Trabajos de Geología, Universidad de Oviedo, 29 : 94-100 (2009)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics
ORSGET

Tectonics from topography: two examples from the Pyrenees and the High Atlas

J. Babault[1]*, J. Van Den Driessche[2] and A. Teixell[1]

[1]*Department de Geologia, Universitat Autònoma de Barcelona, Bellaterra, Spain.*

[2]*Géosciences Rennes, Université de Rennes 1, UMR CNRS 6118, Rennes, France.*

**e-mail: julien.babault@uab.es*

Abstract: The Pyrenees are characterised by remnants of a smooth topography dissected by deep valleys of ~1000 m in the Axial Zone. Babault *et al.* (2005) argue that the piedmont sedimentation in Oligo-Miocene times allowed the inhibition of the erosion at high elevation and the development of a smooth and highly elevated topography before the late Miocene, i.e. after the end of the main stage of shortening. We suggest that the model of inhibition of erosion in altitude must also be taken in consideration in order to explain the whole elevation of low-relief surface remnants in other orogens such as the Moroccan Atlas.

Keywords: uplift, erosion, sedimentation, Pyrenees, Atlas.

In orogens, remnants low-relief erosional surfaces at high elevation put question on their origin. Do they form near to sea-level, and if so what mechanism can explain their later upheaval and dissection by the fluvial network? Or do they develop at an already high elevation in which case what processes are responsible for their subsequent dissection? First we summarize the arguments concerning the Pyrenees published by Babault *et al*. (2005, 2007) deduced by the study of the dynamics of erosion of an uplifting topography bounded by a piedmont, which show that low-relief, erosional surfaces can develop at high elevation. Then we discuss the significance of high-elevation, low-relief erosional surface remnants in the High Atlas Mountains of Morocco. This smooth topography is bounded to the south of the deformed belt, in the Ouarzazate basin, by remnants of a piedmont, the top of which reaches almost 2000 m. These evidences suggest that piedmont sedimentation may have induced an inhibition of the erosion at high elevation in the High Atlas in the same way as it did in the Pyrenees.

High elevation of low-relief surfaces in the Pyrenees: does it equate to post-orogenic surface uplift?

Geological, geophysical and geomorphological characteristics of the Pyrenees: a summary

A striking feature of the Pyrenees morphology is the presence of highly elevated, low relief, erosional surfaces above 2000 m in the Axial Zone of the Pyrenees (Figs. 1 and 2) which have been extensively described since the beginning of the last century by numerous geomorphologists and geologists (e.g. Birot, 1937). Late Miocene continental deposits overlying these surfaces in the Central Pyrenees (Ortuño *et al*., 2008) and in the Eastern Pyrenees (Roca, 1996), provide an upper age limit.

Following previous works, de Sitter (1952) wrote that "admirably preserved post-tectonic erosional leveling surfaces witness to the original low altitude of the folded chain and to later elevation". Thus, in de Sitter's (1952) view, the present-day morphology (and

