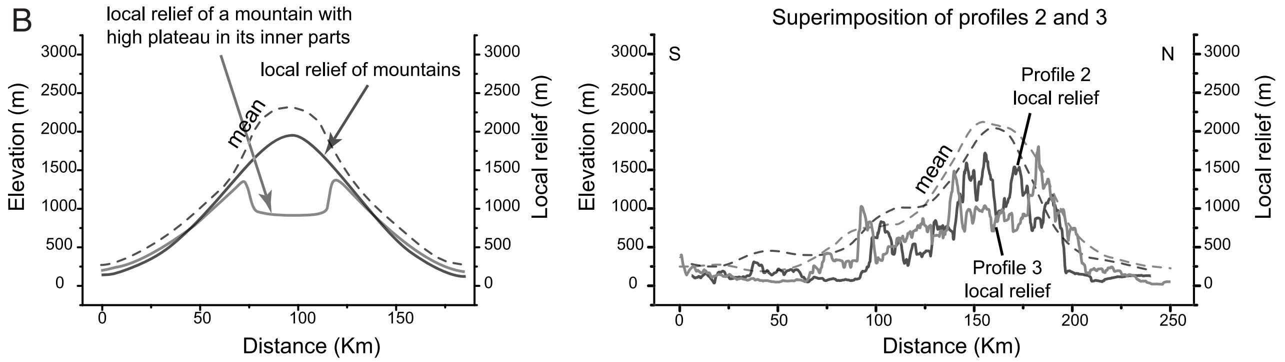


Figure 5. (continued)

contrasts with the surrounding jagged relief of peaks and deeply incised valleys.

[10] These remarkable erosional surfaces are located in two main areas, the central Pyrenees (Encantats) and the eastern Pyrenees (Aston, Andorra, around the Cerdanya and the Capcir basins, cf. Figures 3 and 4 and Table 1).

[11] On the basis of previous studies of the last century [*Penck*, 1894; *Mengel*, 1910; *Sorres*, 1913; *Panzer*, 1926; *Astre*, 1927; *Nussbaum*, 1931; *Boissevain*, 1934; *Pannekoek*, 1935; *Birot*, 1937; *de Sitter*, 1952; *Calvet*, 1994] and using GIS methods we mapped these high-elevation surfaces within the Axial Zone. Their extent ranges from tens to hundreds of square kilometers, which corresponds to 10% of the surface of the Axial Zone (Table 1).

2.2.1. Identification of Highly Elevated, Low-Relief Surfaces

[12] Relief analysis has been performed within a moving circular search window over the SRTM 90 m resolution DEM. According to *Ahnert* [1984], the best result is obtained for a 5 km diameter window. At each point, the maximum range of elevation values within the window was determined and plotted at the centre of the window. The mean elevation of the chain has also been analyzed using a moving circular search window but with a larger diameter of 30 km as in the study of *England and Molnar* [1990].

[13] Figure 4a shows that maximum mean elevation is centered in the Axial Zone. The chain is not cylindrical, with its eastern part being larger than its western part as a result of more tectonic shortening in the former [*Roure et al.*, 1989; *Vergés et al.*, 1995; *Teixell*, 1998]. At the scale of the entire range, the local relief increases with the mean elevation, except in the most eastern part where a very low-relief, high-elevation, NE-SW to N-S narrow zone corresponds to the Tertiary grabens of Cerdanya, Capcir and Conflent basins. When reported on the map (Figures 4b), the high-elevation, low-relief surfaces described in the literature show a rather important local relief (750 m ± 250 m), yet contrasting with the rest of the high chain.

[14] In fact, by analyzing the local slopes, these surface remnants appear as small areas (hundreds of square meters to several square kilometers) with local slopes lower than 10° and situated above 1400 m of altitude (Figures 4c).

2.2.2. Transverse Topographic Profiles

[15] Six topographic profiles perpendicular to the trend of the chain have been constructed from west to east (Figure 5a). Profiles 3 and 5 cut the main high-elevation,

Figure 6. Example of high-elevation, low-relief remnant: The Plan de Beret (view looking to the northeast). The Plan de Beret is located at the drainage divide between the Noguera Pallaresa flowing toward the Mediterranean via the Ebro River, and the Garonne River flowing toward the Atlantic. The Plan de Beret reaches 1900 m above sea level and is surrounded by peaks, the elevation of which range from 2600 m to 2900 m. The morphology of Plan de Beret looks like a gentle landscape despite its being located in the inner part of the chain.

Table 1. Topographic Characteristics of the High-Elevation, Low-Relief Erosional Surfaces[a]

Region	Elevation Range, m	Mean Elevation, m	Extension, km^2	Mean Local Slope, m/m	Mean Local Relief, m
Encantats	1600–3000	2310	390	0.396 (21.5°)	935
Maladetta	1960–3030	2485	26	0.416 (22.6°)	1080
North Cerdanya	1091–2902	2150	623	0.321 (17.8°)	875
South Cerdanya	1315–2902	2140	163	0.344 (19°)	815
East Capcir	950–2450	1800	62	0.270 (15.1°)	832
Aston	1030–2705	1950	233	0.270 (15.1°)	1015

[a]The cumulated surface of these high-elevation surfaces (about 1500 km^2) corresponds to 10% of the surface of the Axial Zone.

low-relief surface remnants. Profile 4 corresponds to the surface profile of the ECORS deep seismic profile. All the profiles have the same characteristic bell-shaped geometry. As expected, the local relief values usually follow the topographic profiles, i.e., increase when elevation increases and vice versa. However, this is not true for profiles 3 and 5 (Figure 5a) where the local relief drastically decreases when the profile cuts the high-elevation, low-relief surfaces. Such a decrease of local relief with increase of mean elevation is also encountered when a high plateau develops in a mountain belt (Figure 5b). This suggests that the small high-elevation, low-relief surfaces encountered today in the Pyrenees may be the remnants of a much more extensive and more or less flat single surface.

2.3. Drainage Network

2.3.1. Drainage Pattern

[16] The chain is deeply incised by transverse streams roughly orientated north-south and regularly spaced (20–30 km [*Hovius*, 1996]) as seen on the map in Figure 7.

[17] Most of the drainage on the northern flank is directed to the Atlantic Ocean. The streams situated in the western

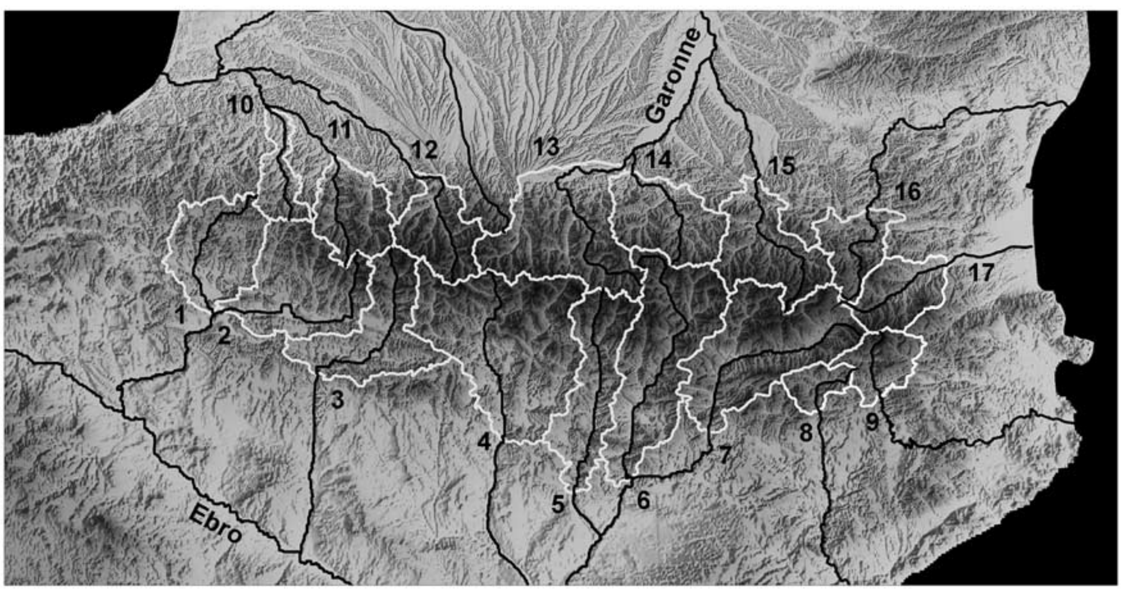


Figure 7. Present-day morphology and main catchments of the Pyrenees. The present-day morphology of the Pyrenees is characterized by transverse rivers that deeply incise the high-elevation, low-relief surfaces. The main transverse rivers on the southern flank and from west to east are as follows: Irati (1), Aragon (2), Gallego (3), Cinca (4), Noguera Ribagorzana (5), Noguera Pallaresa (6), Segre (7), Llobregat (8), and Ter (9). The main transverse rivers on the northern flank and from west to east are as follows: Saison (10), Gave d'Aspe herein referred as "Aspe" (11), Gave de Pau referred as "Gavarnie" (12) (because of the location of its spring in the famous Cirque de Gavarnie), Garonne (13), Salat (14), Ariege (15), and Aude (16). On the eastern part of the chain, although the Tet river (17) flows directly into the Mediterranean, we consider that it belongs to the northern flank. Longitudinal profiles of all these streams are performed using the SRTM90 DEM. White lines delimit the main catchments of the Pyrenees. The outlet of the drainage basins corresponds to the morphological outer limits of the north and south Pyrenean zones.

and eastern parts of the northern flank flow directly into the Atlantic Ocean and Mediterranean Sea (e.g., the Aude and Têt rivers, Figure 7) respectively. Drainage organization is different in the central part of the northern flank where transverse streams connect to the Garonne river which then runs a long distance northwestward across the Aquitaine basin before entering the Atlantic Ocean.

[18] The organization of the southern flank drainage is more classic with most of the transverse streams connecting to the longitudinal drainage of the NW-SE directed Ebro River which flows into the Mediterranean. Only in the most eastern part some streams flow directly toward the Mediterranean (e.g., the Llobregat River, Figure 7).

2.3.2. Longitudinal Profiles of Transverse Rivers

[19] Figure 8 shows the longitudinal profiles of the transverse streams that rise near the topographic ridgepole and that flow either directly into the Atlantic Ocean and the Mediterranean Sea or into the Ebro and Garonne rivers. Accordingly with the morphologic and structural asymmetry of the range previously described, the profiles of rivers of the northern flank are systematically more concave and short than profiles of the southern flank (Figure 9a). This difference has to be related to the mean elevation asymmetry.

[20] *Hack* [1957], *Flint* [1974], and others have reported the following relationship between the slope S and drainage area A in channels:

$$S = kA^{-\theta},$$

where k is the steepness index and θ is the concavity index. We use the concavity index as a measure of the concavity of rivers. This has been achieved for the main transverse rivers as defined above (drainage area $A > 10^8$ m^2) and for their tributaries ($1.10^6 < A < 2.10^8$ m^2) within the drainage basins delimited in Figure 7. Within each plot in log-diagrams, two linear fits were computed to encompass most of data.

[21] Plots of the concavity indexes measured in this way show that (1) the transverse rivers flowing on the northern flank are more concave than rivers of the southern flank (Figure 9a) as also shown on the longitudinal profiles of Figure 8, (2) tributaries of similar drainage areas show similar concavities irrespective of their location on the northern or the southern flank (Figures 9b and 9c), and (3) the concavity of tributaries increases with the elevation of the tributary (Figure 9c).