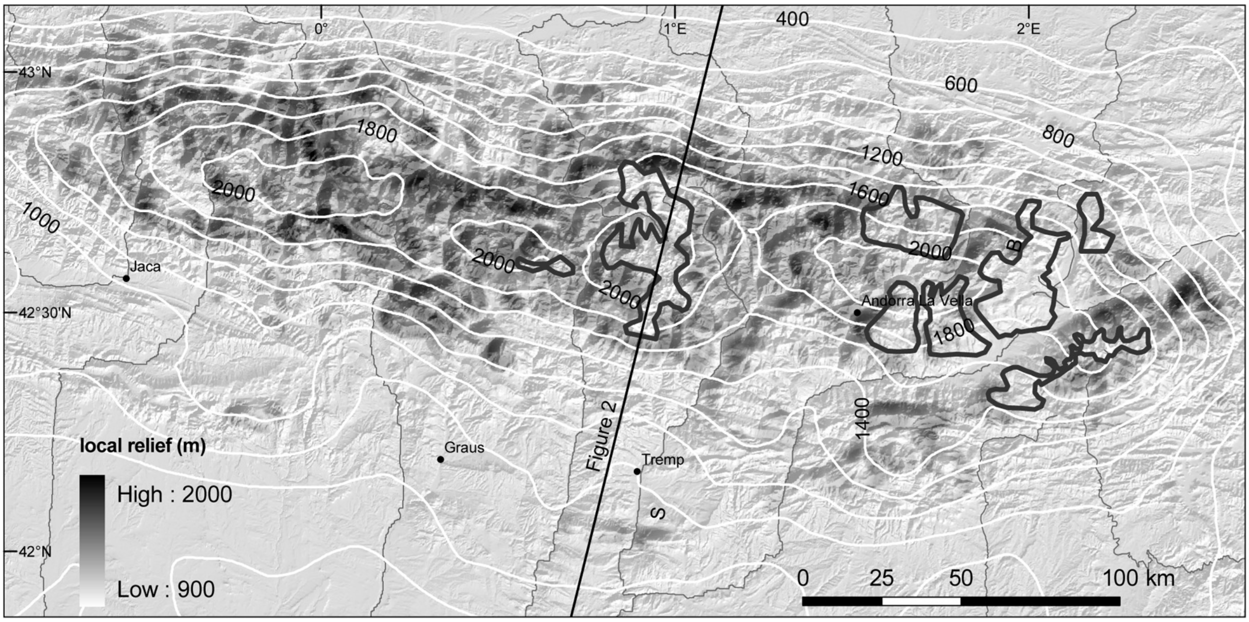

Figure 1. Map of the local relief in the Pyrenees. The local relief is computed for each pixel, which corresponds to the centre of a 5 km window, by the difference between the maximum and the minimum elevations within such a window. The elevation data used are the SRTM90 (2004, 3 Arc Second scene, Version 2, Shuttle Radar Topography Mission NASA-NGA). The best preserved remnants of the high-elevation, low-relief erosional surfaces of the Central and Eastern Pyrenees are countoured (dark gray lines). The white countour lines show the mean elevation at 30 km scale (computed over a 30 km moving window). They lie above 2000 m and are characterized by a local relief of less than 700 m.

mean elevation) of the Pyrenees is unrelated to the Palaeogene Alpine tectonics that led to crustal thickening in the orogen. To explain the Pyrenean high-elevation, low-relief surfaces, he invoked a Pliocene surface uplift 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 ca. 10 km of crustal thickening necessary to induce the 2000 m of Pliocene surface uplift invoked by de Sitter (1952) and other more recent works (see references in Babault *et al.*, 2005).