2.4. Present-Day Morphology of the Pyrenees: Discussion

[22] As mentioned before, morphological asymmetry at the scale of the entire chain, as revealed by mean elevation analysis, can be related to the northward subduction of the Iberian lithosphere beneath the European plate following *Willett and Brandon*'s [2002] model. Drainage network analysis also shows a slight difference in the concavity of the main transverse rivers between the two sides of the chain. Such a difference may be related to the regional slope between the two flanks of the chain just at the onset of the postorogenic decay. This will imply no significant difference in the incision rate of the main transverse rivers on both flanks, so that the initial asymmetry is preserved.

[23] In an alternative explanation to this general asymmetry, the influence of higher precipitation rates on the northern side to that on the southern one [e.g., *Hovius*, 2000] can be considered. Indeed, this contrast between a very humid northern side and an almost dry southern side is a well known characteristic of the Pyrenean climate of today, and is also well documented in the meteorological survey reports [*Météo-France*, 1987].

[24] However, the similarity of concavity indexes for the tributaries on both sides of the mountain range suggests no significant difference of erosional processes on both flanks and no link with particular climatic conditions specific to one or the other side. In summary, it is therefore more reasonable to attribute the large-scale asymmetry of the Pyrenees to the well known crustal and lithospheric structural asymmetry due to Pyrenean tectonics.

[25] One unexplained though striking feature of the Pyrenean morphology is the presence of high-elevation, low-relief erosional surfaces, mostly situated in the Axial Zone. These surfaces are highly dissected by Quaternary glacial and fluvial erosion. While several hypotheses have been proposed to explain the presence of such surfaces, their origin can still be debated. In the following, we present geological and geomorphologic constraints that allow us to draw an attempt to solve this problem by investigating the geological and morphological evolution of the southern flank of the Pyrenees since the Cenozoic.

3. Morphological Evolution of the Southern Pyrenees During the Cenozoic

[26] During early to middle Eocene times, the southern foreland basin of the Pyrenees was an E-W elongated narrow trough that was open toward the Atlantic Ocean allowing the dispersal of sediments supplied from the Axial Zone [e.g., *Puigdefàbregas and Souquet*, 1986; *Mutti et al.*, 1988; *Puigdefàbregas et al.*, 1992]. Further shortening and thickening afterward resulted in the southward and westward migration of the basin depocenter and the progressive deformation and exhumation of the basin northern margin. This period is characterized by both longitudinal and transverse inland drainage on the southern flank [*Nijman*, 1998; *Vincent*, 2001].

[27] Because of coeval southward migration of the deformation and sediment supply increase, the entire basin was rapidly filled from the late Eocene onward, thus entering a long period of continental sedimentation [e.g., *Birot*, 1937; *Reille*, 1971; *Séguret*, 1972; *Riba et al.*, 1983]. At the same time, the initial connection with the Atlantic Ocean closed and the basin drainage became internal [e.g., *Birot*, 1937; *Reille*, 1971; *Riba et al.*, 1983]. This resulted in the burying of the relief in the foreland fold and thrust belt developed during the Eocene period of external drainage which can be observed in a series of particularly well exposed Eocene transverse fluvial paleovalleys filled with Eocene alluvial sediments [e.g., *Birot*, 1937; *Reille*, 1971; *Vincent*, 2001] (e.g., Sierra de Sis paleovalley, Figure 10a).

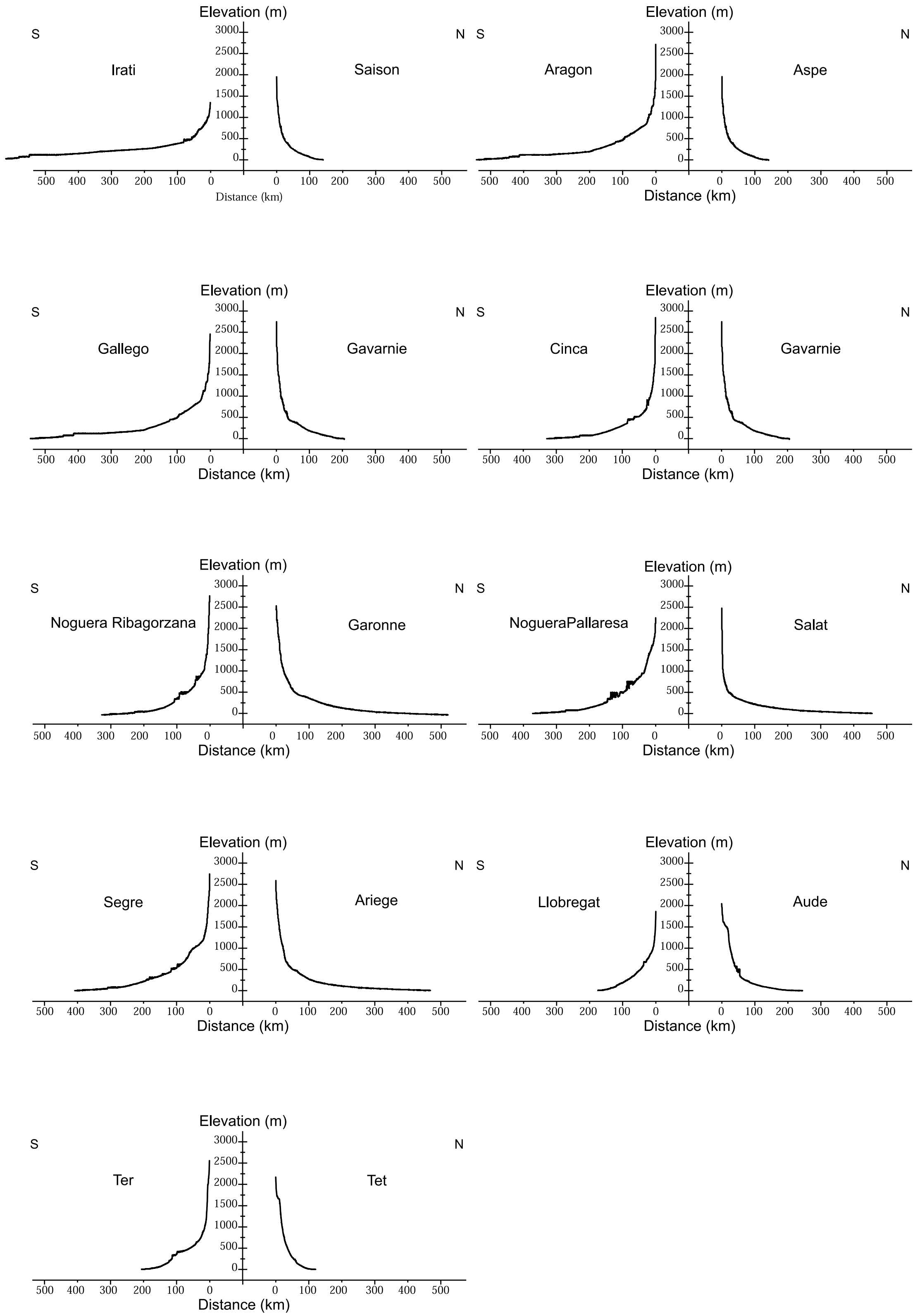


Figure 8. Longitudinal profiles of the main transverses rivers of the Pyrenees. For convenience we compare the northern and southern main transverse river profiles with ridgepole as the origin. The northern rivers are more concave than the southern ones matching the asymmetry of both the structure and the topographic profiles and of the chain, as described in Figures 3 and 5, respectively. See Figure 7 for location of the main transversal streams.

This phenomenon was probably amplified by the fact that this former foreland fold and thrust belt was then transported as piggyback subbasins on the top of southward propagating external thrust sheets, which enhanced subsidence and the trapping of sediments.

[28] *Coney et al.* [1996] summarize this story well as follows: the southern flank "was progressively buried, back to and overlapping the southern margin of the axial zone, in up to 3 km of massive continental fluvial-alluvial deposits." A fundamental observation is that at present, the remnants of subhorizontal uppermost top-wedge alluvial deposits outcrop at an elevation of up to 2000 m where they merge into the highly elevated, low-relief erosional surfaces of the Axial Zone [*Coney et al.*, 1996]. The maximum elevation of these deposits is about 1100 m asl along the frontal thrust of the south Pyrenean zone (Figure 10b) indicating the rise of the southern Pyrenees base level.

[29] After this burying, when and why the reexcavation of the southern flank started remains debated. For most authors [*Birot*, 1937; *Reille*, 1971; *Coney et al.*, 1996; *Garcia-Castellanos et al.*, 2003], reexcavation was induced by the capture of the Ebro River by the Mediterranean Sea, resulting in new external drainage of the Ebro foreland basin. Miocene extensional tectonics within the Catalan chain or dramatic sea level drop of the Mediterranean during the Messinian, or a combination of both, have been invoked to explain this capture [e.g., *Nelson and Maldonado*, 1990; *Coney et al.*, 1996]. Therefore, depending on which of these processes is considered to have been predominant, different ages have been proposed for the capture. Miocene or Quaternary climatic changes have also been considered to be of primary importance in the building of the present jagged relief [e.g., *Nelson*, 1990; *Coney et al.*, 1996; *Garcia-Castellanos et al.*, 2003]. In the following we will tentatively argue that the Ebro River was not connected to the Mediterranean before the Pliocene. In any case, the Ebro foreland basin and in particular the top-wedge basin, suffered strong erosion since the Pliocene, leaving remnants of Eocene to Miocene continental deposits all along the southern flank of the Pyrenees.

4. How Did the High-Elevation, Low-Relief Erosional Surfaces Develop?: A High-Elevation Peneplanation Model

[30] In the classical "geographical cycle" of *Davis* [1889], landscape maturity is reached after orogenic uplift

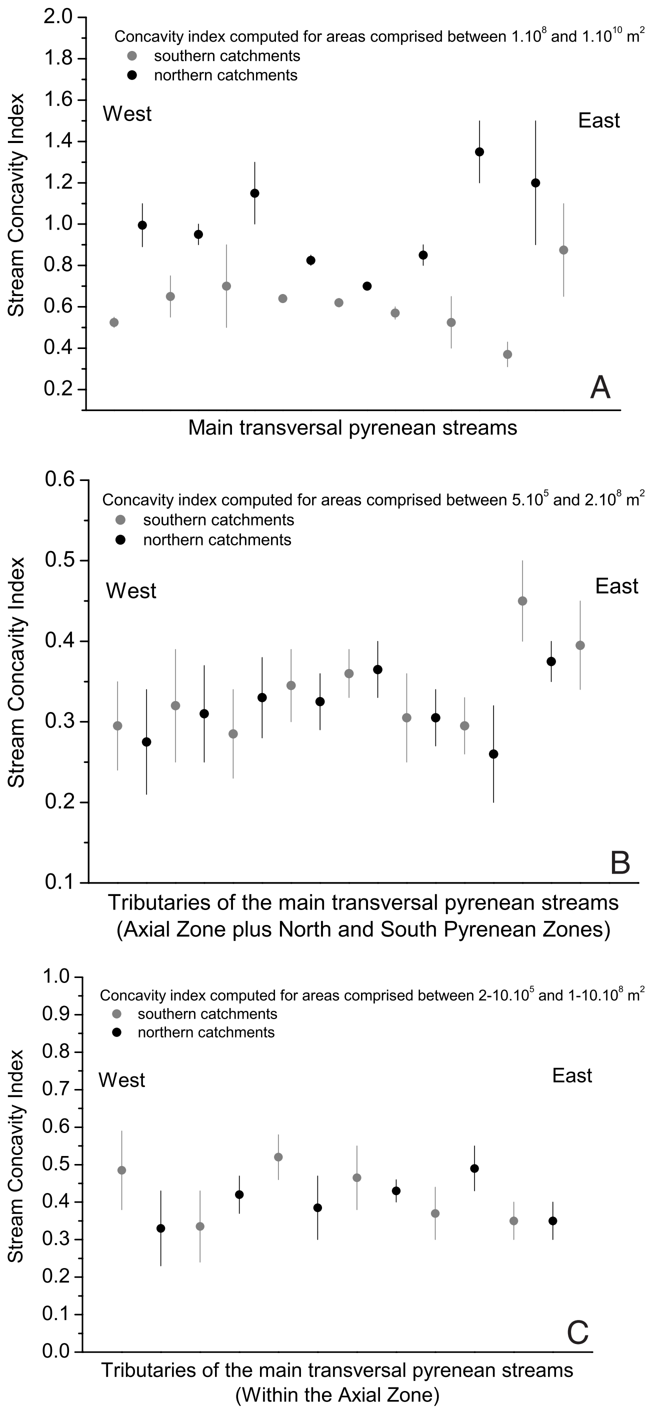


Figure 9. Concavity profiles of the main transverse rivers and their tributaries. Using the slope area relationship we computed the concavity indices for all the mainstreams and their tributaries. (a) The drainage area and local slope value along the main transversal streams were computed using the steepest-slope criteria. The concavity index analysis shows the higher concavity for the northern flank main rivers, that is, for drainage area values higher than 10^8 m^2. (b) The concavity index of all the tributaries is determined by analyzing the slope variation for drainage areas ranging from 5×10^5 m^2 to 10^8 m^2 within the whole area covered by the main drainage basins drawn in Figure 7. The main basin outlets correspond to the morphological fronts of the north and south Pyrenean zones. (c) Subbasins concavity indexes have been performed for parts of the main basins located within the Axial Zone. Whatever their location on the northern or on the southern flank of the Pyrenees, the tributaries have a similar concavity index. Figure 9c shows that the concavity indexes are higher in the high chain than in the rest of the range.