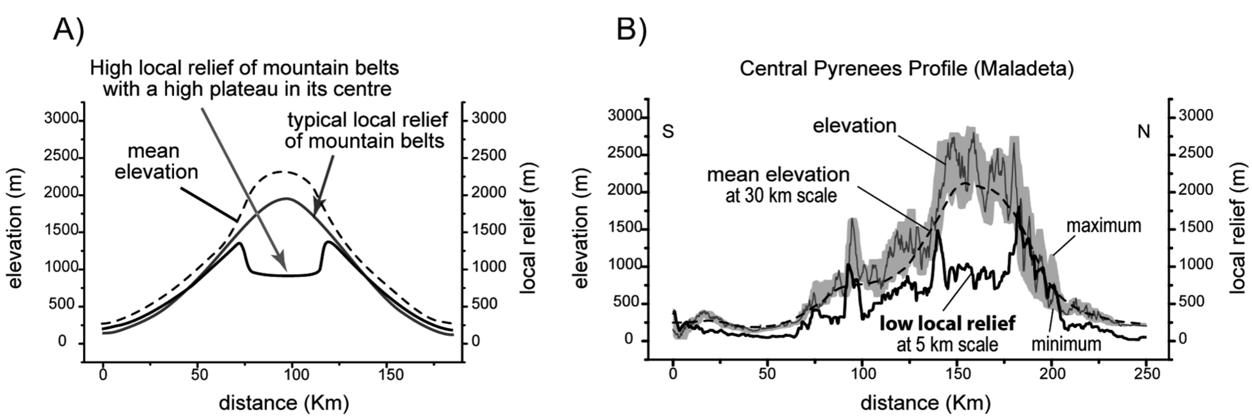

Figure 2. A) Relationship between mean elevation and local relief. Idealized sketch showing the relationship between mean elevation and local relief in mountain ranges including (or not including) a high plateau, B) south to north (transverse) topographic profile across the Central Pyrenees located in figure 1. The elevation, the maximum elevation, the minimum elevation, the mean elevation and the local relief are plotted on the profile. 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, indicating that the high-elevation, low-relief surfaces represents the remnants of an extensive smooth topography. The profile also shows maximum and minimum elevations (shading).

Moreover, Pliocene normal faulting in the eastern Axial Zone of the Pyrenees implies local horizontal extension. Indeed, extension results essentially in surface collapse, except at rift margins or when it involves a strong thermal anomaly. The main extensional event in the Eastern Pyrenees developed during the Oligocene-Miocene. There is no evidence that a major thermal anomaly developed afterwards below the Pyrenees. The current surface heat flow below the northern and southern Pyrenees is not anomalous and it is 69±10 mW m^{-2} and 50 to 70 mW m^{-2} respectively.

An alternative explanation that has been proposed is that the Palaeogene lithospheric root of the Pyrenees was removed during the Neogene, inducing a Pliocene surface uplift (Brunet, 1986). The Pyrenean mountain chain is presently overcompensated at crustal level (Vacher and Souriau, 2001), leaving little space for mantle-related uplift.

Inhibition of erosion at elevation induced by piedmont sedimentation

Based on fieldwork carried out in the Pyrenees and topography analysis, Babault *et al.* (2005) demonstrate that the aggradation of the eroded products in the margins of the Pyrenean Axial Zone reached an elevation of up to 2000 m and that the extension of the piedmont remnants merge with the erosional surfaces above 2000 m in the Axial Zone. The authors interpret it, first, as the rise of the efficient base level of the chain, and second, as the decrease of the potential energy for erosion, allowing high-elevation and low-relief erosional surfaces to develop. This model has been successfully tested experimentally (Babault *et al.*, 2007) (Fig. 3). Such a process gives an explanation for the development of a high-elevation, low-relief erosional surface in the Pyrenees and, as a consequence, the post-tectonic preservation of its crustal root instead of its erosionally driven isostatic rebound (Fig. 4).