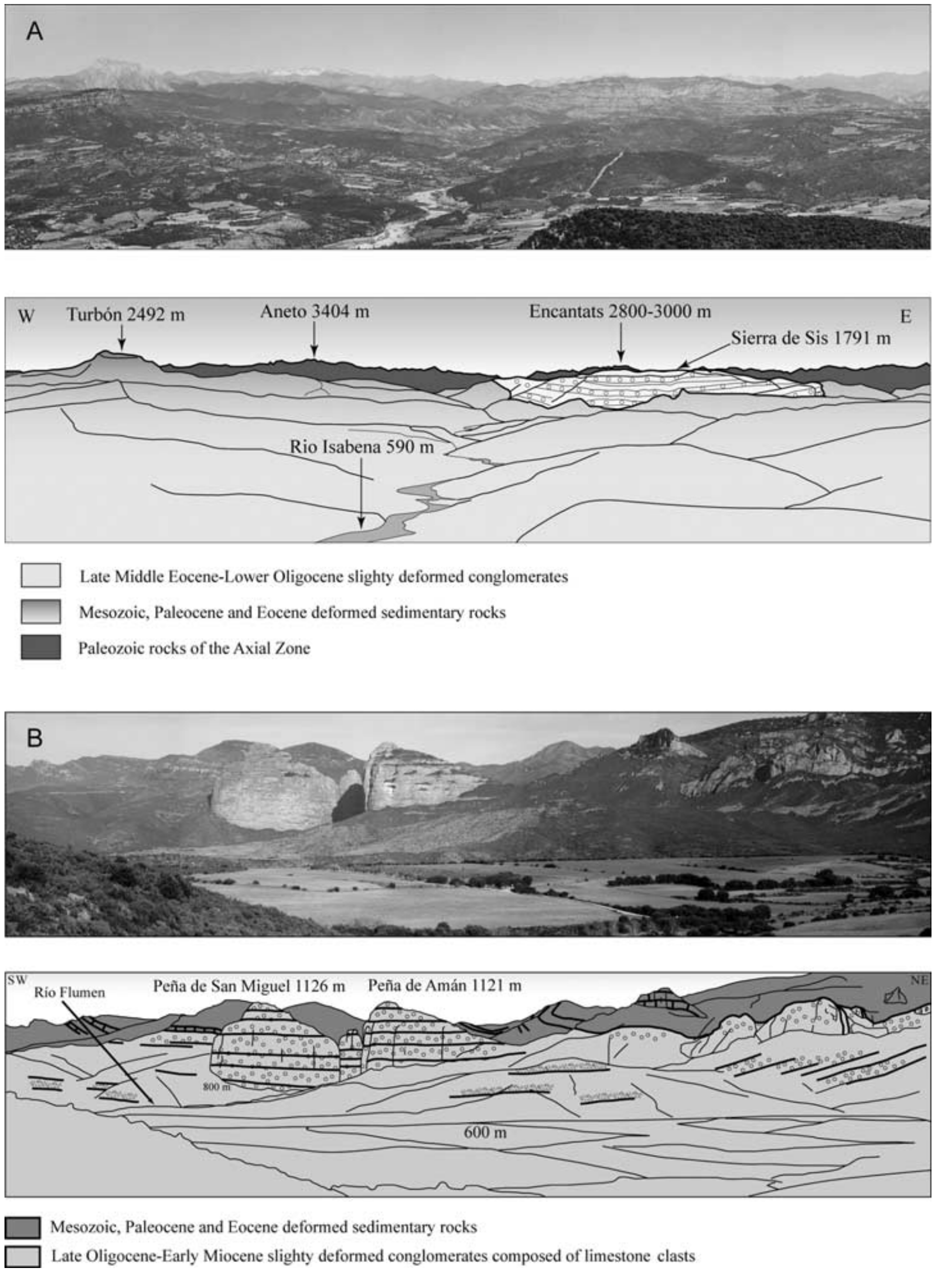


Figure 10. (a) Panorama looking to the north of the south Pyrenees showing N-S directed late Eocene-Oligocene paleovalley (Sierra de Sis). The late Eocene-Oligocene paleovalley is filled with alluvial conglomerates reaching nearly 1800 m asl. The Sierra de Sis conglomerate form a linear body extending up to 20 km long and 5 km wide. The picture is taken from a promontory made of the same undeformed conglomerates. Before dissection, the valley of the Rio Isabena was most probably looking like a bajada overlapping the southern margin of the Axial Zone up to 2000 m, or even higher, in the background and sloping down to 1000 m or more in the foreground. At the foot of the Sierra de Sis, the Rio Isabena reaches an elevation of 750 m implying about 1000 m of dissection. (b) View looking to the northwest of the early Miocene conglomerates of the Salto de Roldán (northern margin of the Ebro basin, north of Huesca). The conglomerates, which correspond to proximal fan delta and mass flow deposits, uncomformably overlie deformed Mesozoic, Paleocene and Eocene sedimentary rocks. They form spectacular high cliffs towering above the Ebro basin depression whose elevation ranges from around 300 – 500 m. The elevation of the conglomerates reaches 1120 m. (c) Eocene paleorelief buried by Oligocene conglomerates (Olvena, northeast of Barbastro). Oligocene conglomerates fill in a structural paleorelief that formed during folding of late Cretaceous limestones. Growth strata at the base show that folding was partly synsedimentary. See color version of this figure at back of this issue.

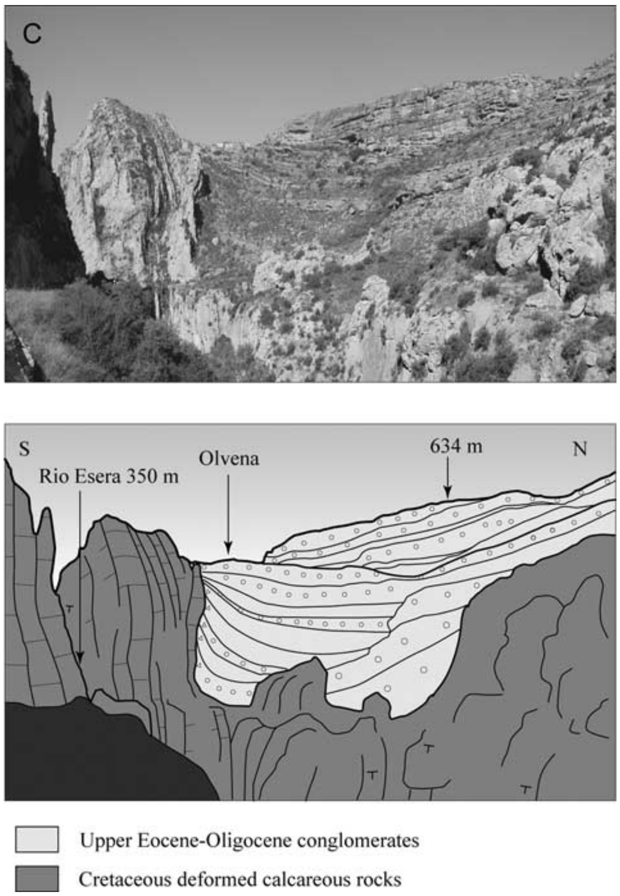


Figure 10. (continued)

when the valleys have reached maximum relief. Then, as degradation occurs, both relief and mean elevation are gradually reduced. At the end of the cycle, the landscape has been degraded to a surface of very low relief near base level called a "peneplain." In others words the decrease of the mean elevation toward sea level is accompanied by a progressive smoothing of the landscape. In this model, the sea level is viewed as the ultimate base level to which the landscape eventually grades. In this paper we further this idea by proposing that the same effect can result from a rise of base level (Figure 2). In particular, this can be expected at the front of mountain belts when foreland basins become closed and progressively filled with sediments. In such a case, internal drainage results in a general rise of the base level in the foreland basin and in considerable continental sedimentation. This is exactly what happened for the southern flank of the Pyrenees and the entire Ebro basin. The fluvial valleys developed on the southern flank of the Pyrenees during the period of external drainage were then rapidly filled when the Ebro foreland basin became internal, with the aggradation of sediments far inland the mountain range witnessing a large base level rise. We suggest here that before its recent excavation, the Pyrenean southern flank looked like a large-scale E-W elongated smoothed half-dome, at the top of which Paleozoic basement and minor Mesozoic sedimentary cover were outcropping, surrounded by Tertiary detrital sediments. We develop in the following two types of arguments that lead us to this conclusion.

4.1. Present Slight Difference in Elevation Between the Axial Zone and the Top of the Detrital Series is Inherited From the Internal Drainage Stage

[31] The unusual slight difference between the elevation of the Axial Zone summit and the Ebro foreland basin top-wedge at present cannot be entirely explained by the recent rejuvenation of the relief because this would assume much more erosion of the former. Indeed, the effect of recent rejuvenation can easily be distinguished when looking at the geomorphology of the Cerdanya region (Figure 11a). Cerdanya corresponds to a Miocene half-graben bounded to the south by a north dipping normal fault zone. The graben is filled by detrital continental sediments which overlap the basement to the north. Sedimentological analysis of the basin fill reveals the development of shallow ponds, swampy zones, and lacustrine paleoenvironment [*Cabrera et al.*, 1988; *Roca*, 1996]. All together, those observations suggest internal drainage of the graben. The fine-grained nature of most of the deposits also suggests that the surrounding summits were not very high with regard to the basin base level. At present, the erosional surface on top of the basement shows a gentle southward dipping slope of about 10° [*Briais et al.*, 1990] (0.17 m/m, Figure 11b) which was induced by Miocene tilting along the southern boundary fault. Therefore this surface was subhorizontal before the Miocene. This surface is now incised by the current drainage network (Figure 11c). It consists of a main longitudinal drain, the Segre River which is flowing south-westward, and several transverse tributaries on each side of the trough. In fact neither these tributaries nor the uppermost course of the Segre River do incise strongly the sedimentary basin fill and underlying basement. Both the

Figure 11. (a) Topography of the Eastern Pyrenees (SRTM90 DEM data) including the Cerdanya, Capcir, and Conflent intermontane basins. Black lines delimit the three main catchments drained respectively by the Segre, Aude and Têt rivers. Maximum elevation in the Miocene half graben of Cerdanya is about 1000 m. (b) The local slope map shows that north of Cerdanya and west of Capcir, extensive remnants of the Miocene erosional surface are preserved that show a slope of about 10° toward the S-SE. (c) Local geophysical relief highlighting the dissection of the high-elevation, low-relief surfaces and the margins of the Cerdanya Basin. It consists of the difference between two surfaces: a smooth surface that fits all the ridges and summits of tributaries of the Segre, Aude and Têt rivers and the current topography itself [e.g., *Abbott et al.*, 1997; *Small and Anderson*, 1998]. Deep incision develops on both southwestern and northeastern edges of the Cerdanya trough, contrasting with its rather gentle slopes (see text for further explanation).

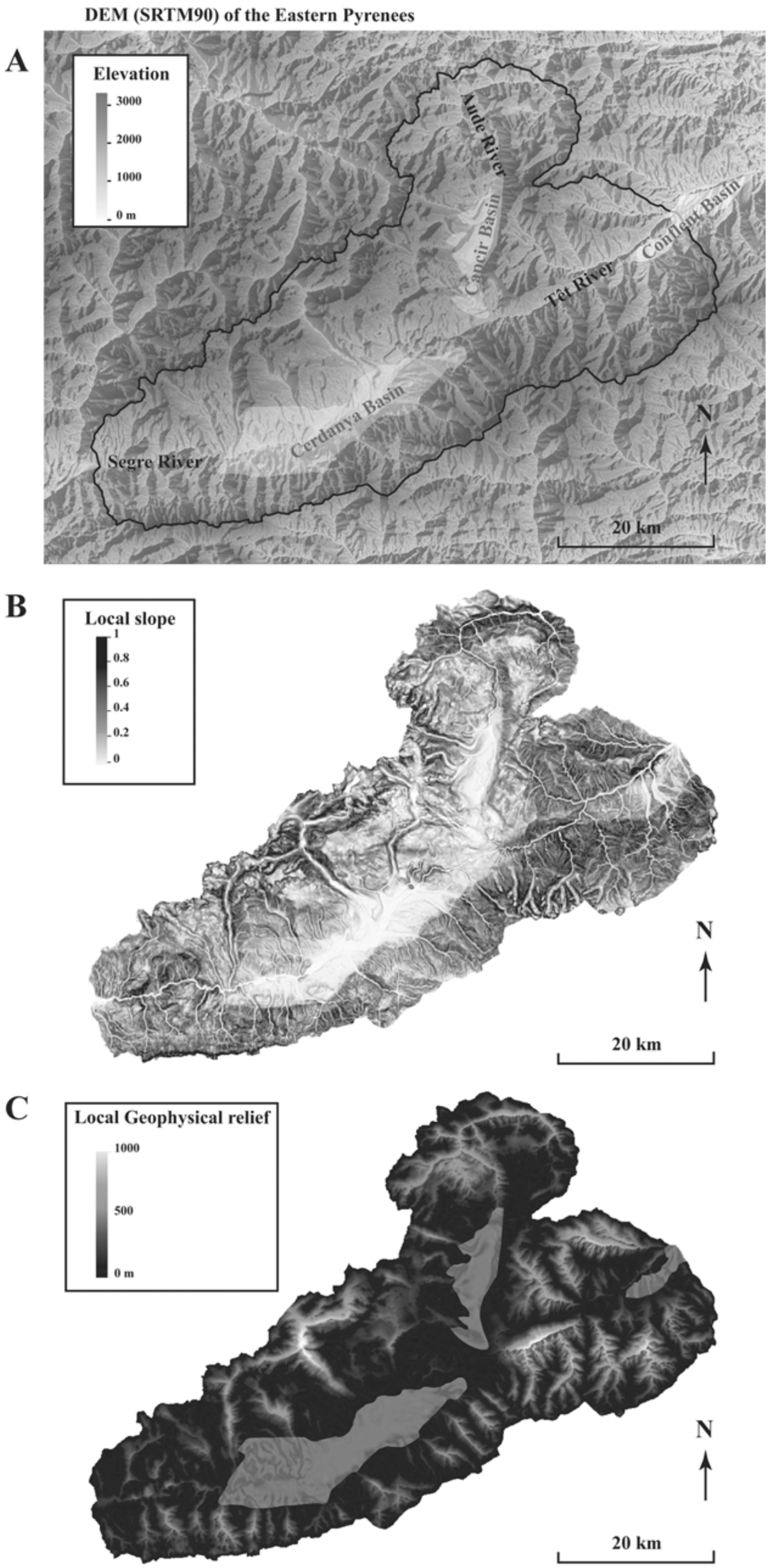

DEM (SRTM90) of the Eastern Pyrenees
A
Elevation
3000
2000
1000
0 m
Aude River
Capcir Basin
Conflent Basin
Têt River
Cerdanya Basin
Segre River
N
20 km
B
Local slope
1
0.8
0.6
0.4
0.2
0
N
20 km
C
Local Geophysical relief
1000
500
0 m
N
20 km

Figure 11

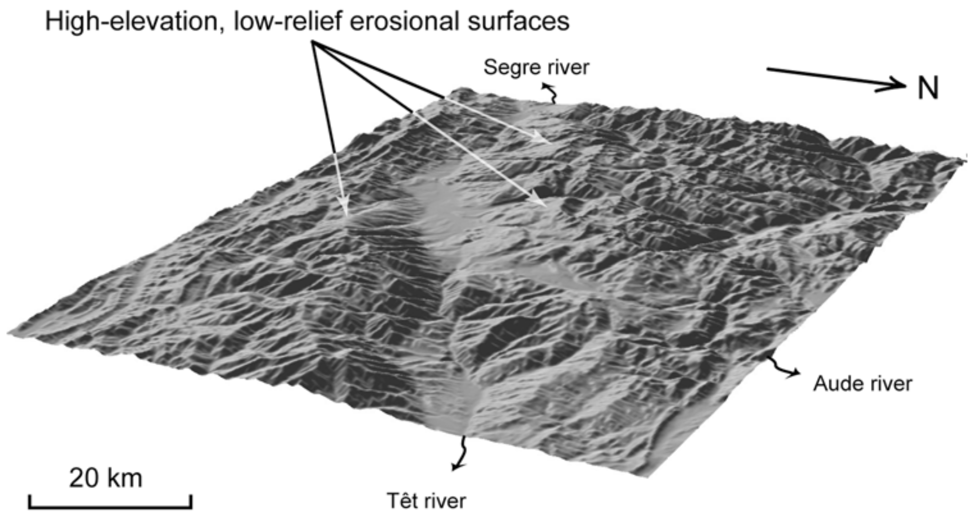


Figure 12. Three-dimensional view looking to the southwest of the Eastern Pyrenees showing high-elevation, low-relief surface remnants of the Miocene erosional surface. The remnants of the Miocene erosional surface are incised by the tributaries of the Segre. Note the knickpoint of the Têt river, at the northeastern edge of the Cerdanya Basin (similar knickpoint occurs along the Segre river, at the southwestern edge of the Cerdanya Basin, in the background. (No vertical exaggeration.)

Segre River and the Têt River begin to incise dramatically when they leave the Cerdanya trough at its southwestern and northeastern edges, respectively. In others words, the Cerdanya trough appears as an area mostly preserved from erosion by the current rivers, the Segre and the Têt rivers, whose longitudinal profiles display huge knick points when approaching the Cerdanya trough (Figures 8 and 12). A remarkable geomorphologic feature of this area is the contrast of relief and roughness of the valley sides observed between outside and within the Cerdanya area. Where the Segre and the Têt rivers leave the Cerdanya basin and begin to form deep valleys in the basement, the valley sides become strongly incised by their tributaries (Figures 11c and 12). This results from the fact that in this area the difference of local relief between the borders of the Cerdanya basin and valley sides of the Segre and Têt is directly related to the difference of base level position in both areas.

[32] This example can be viewed as a small-scale example of what happened at the scale of the Pyrenees (their southern flank at least) when the base level was much higher and Eocene valleys where filled with sediments. We therefore conclude that before the rejuvenation of the relief by the present drainage network, landscape in the Axial Zone was probably poorly incised and looking rather smooth because denudation was relative to a much higher base level. This implies (1) that the slight difference observed today between the mean elevation of the Axial zone and the top of the Tertiary detrital series cannot be attributed to the much more intense erosion of the Axial Zone during the recent period of relief rejuvenation, and (2) that high-elevation, low-relief surfaces were already present during Miocene times.

[33] In the Maladeta massif, *Fitzgerald et al.* [1999] have argued for a recent exhumation of about 2–3 km since the late Miocene. In this area, high-elevation, low-relief erosional surfaces lie between 2000 to 2600 m asl, whereas the uppermost Oligocene detrital series, located 20 km farther to the south, reaches an altitude of 1800 m. The maximum exhumation estimate was deduced from radiometric dating of samples located in a valley at an elevation of 1100 m. As quoted by *Fitzgerald et al.* [1999], "the present-day topographic form of the Pyrenees is largely a relict of the topography that formed in the Eocene and Oligocene." Hence their estimate only refers to exhumation in relation with recent valley incision. Their conclusions therefore do not hold for the whole area, and in particular for the area where high-elevation, low-relief surfaces are preserved. If their conclusions were valid for the whole area, this would imply that most of the detrital deposits of the Sis paleovalley would have been eroded. According to *Vincent* [2001], only 400 m were eroded on the top of the Sis paleovalley since the Oligocene-Miocene. Finally, *Fitzgerald et al.* [1999] also state that their exhumation model describes the recent rejuvenation of the southern flank, including the dissection of a previous highly elevated peneplain, which reinforces the idea we develop here.

4.2. Base Level Rise as a Cause for Relief Decrease Between the Axial Zone Summits (Mean of Peak Elevations) and the Top of the Detrital Series

[34] There is no doubt that the base level of the Pyrenean southern flank has dramatically risen since the closure of the Ebro basin. Huge discharge of continental detrital sediments, especially conglomerates, has back-stepped toward the chain, onlapping previously deformed basement. Conglomerates filled the paleovalleys which developed during the period of external drainage. Some of them, such as the

Sis valley, were up to 800 m deep, suggesting jagged relief on the southern flank during the period of external drainage. However the morphology of certain paleovalleys appears to have been controlled by large-scale folds so that the valley depth does not reflect vertical incision (Figure 10c). Moreover, the conglomerates that now fill these paleovalleys do not seem to have eroded the floor and walls much, they simply overlap them.

[35] However, the fact that the base level rose, does not imply that the relief between the Axial Zone summit and the top of the detrital series was decreasing, a requisite condition to smooth relief roughness. According to most authors [*Séguret*, 1972; *Choukroune et al.*, 1989] the main phase of tectonic shortening in the Pyrenees occurs during Eocene times and a second minor phase develops during the Oligocene in the most external parts of the chain. So, tectonic uplift was paroxysmal during Eocene times, and it can be reasonably expected that the chain reached its maximum elevation by the end of the Eocene. In a similar way, it can be expected that from the Oligocene onward, the mean elevation of the chain was progressively decreasing as tectonic uplift vanished. Continuation of continental sedimentation on the top of the previous Eocene top-wedge basin shows that the local base level of the Pyrenean southern flank was at least as high during the Oligocene and the Miocene as it was at the end of the Eocene. As the top of the detrital series overlaps the Axial Zone, if subsidence were to have occurred, inducing a decrease of the local base level elevation, it would have resulted in a similar effect for the elevation of the Axial Zone. Therefore, from the Oligocene onward, the relief between the Axial Zone summit and the top of the sediments was most probably decreasing, a process that will have strengthened during Miocene times as continental sedimentation still lasts. This results in the progressive smoothing of the relief roughness in the Axial Zone and the development of high-elevation, low-relief erosional surfaces.