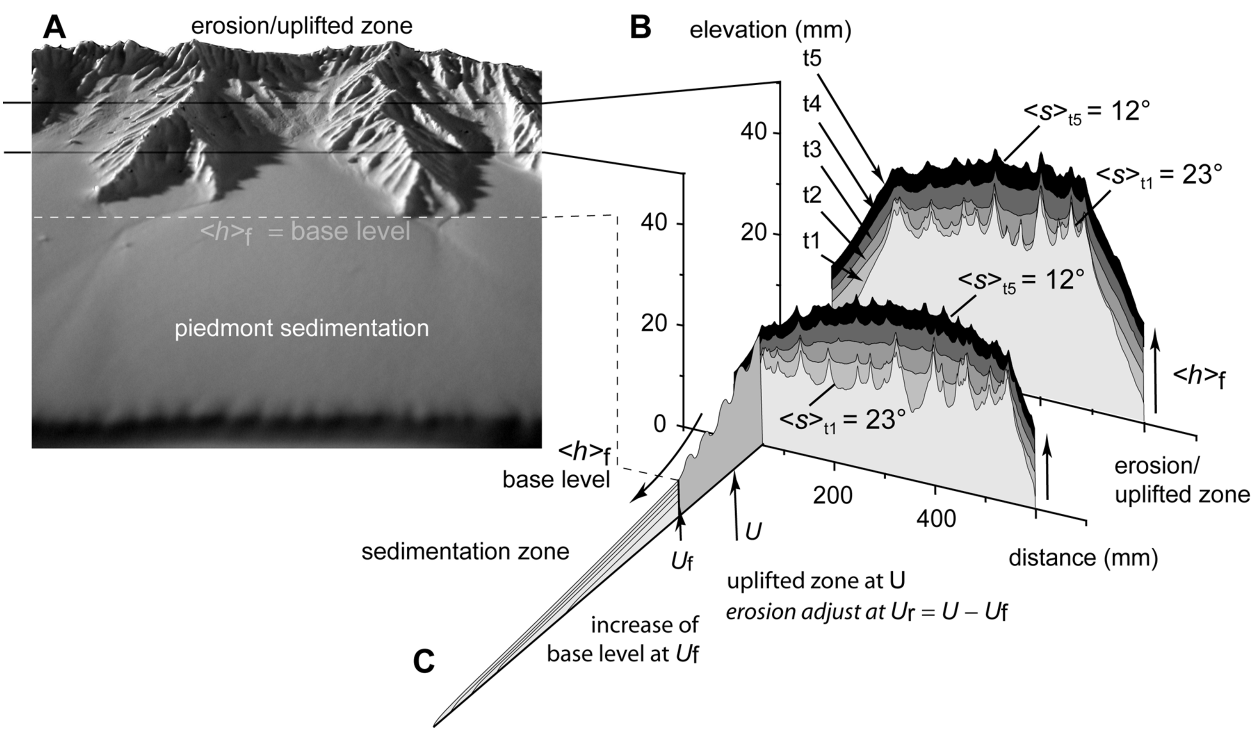

Figure 3. A) Photograph of a model experiment (valley size is about 50 mm), made of silica paste (description in Babault *et al.*, 2007), B) topographic profiles transverse to the water flow direction for 5 stages of relief evolution within the uplifted zone that experience runoff erosion, C) profile of the flanking sedimentation zone. The experiments show that relief subduing, which corresponds to local slope decrease ($\langle s \rangle_{t1}$ to $\langle s \rangle_{t5}$), may develop during the new growth stage of an uplifting (at a rate of U) topography initially at steady state in response to the development of an aggrading piedmont (at a rate of U_f, t1 to t5, Babault *et al.*, 2007). In experiments, relief subduing results from the rise of the efficient base level of the uplifting topography that corresponds to the fan apex ($\langle h \rangle_f$). The development of a piedmont during relief decay induces relief subduing at high elevation, the value of which is a function of the final elevation reached by the piedmont apex (i.e. final $\langle h \rangle_f$).