[36] Finally, we cannot exclude the possibility that such a process initiated during Eocene times, when huge amount of conglomerates start to sediment. Indeed, as far as the surface elevation as defined by *England and Molnar* [1990], could be considered it was roughly constant during Eocene times, with the rapid filling of the initial marine foreland basin reflecting the rise of the southern flank base level as a whole. This relative relief decrease between the high chain and the sedimentary wedge could have therefore initiated the decrease of the local relief within the Axial Zone as soon as the mid-Eocene.

5. When Does the Dissection of the High-Elevation, Low-Relief Surfaces Begin?

[37] As discussed before, high-elevation, low-relief erosional surfaces in the Pyrenean southern flank are remnants of a smooth landscape that has been rejuvenated by a recent drainage network. Several explanations have been proposed to account for this rejuvenation (see above). Among them, the new connection of the Ebro River to the Mediterranean has been invoked, which is supposed to have occurred just after the dramatic sea level fall of the Mediterranean during the Messinian Salinity Crisis. Resulting strong regressive erosion along the eastern margin of the Catalan ranges would have broken the previous Catalan dam and finally induced the capture of the Ebro drainage network by the Mediterranean. It is well known that the sea level fall of around 1500 m in the Mediterranean induced strong incision of the continental surface by rivers and the creation of deep canyons all around the Mediterranean region [*Hsü et al.*, 1973; *Ryan*, 1976; *Clauzon*, 1978; *Clauzon et al.*, 1996; *Krijgsman et al.*, 1999]. The subsequent opening of the Strait of Gibraltar caused the catastrophic reflooding of the desiccated Mediterranean basin, stopping rivers incising and allowing the inland canyons to be preserved by early Pliocene marine deposits [*Denizot*, 1952; *Chumakov*, 1973].

[38] In the Rhone valley, fluvial incision propagated more than 300 km inland and canyons reached more than 1000 m depth in the downstream part. The present drainage area of the Ebro basin (A = 0.9.10^5 km^2) is similar to that of the Rhone (A = 1.10^5 Km^2). If the Ebro basin had been connected to the Mediterranean before or during the Messinian Salinity Crisis then similar canyons would have developed within the Ebro basin, but none has been identified at present. Messinian inland canyons that were identified do not cross through the Catalan coastal ranges [*Agustí et al.*, 1983; *Arasa Tuliesa*, 1990]. We therefore conclude that the Ebro River was not connected to the Mediterranean before the Pliocene. By analyzing the Valencia trough fill, where the Ebro enters the Mediterranean, *Field and Gardner* [1990] observe a major change in sedimentation style from clays to prograding sands. *Field and Gardner* [1990] link this change to the discharge of the Ebro River, suggesting that the Ebro River connected to the Mediterranean during the Quaternary. However a first order evaluation of the balance between the amount of eroded terranes within the Ebro basin and the amount of sediments deposited within the Valencia Trough, in which the Ebro River enters, since the Messinian Salinity Crisis shows that the Ebro River could have flowed into the Mediterranean as soon as the Pliocene (Figure 13). This means that the new base level of the Ebro basin has dropped at least since the Pliocene leading inevitably to regressive erosion within the entire Ebro catchment. In this way, relief rejuvenation in the Pyrenean southern flank could have started as soon as Pliocene times. Alternatively, major change in type of sedimentation from clays to sands recorded in the Valencia trough at the end of the Pliocene as well as the three times increase of sediment influx during late Pliocene, also suggests that relief rejuvenation could have been triggered by global climate change.

6. Discussion

6.1. Foreland Basin Overfilling and Base Level Rise

[39] We have tentatively demonstrated that the development of the high-elevation, low-relief erosional surfaces that are a striking feature of the Pyrenees morphology resulted from the rise of the base level of the southern foreland basin whereas surface uplift (i.e., uplift of rocks-exhumation) of

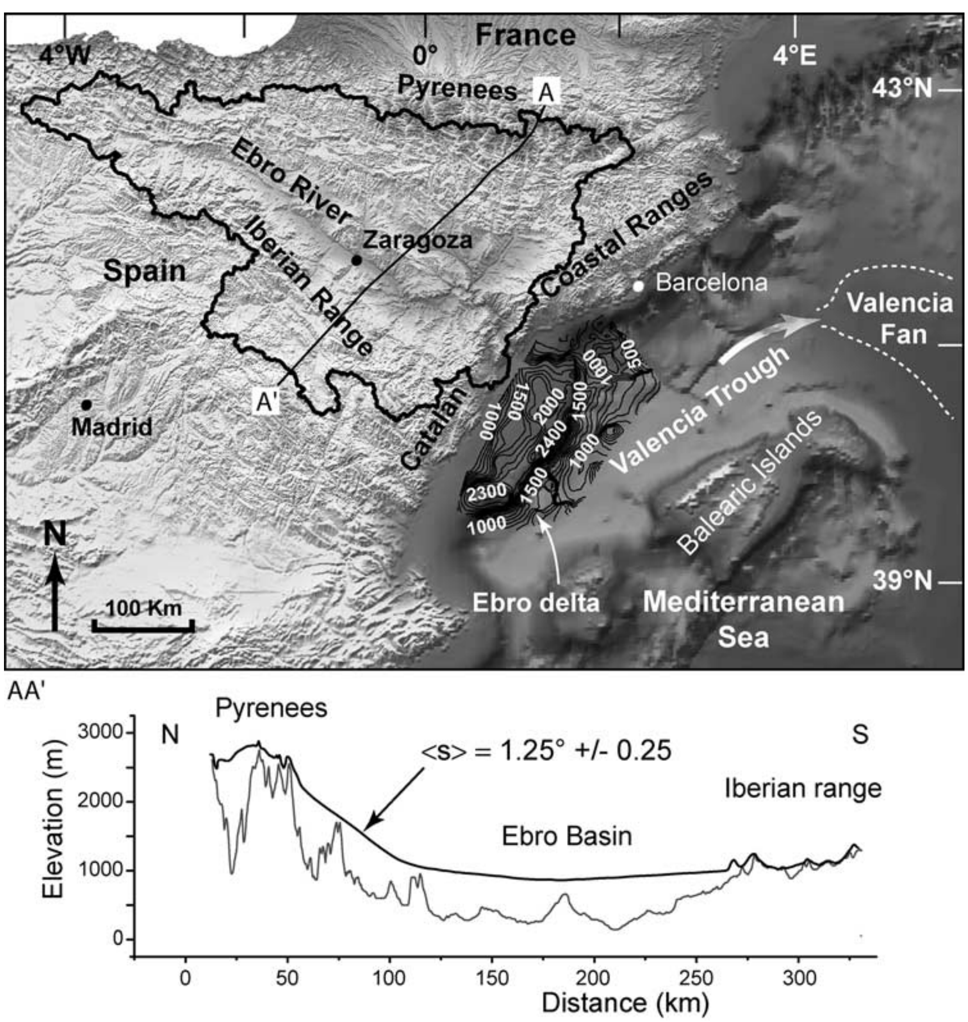


Figure 13. Estimate of the eroded volume in the Ebro basin since the Pliocene. (top) Topography of the Ebro drainage area (SRTM90 DEM data). Black line AA' marks location of the topographic profile shown below. The catchment contour of the Ebro River is also shown. The volume of post-Messinian detrital sediments within the Valencia trough has been determined as 25,700 km^3 from the difference between the Messinian top-surface and the current bathymetry (accurate reconstruction of the top-Messinian surface is from *Maillard* [1993]). *Nelson* [1990] estimated the volume of post-Messinian detrital sediments that are discharged by the Ebro River in the Valencia fan to be 6300 km^3. This provides a total amount of post-Messinian sediment of 32,000 km^3. (Black lines show isobaths of Pliocene and Quaternary deposits.) (bottom) Topographic profile of the reconstructed paleotopography and the current topography. The paleotopography has been computed by fitting a smooth surface between the Pyrenean summits, and the center of the Ebro basin within all the catchment of the Ebro river. The Ebro basin is a trough, the maximum elevation of which is 860 m [*Arenas*, 1993]. Elevation of the basin edges reaches 1000 m. From the southern limit of the Axial Zone to the limit of the south Pyrenean zone the paleosurface elevation decreases from 2000 m to 1000 m. The paleotopography is calculated with a mean slope $\langle s \rangle = 1.25°$. The eroded volume (37,800 km^3, computed from the difference between two surfaces: the paleotopography surface and the current topography) is comparable to that of post-Messinian deposits in the Valencia trough and Valencia fan.

the high chain was vanishing. We also suggest that this process of "high-altitude peneplanation" could have started during Eocene uplift, when the foreland basin became closed and started to overfill. From the Pliocene onward, excavation leads to the present morphology of the Pyrenean southern flank including the dissection of the high-elevation, low-relief erosional surfaces. Our interpretation disagrees with previous interpretations which consider that the high-elevation, low-relief surfaces were remnants of a low-elevation peneplain that resulted from long-term erosion of the Pyrenees and that was uplifted to 2000 m during the Pliocene. As shown by *Babault* [2004] and

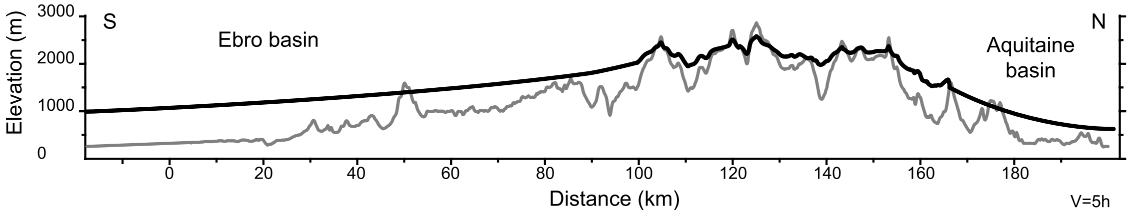


Figure 14. Idealized reconstruction of the paleotopography of the Pyrenees before post-Miocene landscape rejuvenation.

according to *England and Molnar*'s model [1990], removal by recent erosion accounts for a maximum of 400 m of isostatic rebound, which cannot explain the present-day high elevation of these low-relief surfaces.

[40] It has long been recognized that, at midlatitude, erosion is mainly governed by the potential energy of streams which depends on the difference in elevation between their source and base level. Whatever the process that will lower the potential energy, it will result in peneplanation but not necessarily near sea level. In the case of the southern flank of the Pyrenees the base level rose as sediments accumulated at the surface of the top-wedge foreland basin. Following tectonic uplift, ongoing sediment accumulation was obviously resulting in lowering such an elevation difference. Depending on the relative rates of both surface uplift and sedimentation, this difference may have decreased during tectonic uplift. This could be achieved if the difference between the surface uplift rate and the rate of the base level rise decreased. As discussed in section 4, it was probably the case from late Eocene to early Oligocene, in as far as one can consider that erosion was counter-balancing tectonic uplift when the chain was fully active (i.e., in steady state equilibrium [*Hack*, 1960]).

6.2. Internal/External Drainage and Sediment Length Transfer

[41] High-elevation, low-relief erosional surfaces also exist on the northern flank of the eastern Pyrenees. Their elevation reaches up to 1800–1900 m as in the Aston massif. They have been described as the continuation of the low-relief, erosional surfaces that occur at lower elevation, between 700–800 m. Both these erosional surfaces are supposed to belong to a posttectonic Miocene ‘‘gently undulating, very mature landscape, almost peneplain with low hills, which in the centre did not rise above 1000 m altitude’’ [*de Sitter*, 1952]. In others words, these surfaces would have been warped and uplifted up to 2000 m, long after Pyrenean tectonics [*Pannekoek*, 1935; *Birot*, 1937; *de Sitter*, 1952], an interpretation that is opposite with that proposed here for the high-elevation, low-relief surfaces of the southern flank.