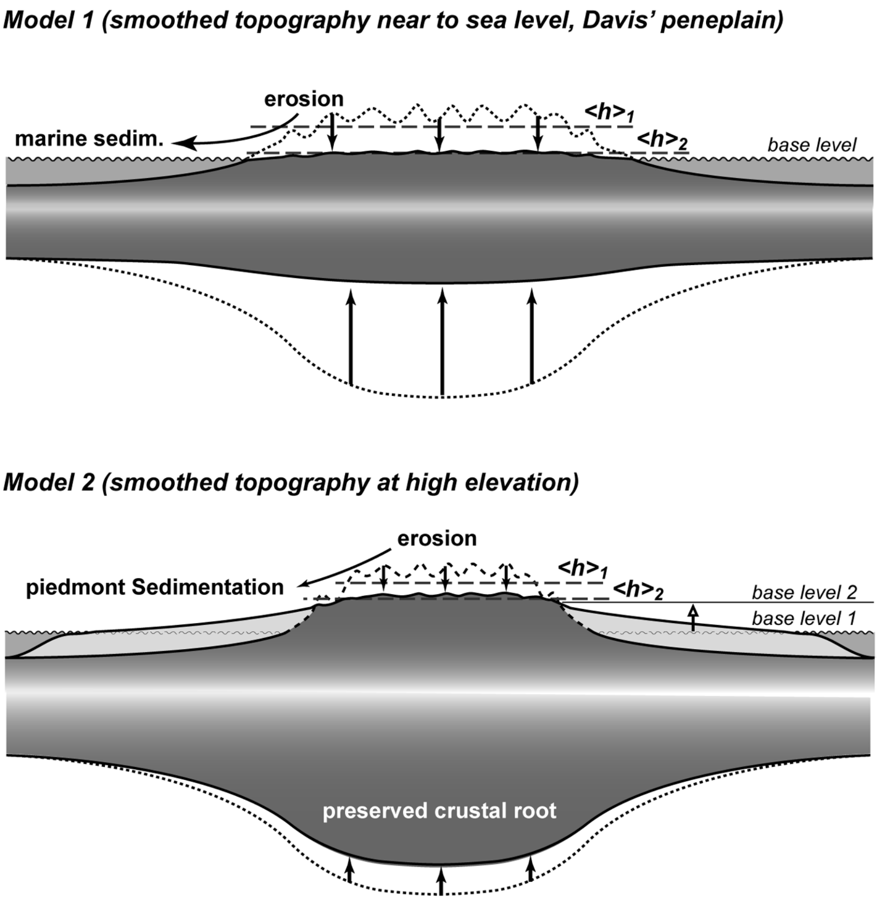

Figure 4. Models of peneplain development in mountain ranges. In model 1, the peneplanation results from erosion that induces the progressive exhumation and the forward removing of the crustal root by isostatic compensation. In model 2 (applanation at high elevation), the change from marine to continental sedimentation in foreland basins induces the rise of the base level of mountain belts. Eventually piedmont sedimentation causes a peneplain to develop at high elevation and a crustal root to be preserved. $\langle h\rangle_1$: initial mean elevation of the chain; $\langle h\rangle_2$: final mean elevation.

The other corollary is that Plio-Quaternary global climate change must be the cause for the deep incision of the rivers in the Miocene smooth topography. The three times increase of sedimentation rates in the Ebro delta since the end of the Pliocene (Nelson, 1990) correlates with the onset of the Late Cenozoic global climate change. The climate shift from the Pliocene should have enhanced the transport capacity of rivers and/or the size reduction of eroded particles, hence favouring their discharge down to the sea. Consequently, the efficient base level of the Pyrenees lowered, thus giving the Pyrenees a jagged Alpine morphology of a young orogen in spite of the fact that shortening ended 20 Ma ago. This result contrasts with the previously accepted idea of a rejuvenation of the Pyrenean landscape in response to enigmatic tectonics and resulting recent upheaval of the Pyrenees.

Significance of high-elevation, low-relief surface remnants in the High Atlas

Geological evidence for a late Cenozoic mantle-related uplift in the High Atlas intracontinental belt of Morocco

The Atlas Mountains have been uplifted by two mechanisms: Cenozoic thickening of the crust and thinning of the mantle lithosphere due to a buoyant thermal anomaly beneath the mountains. The second mechanism has been evidenced recently by the modelling of the lithospheric structure based on potential fields. Where the thinning is maximum, 1000 m of the topography is supported by mantle processes, inferred by indirect criteria to have started some 15 Ma ago (e.g. Teixell *et al.*, 2005).

Because crustal shortening-related surface uplift and mantle-related surface uplift affect the topography at different spatial scales, Babault *et al.* (2008) used scattered direct surface evidence to clarify the paleoelevation dynamics. Uplifted Messinian shallow marine sediments in the southern margin of the Saïss basin, tilted Pliocene lacustrine deposits in the Saïss basin and in the piedmont of the southern High Atlas (Hamadas), and drainage-network reorganization in the Saïss basin underscore the long-wavelength rock uplift of the Atlas domain of mantle origin (Fig. 5). The low erosion of the aforementioned deposits indicates that such uplift is a true surface uplift that occurred in post-Miocene times at a minimum rate ranging from 0.17 to 0.22 mm a^{-1}.

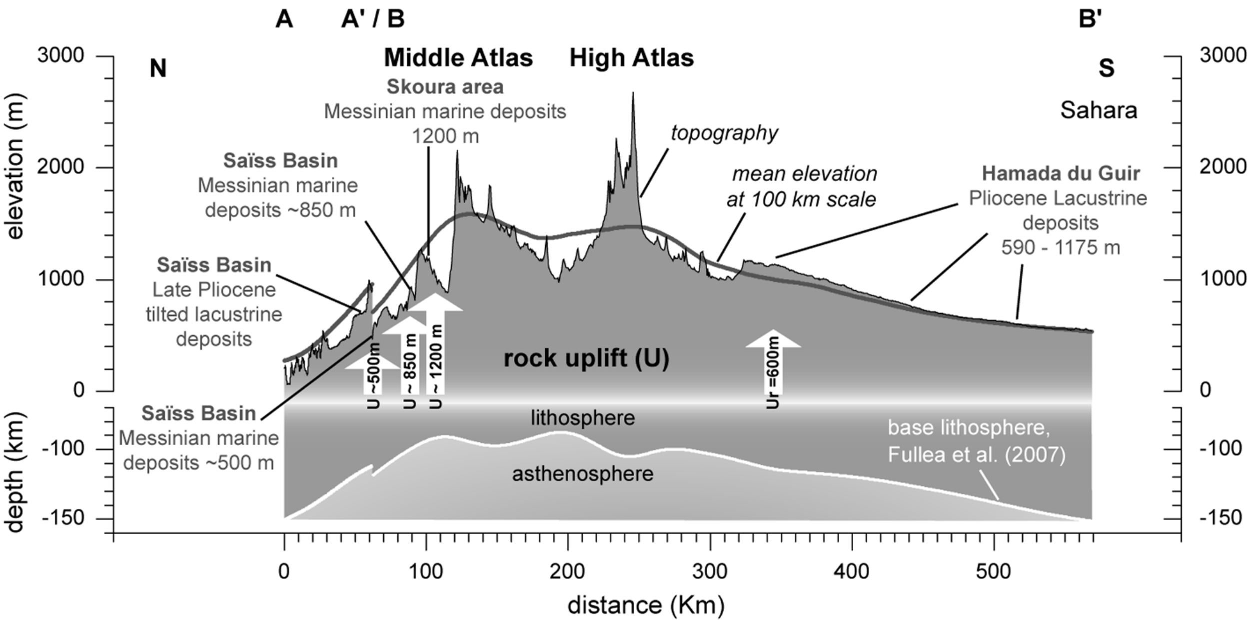

Figure 5. Topographic transect illustrating the post-Miocene doming of the Atlas Mountains and plateaux of Morocco (location in figure 6). Rock uplift criteria used in Babault *et al.* (2008) work is indicated. Mean elevation is calculated by a moving window of 100 km diameter. The position of the lithosphere/astenosphere boundary modelled by Fullea *et al.* (2007) shows a good correlation with the long-wavelength doming.

Piedmont sedimentation and relict landscape at high elevation in the High Atlas of Morocco: a causal link?

On the southern flank of the High Atlas, piedmont sedimentation reaches ~2000 m along the northern margin of the Ouarzazate basin and interestingly, small conglomerate and lacustrine limestone inliers attributed to the Neogene are preserved in the interior of the High Atlas, occasionally tens of km away from the borders and at almost 2000 m asl (e.g. Rocher La Cathédrale). These may reach thicknesses of over 500 m, and suggest that part of the High Atlas may once have been buried by synorogenic sediments but was later reexhumed (Teixell *et al.*, 2003). Recent dating by magnetostratigraphy of the Neogene succession within the Ouarzazate basin indicates that piedmont accumulation finished before the end of the Miocene (Tesón *et al.*, *submitted*).

Mean elevation (at 30 km scale), in the Central High Atlas ranges between 2000 and 2600 m (Fig. 6). Therefore, the Miocene piedmont sedimentation that took place before the 1000 m of Plio-Quaternary mantle related surface uplift of the Atlas system (which affected both the deformed belt and the adjacent basins), probably allowed the inhibition of erosion in altitude and the development of a highly-elevated, low-relief topography. Such process has to be taken in consideration in order to explain the high elevation of low-relief surface remnants in the High Atlas.

The Moroccan relict topography is dissected by the current drainage network in the same way as the high-elevation, low-relief surfaces are incised in the Pyrenees. In the High Atlas, the mantle-related surface uplift gives an explanation to the enigmatic late Cenozoic uplift inferred by de Sitter (1952) to account for renewed erosion and incision of river canyons in the Ziz valley. However, it remains to be ascertained what the influence of the Late Cenozoic climatic change was, and to what extent this amplified the erosional response (e.g. Molnar and England, 1990; Babault *et al.*, 2005) to the new boundary conditions.