[42] A major difference between the northern and southern Pyrenees is the fact that the drainage of the northern foreland basin (Aquitaine basin) remains external all along the building of the chain. However the sedimentation pattern, that is basin progressive overfilling, of the Aquitaine basin is rather similar to that of the Ebro basin [e.g., *Bureau de Recherches Géologiques et Minières* (*BRGM*), 1974; *Dubreuilh et al.*, 1995]. Indeed, from the mid-Eocene onward, previous marine sedimentation is replaced by continental sedimentation, including conglomerates. Moreover occurrence of extensive evaporites during the late Eocene in the western part of the basin [*BRGM*, 1974; *Crochet*, 1991] suggests a poorly drained area. However, coarse detrital deposits as observed today do not reach so high an elevation as they do on the southern flank. Miocene subhorizontal deposits reach 600 to 700 m asl at the top of Lannemezan fan in central part of the northern Pyrenees [*Goron*, 1941]. It is difficult to determine the maximum elevation pre-Miocene detrital deposits in the northern flank could have reached. Scarce continental coarse Eocene deposits occur up to 1700m asl in the Lers area (Central Pyrenees) [*Choukroune*, 1973, 1980]. Intercalation of conglomerates within extensive more fined-grained sediments, are also present all along the foothills. This suggests that coarse continental proximal deposits probably overlapped the northern flank during the Paleogene, and were later eroded. We therefore infer that the high-elevation, low-relief surfaces of the northern flank developed in the same way as the high-elevation, low-relief surfaces of the southern flank did (Figure 14).

[43] An important point to consider is the nature of the drainage with regard to the base level elevation. Although we mention that the northern flank was poorly drained, the drainage remains external all along the building of the chain contrary to the drainage of the southern flank which became internal from the late Eocene. This suggests that it is not so much the nature of drainage as the river capacity to transport sediments (sediment length transfer) that is the most influential factor in setting the base level of the chain. As a consequence, the limit of the most proximal, extensive detrital sedimentation can be considered as the ‘‘efficient’’ base level of a chain.

6.3. Rejuvenation of the Pyrenees Relief: Role of Climate

[44] It is clear that the present jagged relief of the Pyrenees has no relation with Palaeogene tectonic building of the chain insofar as the high elevation of the base level resulted in the high elevated applanation. By analyzing the characteristics of the present network on both flanks, we have concluded that the recent morphology of the Pyrenees results from rather uniform climatic conditions. Therefore the hypothesis where the Ebro River capture by the Mediterranean was merely the cause of the reexcavation of the buried southern flank needs to be revised. This is in

accordance with our remark about the relative relation of the drainage nature and the river capacity to transport sediments with the efficient base level of a chain.

[45] According to recent works [e.g., *Zhang et al.*, 2001], the marked increase, since the last 2 to 4 Ma, of both the sedimentation and erosion rates throughout the world has to be related to global climate change from rather equable climate during the Neogene to a period characterized by frequent and abrupt changes in temperature, rainfall and vegetation, from the late Pliocene. We suggest that in the case of the Pyrenees the climate shift from the Pliocene should have enhanced the transport capacity of rivers, resulting in the lowering of the Pyrenees efficient base level down to sea level. An alternative explanation is to consider late Pliocene and Quaternary oscillatory climate as much more efficient to erode and denude, than past equable climates, by combining different erosional processes such as chemical weathering, periglacial fracturing or other forms of mass wasting [*Zhang et al.*, 2001]. This would result in strong size reduction of eroded particles, hence favoring their discharge down to the sea.

[46] Finally we agree with *England and Molnar* [1990] when they wrote that "the marked climatic changes in the last few million years may be responsible for increased rates of denudation, and the creation of dramatic morphology, without any associated surface uplift."

7. Conclusion

[47] In contrast with the classical view of mountain chains peneplanation by long-term erosion as described by the "geographical cycle" of *Davis* [1889], we suggest that relief subduing does not necessarily equate to surface elevation lowering, so that relief of mountain belts can be smoothed at high elevation. Such a process is allowed by the piedmont aggradation of the eroded products of mountain ranges, resulting in the increase of their base level and the relative lowering of their mean elevation, and in the concomitant progressive decrease of the erosive power of their drainage system. This explains in our opinion the paradox of the occurrence of posttectonic high-elevation, low-relief surface remnants of peneplain within the Pyrenees, the elevation of which has been previously misinterpreted as resulting from enigmatic Pliocene uplift. The rejuvenation of the Pyrenean relief starts most probably during the Pliocene. As the current morphology of both sides of the chain present similar characteristics, we believe that rejuvenation is mostly due to the climate shift that occurs from the late Pliocene, rather than due to changing boundary conditions at the foreland basin margins such as the capture of the Ebro River by the Mediterranean sea. During Neogene times, most eroded products of the chain were trapped in the northern and southern Pyrenean foreland basins. Global climate change from the Pliocene might have enhanced the river capacity to transport the eroded products, so that the efficient base level of the Pyrenees was no longer their northern and southern piedmonts but the Atlantic Ocean and the Mediterranean Sea, respectively.

[48] Finally, the example of the Pyrenees is probably not a single case. Many ancient mountain chains show remaining elevation and relative jagged relief, as well as preserved crustal roots. The model of high peneplanation suggested for the Pyrenees and the role of recent global climate change in relief rejuvenation might also provide one explanation for such features.

[49] **Acknowledgments.** We are most grateful to Antonio Teixell and Peter Molnar for helpful reviews. Special thanks to P. Molnar for his warm encouragement to carry on this work. Mimi Hill kindly improved the English. Financial support was provided by CNRS-INSU research program PNSE and ATI. This study was also supported by the Ministère de l'Education Nationale, de la Recherche et de la Technologie, who funded Julien Babault's Ph.D. thesis.

References

Abbott, L. D., E. A. Silver, R. S. Anderson, R. Smith, J. C. Ingle, S. A. King, D. Haig, E. Small, J. Galewsky, and W. Sliter (1997), Measurement of tectonic surface uplift rate in a young collisional mountain belt, *Nature*, *385*, 501–507.

Agustí, J., P. Anadón, and R. Julia (1983), Nuevos datos sobre el Plioceno del Baix Ebre: Aportación a la correlación entre las escalas marina y continental, *Acta Geol. Hisp.*, *18*, 123–130.

Ahnert, F. (1984), Local relief and the height limits of mountain ranges, *Am. J. Sci.*, *284*, 1035–1055.

Arasa Tuliesa, A. (1990), El terciario del Baix Ebre: Aportaciones estratigráficas y sedimentológicas, *Acta Geol. Hisp.*, *25*, 271–287.

Arenas, C. (1993), Sedimentología y paleogeografía del Terciario del margen pirenaico y sector central de la cuenca del Ebro (zona aragonesa occidental), Ph.D. thesis, 858 pp., Univ. de Zaragoza, Zaragoza, Spain.

Astre, G. (1927), Le bassin Néogène de Bellver, *Bull. Soc. Hist. Nat. Toulouse*, *LVI*, 231–258.

Babault, J. (2004), Dynamique de l'érosion dans une chaîne de montagnes: Influence de la sédimentation de piedmont: L'exemple des Pyrénées, Ph.D. thesis, 218 pp., Univ. de Rennes 1, Rennes, France.

Bates, R. L., and J. A. Jackson (1980), *Glossary of Geology*, Am. Geol. Inst., Falls Church, Va.

Birot, P. (1937), Recherches sur la morphologie des Pyrénées orientales franco-espagnoles, Doctorat ès Lettres thesis, 318 pp., Paris.

Blackstone, D. L. (1975), Late Cretaceous and Cenozoic history of Laramie Basin Region, southeast Wyoming, *Mem. Geol. Soc. Am.*, *144*, 249–279.

Boissevain, H. (1934), Etude géologique et géomorphologique de la vallée de la haute Sègre, *Bull. Soc. Hist. Nat. Toulouse*, *LXVI*, 33–170.

Briais, A., R. Armijo, T. Winter, P. Tapponnier, and A. Herbecq (1990), Morphological evidence for Quaternary normal faulting and seismic hazard in the eastern Pyrenees, *Ann. Tectonicae*, *IV*, 19–42.

Brunet, M. F. (1986), The influence of the evolution of the Pyrenees on adjacent basins, *Tectonophysics*, *129*, 343–354.

Bureau de Recherches Géologiques et Minières (BRGM) (1974), *Géologie du Bassin d'Aquitaine*, 26 pp., Ed. BRGM, Paris.

Cabrera, L., E. Roca, and P. Santanach (1988), Basin formation at the end of a strike-slip fault: The Cerdanya Basin (eastern Pyrenees), *J. Geol. Soc. London*, *145*, 261–268.

Calvet, M. (1985), Néotectonique et mise en place des reliefs dans l'Est des Pyrénées: L'exemple du horst des Albères, *Rev. Geol. Dyn. Geogr. Phys.*, *26*, 119–130.

Calvet, M. (1994), Morphogénèse d'une montagne méditerranéenne: Les Pyrénées orientales, Doctorat d'Etat thesis, 1177 pp., Univ. de Paris I Panthéon, Sorbonne, Paris.

Carozza, J. M., and S. Baize (2004), L'escarpement de la faille de la Têt est-il le résultat de la tectonique active Plio-Pléistocène ou d'une exhumation Pléistocène, *C. R. Geosci.*, *336*, 217–226.

Choukroune, P. (1973), La brèche de Lherz dite "d'explosion liée à la mise en place des lherzolites" est une brèche sédimentaire d'âge cénozoïque (Pyrénées Ariégeoises), *C. R. Acad. Sci. Paris*, *277*, 2621–2624.

Choukroune, P. (1980), Comment and Reply on "Quenching: An additional model for emplacement of the lherzolite at Lers (French Pyrenees)," *Geology*, *8*, 514–515.

Choukroune, P., et al. (1989), The ECORS Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt, *Tectonics*, *8*, 23–39.