As documented by the cases of the Pyrenees and the High Atlas, mountain belt building is generally accompanied by piedmont aggradation, which suggests that relief subduing at high elevation is most likely an intrinsic erosional process to post-orogenic decay of mountain belts.

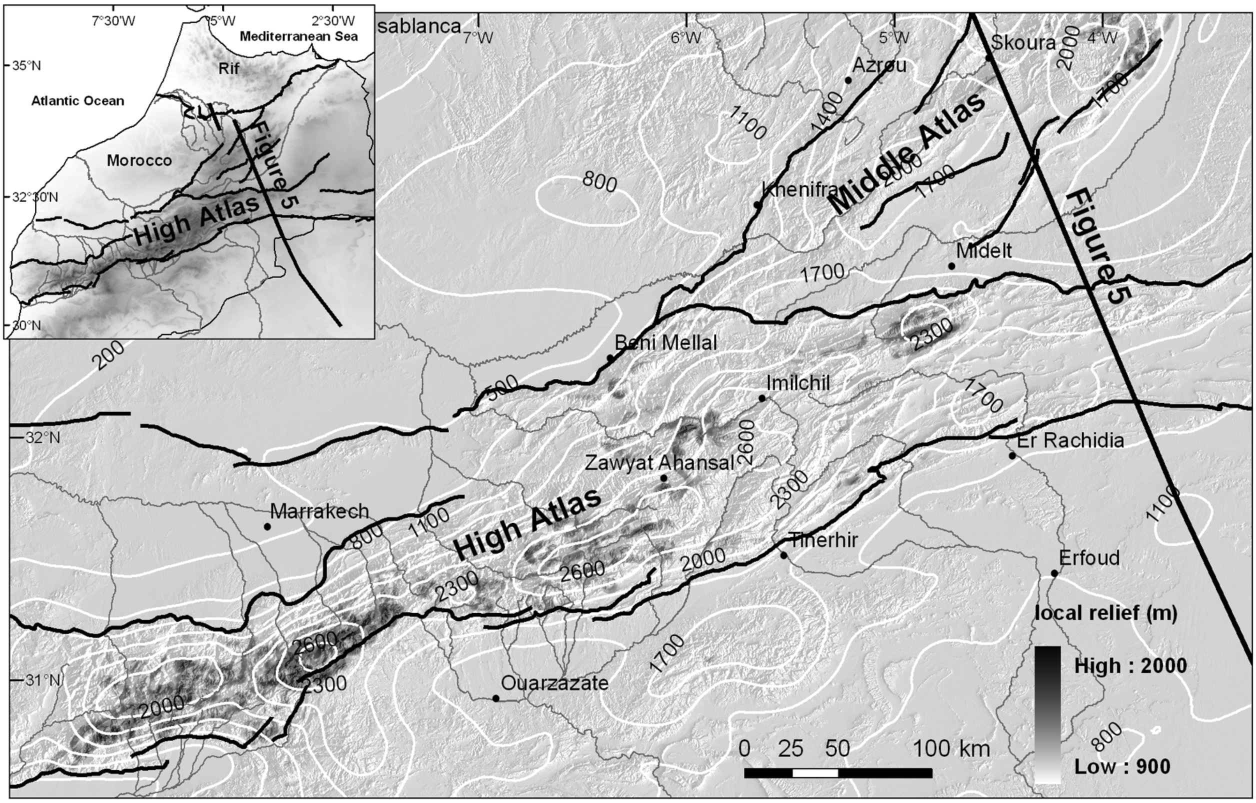

Figure 6. Map of the local relief in the High Atlas. East of longitude 6° W, a smooth topography is present at high elevation, ranging from 1500 m to more than 2700 m, from 4° W to 6° W. West of 6° W, the remnants of this smooth topography are deeply dissected by up to 700 m of fluvial incision. Note that west of 6° W the local relief is higher than east of 6° W. Also plotted is the location of the profile of figure 5.

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