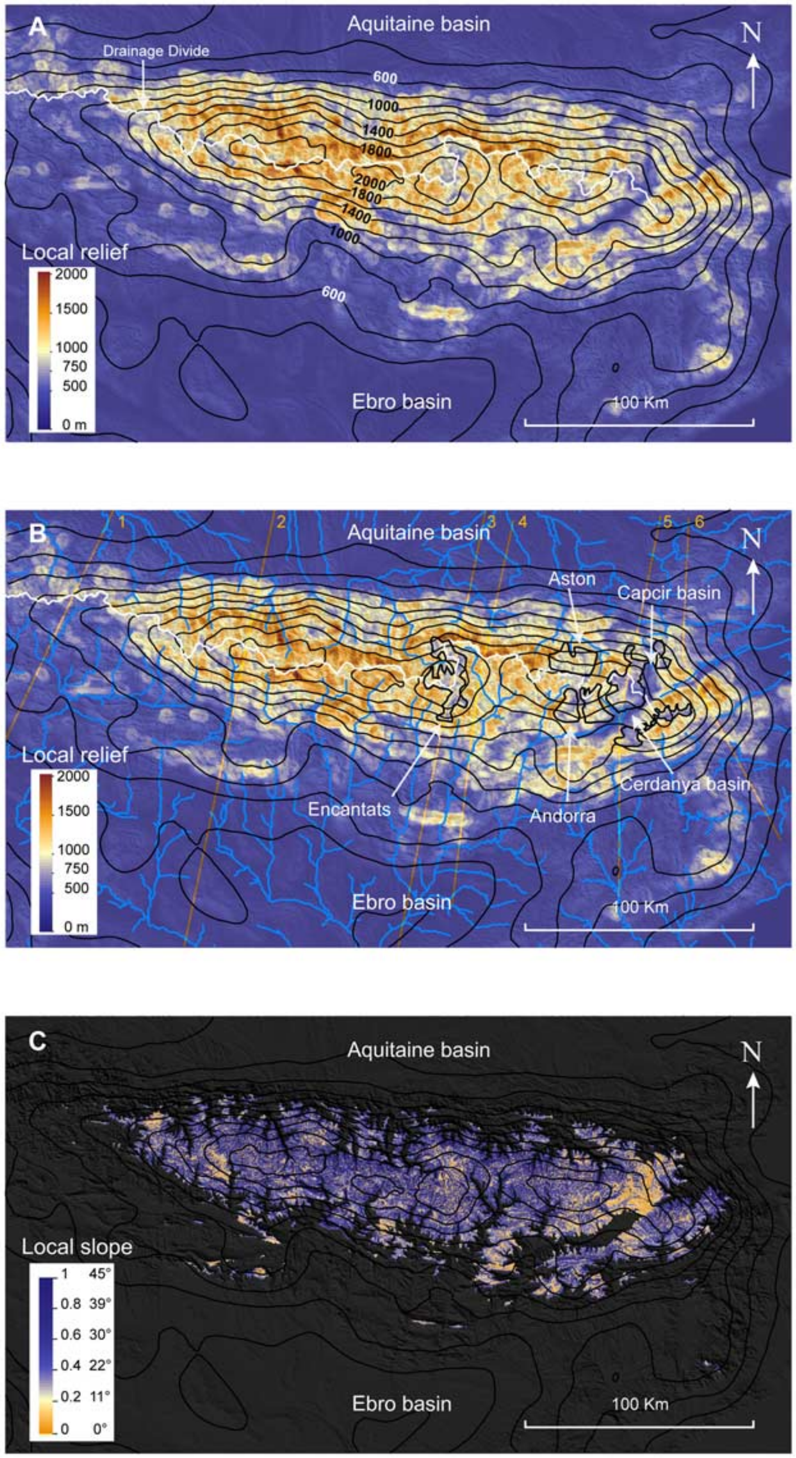
Chumakov, I. S. (1973), Pliocene and Pleistocene deposits of the Nile valley in Nubia and upper Egypt, *Initial Rep. Deep Sea Drill. Proj.*, *13*, 1242–1243.

Clauzon, G. (1978), The Messinian Var canyon (Provence, southern France): Paleogeographic implications, *Mar. Geol.*, *27*, 231 – 246.
Clauzon, G., J.-P. Suc, F. Gautier, A. Berger, and M.-F. Loutre (1996), Alternate interpretation of the Messinian salinity crisis: Controversy resolved?, *Geology*, *24*, 363 – 366.
Coney, P. J., J. A. Muñoz, K. R. McClay, and C. A. Evenchick (1996), Syntectonic burial and post-tectonic exhumation of the southern Pyrenees foreland fold-thrust belt, *J. Geol. Soc. London*, *153*, 9 – 16.
Crochet, B. (1991), Molasses syntectoniques du versant nord des Pyrénées: La série de Palassou, *Doc. B. R. G. M.*, *199*.
Davis, W. M. (1889), The geographical cycle, *Geogr. J.*, *14*, 481 – 504.
Denizot, G. (1952), Le Pliocène dans la vallée du Rhône, *Rev. Geogr. Lyon*, *27*, 327 – 357.
de Sitter, L. U. (1952), Pliocene uplift of Tertiary mountain chains, *Am. J. Sci.*, *250*, 297 – 307.
Dubreuilh, J., J. P. Capdeville, G. Farjanel, G. Karnay, J. P. Platel, and R. Simon-Coinçon (1995), Dynamique d'un comblement continental néogène et quaternaire: L'exemple du bassin d'Aquitaine, *Geol. Fr.*, *4*, 3 – 26.
England, P., and P. Molnar (1990), Surface uplift, uplift of rocks, and exhumation of rocks, *Geology*, *18*, 1173 – 1177.
Field, M. E., and J. V. Gardner (1990), Pliocene-Pleistocene growth of the Rio Ebro margin, northeast Spain: A prograding-slope model, *Geol. Soc. Am. Bull.*, *102*, 721 – 733.
Fitzgerald, P. G., J. A. Muñoz, P. J. Coney, and S. L. Baldwin (1999), Asymmetric exhumation across the Pyrenean orogen: Implications for the tectonic evolution of a collisional orogen, *Earth Planet. Sci. Lett.*, *173*, 157 – 170.
Flint, J. J. (1974), Stream gradient as a function of order, magnitude, and discharge, *Water Resour. Res.*, *10*, 969 – 973.
Garcia-Castellanos, D., J. Vergés, J. Gaspar-Escribano, and S. Cloetingh (2003), Interplay between tectonics, climate, and fluvial transport during the Cenozoic evolution of the Ebro Basin (NE Iberia), *J. Geophys. Res.*, *108*(B7), 2347, doi:10.1029/2002JB002073.
Goron, L. (1941), Les Pré-Pyrénées ariégeoises et garonnaises: Essai d'étude morphologique d'une lisière de montagne, Doctorat thesis, Fac. des Lettres, Univ. de Toulouse, Toulouse, France.
Hack, J. T. (1957), Studies of longitudinal stream profiles in Virginia and Maryland, *U.S. Geol. Surv. Prof. Pap.*, *294*, 45 – 94.
Hack, J. T. (1960), Interpretation of erosional topography in humid temperate regions, *Am. J. Sci.*, *258*, 80 – 97.
Hovius, N. (1996), Regular spacing of drainage outlets from linear mountain belts, *Basin Res.*, *8*, 29 – 44.
Hovius, N. (2000), Macroscale process systems of mountain belt erosion, in *Geomorphology and Global Tectonics*, edited by M. A. Summerfield, pp. 77 – 105, John Wiley, Hoboken, N. J.
Hsü, K. J., M. B. Cita, and W. B. F. Ryan (1973), The origin of the Mediterranean evaporites, in *Initial Rep. Deep Sea Drill. Proj.*, *13*, 1203 – 1231.
Keefer, W. R. (1970), Structural geology of the Wind River Basin, Wyoming, *U.S. Geol. Surv. Prof. Pap.*, *495 – D*.
Krijgsman, W., F. J. Hiigeni, I. Raffi, F. J. Sierro, and D. S. Wilson (1999), Chronology, causes and progression of the Messinian salinity crisis, *Nature*, *400*, 652 – 655.
Maillard, A. (1993), Structure et riftogénèse du Golfe de Valence (Méditerranée Nord-Occidentale), Ph.D. thesis, 284 pp., Univ. Pierre et Marie Curie-Paris 6, Paris.
Mattauer, M. (1968), Les traits structuraux essentiels de la chaîne Pyrénéenne, *Rev. Geogr. Phys Geol. Dyn.*, *X*, 3 – 12.
Mattauer, M. (1985), Présentation d'un modèle lithosphérique de la chaîne des Pyrénées, *C. R. Acad. Sci. Paris, Ser. II*, *300*, 71 – 74.
Mengel, O. (1910), A propos des paliers des vallées des Pyrénées-Orientales (réponse à M. de Martonne), *Bull. Soc. Geol. Fr., Ser. 4*, *X*, 427.
Météo-France (1987), *Atlas Climatique de la France*, 30 pp., Paris.
Molnar, P., and P. England (1990), Late Cenozoic uplift of mountain ranges and global climate change: Chicken or egg?, *Nature*, *346*, 29 – 34.
Muñoz, J. A. (1992), Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross section, in *Thrust Tectonics*, edited by K. R. McClay, pp. 235 – 246, CRC Press, Boca Raton, Fla.
Mutti, E., M. Séguret, and M. Sgavetti (1988), Sedimentation and deformation in the Tertiary sequences of the southern Pyrenees, *Field Trip Guide 7*, 153 pp., Am. Assoc. of Pet. Geol., Tulsa, Okla.
Nelson, C. H. (1990), Estimated post-Messinian supply and sedimentation rates on the Ebro continental margin, Spain, *Mar. Geol.*, *95*, 395 – 418.
Nelson, C. H., and A. Maldonado (1990), Factors controlling late Cenozoic continental margin growth from the Ebro Delta to the western Mediterranean deep sea, *Mar. Geol.*, *95*, 419 – 440.
Nijman, W. (1998), Cyclicity and basin axis shift in piggyback basin: Towards modelling of the Eocene Tremp-Ager Basin, south Pyrenees, Spain, in *Cenozoic Foreland Basin of Western Europe*, edited by A. Mascle et al., *Geol. Soc. Spec. Publ.*, *134*, 135 – 162.
Nussbaum, F. (1931), Sur les surfaces d'aplanissement d'âge tertiaire dans les Pyrénées-Orientales et leurs transformations pendant l'époque quaternaire, in *C. R. Congr. Int. Geogr.*, *II*, 529 – 534.
Pannekoek, A. J. (1935), *Evolution du Bassin de la Têt dans les Pyrénées Orientales Pendant le Néogène: Edtude de morphotectonique*, 72 pp., N. V. Ooshoek's, Utrecht.
Panzer, W. (1926), Talentwicklung und Eiszeitklima in nord-östlichen Spanien, *Abh. Senckenberg. Nat. Ges.*, *39*, 141 – 182.
Penck, A. (1894), Studien über das Klima Nordspaniens während der jungeren Terciärperiode und der diluvialperiode, *Z. Ges. Erdkunde Berlin*, *29*, 109 – 141.
Puigdefàbregas, C., and P. Souquet (1986), Tectono-sedimentary cycles and depositional sequences of the Mesozoic and Tertiary from the Pyrenees, *Tectonophysics*, *129*, 173 – 204.
Puigdefàbregas, C., J. A. Muñoz, and J. Vergés (1992), Thrusting and foreland basin evolution in the southern Pyrenees, in *Thrust Tectonics*, edited by K. R. McClay, pp. 247 – 254, CRC Press, Boca Raton, Fla.
Reille, J. L. (1971), Les relations entre tectorogénèse et sédimentation sur le versant sud des Pyrénées centrales d'après l'étude des formations terciaires essentiellement continentales, Doctorat d'Etat Science thesis, 330 pp., Univ. des Sci. et Technol. du Languedoc, Montpellier, France.
Riba, O., S. Reguant, and J. Villena (1983), Ensayo de síntesis estratigráfica y evolutiva de la cuenca terciaria del Ebro, in *Libro Jubilar de J. M. Ríos*, *Geol. Esp.*, vol. 2, edited by J. A. Comba, pp. 131 – 159, Inst. Geol. y Min. de Esp., Madrid.
Roca, E. (1996), The Neogene Cerdanya and Seu d'Urgell intramontane basins (eastern Pyrenees), in *Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics*, edited by P. F. Friend and C. J. Dabrio, pp. 114 – 119, Cambridge Univ. Press, New York.
Roure, F., P. Choukroune, X. Berastegui, J. A. Muñoz, A. Villien, P. Matheron, M. Bareyt, M. Séguret, P. Camara, and J. Deramond (1989), ECORS deep seismic data and balanced cross section: Geometric constraints on the evolution of the Pyrenees, *Tectonics*, *8*, 41 – 50.
Ryan, W. B. F. (1976), Quantitative evaluation of the depth of the western Mediterranean before, during and after the late Miocene salinity crisis, *Sedimentology*, *23*, 791 – 813.
Scott, G. R. (1975), Cenozoic Surfaces and Deposits in the Southern Rocky Mountains, *Mem. Geol. Soc. Am.*, *144*, 227 – 248.
Séguret, M. (1972), Etude tectonique des nappes et séries décollées de la partie centrale du versant sud des Pyrénées: Caractère synsédimentaire, rôle de la compression et de la gravité, Ph.D. thesis, Univ. Montpellier, Montpellier, France.
Small, E. E., and R. S. Anderson (1998), Pleistocene relief production in Laramide mountain ranges, western United States, *Geology*, *26*, 123 – 126.
Sorres, M. (1913), *Les Pyrénées Méditerranéennes: Étude de Géographie Biologique*, 508 pp., A. Collin, Paris.
Souriau, A., and M. Granet (1995), A tomographic study of the lithosphere beneath the Pyrenees from local and teleseismic data, *J. Geophys. Res.*, *100*, 18,117 – 18,134.
Teixell, A. (1998), Crustal structure and orogenic material budget in the west central Pyrenees, *Tectonics*, *17*, 395 – 406.
Tweto, O. (1975), Laramide (Late Cretaceous-early Tertiary) orogeny in the southern Rocky Mountains, *Mem. Geol. Soc. Am.*, *144*, 1 – 44.
Vacher, P., and A. Souriau (2001), A three-dimensional model of the Pyrenean deep structure based on the gravity modelling, seismic images and petrological constraints, *Geophys. J. Int.*, *145*, 460 – 470.
Vergés, J., H. Millán, E. Roca, J. A. Muõz, M. Marzo, J. Cirés, T. Den Bezemer, R. Zoetemeijer, and S. Cloetingh (1995), Eastern Pyrenees and related foreland basins: Pre-, syn- and post-collisional crustal-scale cross-section, *Mar. Pet. Geol.*, *12*, 893 – 915.
Vincent, S. J. (2001), The Sis paleovalley: A record of proximal fluvial sedimentation and drainage basin development in response to Pyrenean mountain building, *Sedimentology*, *48*, 1235 – 1276.
Willett, S. D., and M. T. Brandon (2002), On steady states in mountain belts, *Geology*, *30*, 175 – 178.
Zhang, P., P. Molnar, and W. R. Downs (2001), Increased sedimentation rates and grain sizes 2 – 4 Myr ago due to the influence of climate change on erosion rates, *Nature*, *410*, 891 – 897.

J. Babault, S. Bonnet, A. Crave, and J. Van Den Driessche, Géosciences Rennes, UMR CNRS 6118, Université de Rennes 1, 35 av. du General Leclerc, F-35042, Rennes Cedex, France. (julien.babault@univ-rennes1.fr)

S. Castelltort, Department of Earth Sciences, ETH-Zentrum, Sonneggstrasse 5, CH-8092 Zürich, Switzerland.

Figure 4. Analysis of the local relief of the Pyrenees derived from SRTM90 DEM data. Local relief is calculated by moving a 5 km wide circular search window over the DEM. At each point, the maximum range of elevation values within the window is determined and plotted at the center of the circle. The same method is used to perform the mean elevation by moving a 30 km wide window. (a) The mean elevation value is indicated and represented by lines superimposed on the local relief. The drainage divide between the northern and the southern flank is also reported. The map shows low values of local relief corresponding to low mean elevation and higher values of local relief corresponding to high mean elevation, except in the Encantats and the eastern Pyrenees. The low relief of Cerdanya and Capcir corresponds in part to Neogene and Quaternary depositional flat surfaces of extensional basins lying at 1000 m asl. (b) Rough contours of high-elevation, low-relief erosional surface remnants, such as described in the literature, superimposed on the local relief. Dissection of the initial erosional surface by the recent drainage system has resulted in small high-elevation, low-relief surface remnants of hundreds of square meters to several square kilometers which cannot be represented on the map, explaining the misfit between the contour lines and the local relief data. (c) The local slope map shows that high-elevation, low-relief surface remnants appear as small areas with a local slope less than 11°.



A
Aquitaine basin
N
Drainage Divide
600
1000
1400
1800
2000
1800
1400
1000
600
Local relief
2000
1500
1000
750
500
0 m
Ebro basin
100 Km
B
1
2
3
4
5
6
Aquitaine basin
N
Aston
Capcir basin
Local relief
2000
1500
1000
750
500
0 m
Encantats
Andorra
Cerdanya basin
Ebro basin
100 Km
C
Aquitaine basin
N
Local slope
1 45°
0.8 39°
0.6 30°
0.4 22°
0.2 11°
0 0°
Ebro basin
100 Km

Figure 4

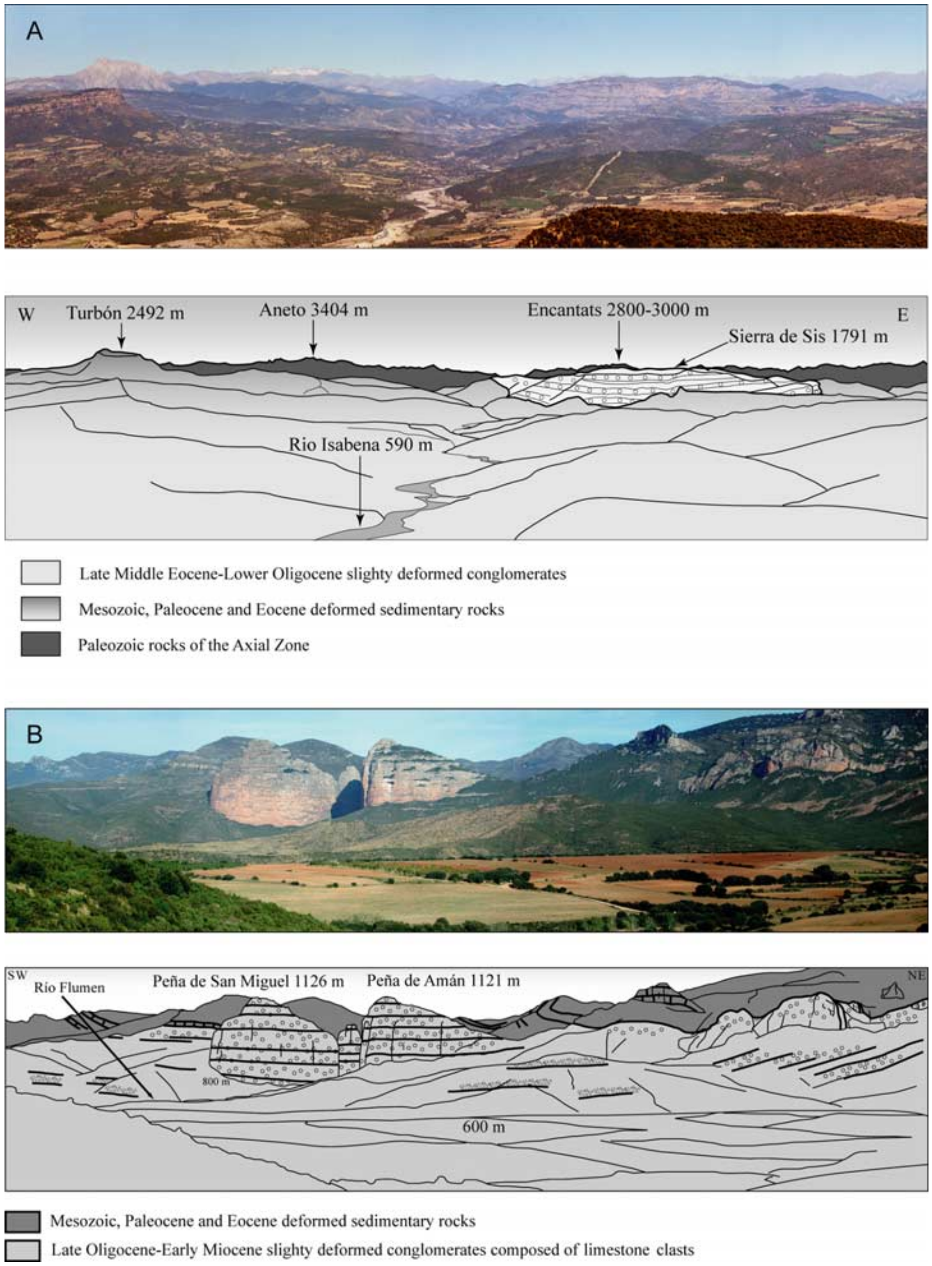


Figure 10. (a) Panorama looking to the north of the south Pyrenees showing N-S directed late Eocene-Oligocene paleovalley (Sierra de Sis). The late Eocene-Oligocene paleovalley is filled with alluvial conglomerates reaching nearly 1800 m asl. The Sierra de Sis conglomerate form a linear body extending up to 20 km long and 5 km wide. The picture is taken from a promontory made of the same undeformed conglomerates. Before dissection, the valley of the Rio Isabena was most probably looking like a bajada overlapping the southern margin of the Axial Zone up to 2000 m, or even higher, in the background and sloping down to 1000 m or more in the foreground. At the foot of the Sierra de Sis, the Rio Isabena reaches an elevation of 750 m implying about 1000 m of dissection. (b) View looking to the northwest of the early Miocene conglomerates of the Salto de Roldán (northern margin of the Ebro basin, north of Huesca). The conglomerates, which correspond to proximal fan delta and mass flow deposits, uncomformably overlie deformed Mesozoic, Paleocene and Eocene sedimentary rocks. They form spectacular high cliffs towering above the Ebro basin depression whose elevation ranges from around 300 – 500 m. The elevation of the conglomerates reaches 1120 m. (c) Eocene paleorelief buried by Oligocene conglomerates (Olvena, northeast of Barbastro). Oligocene conglomerates fill in a structural paleorelief that formed during folding of late Cretaceous limestones. Growth strata at the base show that folding was partly synsedimentary.

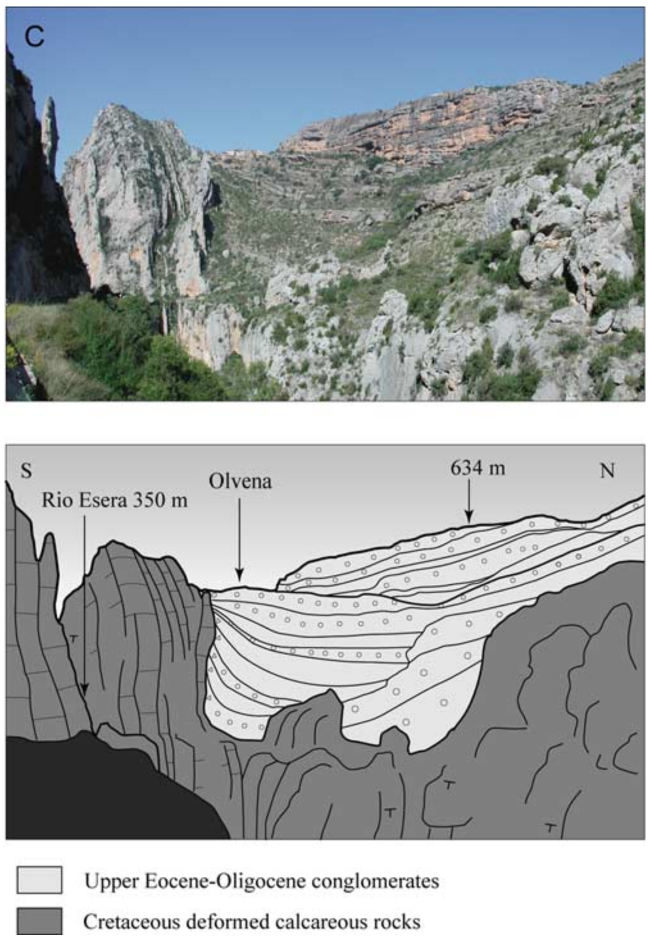


Figure 10. (continued)