



## Postorogenic planar paleosurfaces of the central Pyrenees: weathering and neotectonic records

Bernard Monod, Vincent Regard, Julie Carcone, Robert Wyns, Frédéric Christophoul

### ► To cite this version:

Bernard Monod, Vincent Regard, Julie Carcone, Robert Wyns, Frédéric Christophoul. Postorogenic planar paleosurfaces of the central Pyrenees: weathering and neotectonic records. *Comptes Rendus Géoscience*, 2016, 348 (3-4), pp.184-193. 10.1016/j.crte.2015.09.005 . hal-01212752

**HAL Id: hal-01212752**

**<https://hal.science/hal-01212752>**

Submitted on 7 Oct 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Postorogenic planar paleosurfaces of the central Pyrenees: weathering and neotectonic records.

**Bernard Monod<sup>1</sup>, Vincent Regard<sup>2,3,4</sup>, Julie Carcone<sup>2,3,4</sup>, Robert Wyns<sup>5</sup>, Frédéric Christophoul<sup>2,3,4</sup>**

1. BRGM Midi-Pyrénées, 3 rue Marie Curie, 31527 Ramonville-Saint-Agne, France

2. Université de Toulouse ; UPS GET, 14 avenue E. Belin, F-31400 Toulouse, France

3. CNRS ; GET ; 14 avenue E. Belin, F-31400, Toulouse, France

4. IRD ; UR 234, GET ; 14 avenue E. Belin, F-31400, Toulouse, France

5. BRGM DGR/GAT, 3 av. Claude Guillemin, 45060 Orléans, France

## Abstract

Flat high-elevation surfaces in the Pyrenees are defined by thick weathered horizons that were developed from granitic lithology. We analysed such horizons in detail within two areas: the Bordères-Louron granite and the Aston massif. They are characterized by a lower fissured zone overlain by unconsolidated saprolite. Mapping these horizons allows a 3D reconstruction of the ancient paleosurface with an elevation uncertainty of 50 m. We discuss the age of weathering by means of stratigraphy and low-temperature thermochronology. The surfaces are clearly postorogenic, postdating Eocene-Oligocene denudation. Their incision and the fact they are stepped suggest (1) an increase of the local relief and (2) recent normal faulting.

Keywords: Paleosurfaces, Weathering, Pyrenees, Postorogenic

## 1. Introduction

Relicts of ancient surfaces have been observed in the Pyrenees (Figure 1), mostly in their eastern part (Goron, 1937; Calvet, 1996; Babault et al., 2005; Calvet and Gunnell, 2008; Ortuño et al., 2013). Similar surfaces have been observed in other mountain ranges like the Rocky Mountains, the Atlas, the Betic Cordillera, or the Altay and Gobi-Altay mountains (e.g., De Sitter, 1952; Scott, 1975; Jolivet et al., 2007b; Farines et al., 2015). They are considered key features for investigating the recent history of such mountain ranges, with special attention to their relief and elevation history (Calvet et al., 2015). Here, we evidence that some of these surfaces are associated with strong weathering profiles, before reconstructing their shape and determining whether they record deformations related to recent tectonic activity.

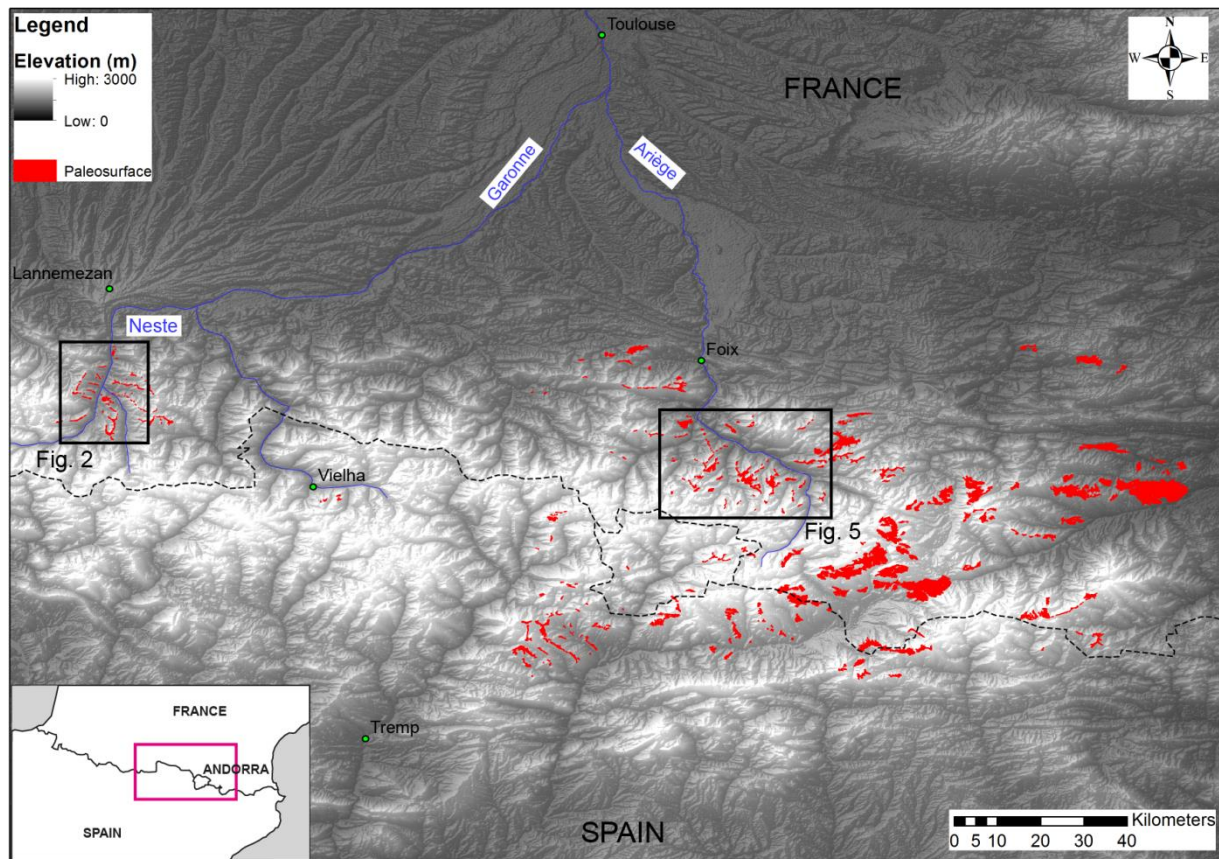


Figure 1 : The relief of the Pyrenees and paleosurfaces mapped within the mountain belt. The compilation of paleosurfaces is derived from the computation of slopes lower than 10°, and from Calvet (1996) and Delmas (2009). Fig. 2: Bordères-Louron area; Fig. 5: Aston area. Dashed line is the border between France and Spain, with Andorra in the middle.

The nearby Massif Central is known to have undergone strong weathering phases whose ages are: (i) pre Late Carboniferous; (ii) pre Permian; (iii) pre Triassic; (iv) pre Liassic; (v) pre Late Cretaceous; and (vi) Eocene (e.g. Pierre, 1989; Migoñ and Lidmar-Bergström, 2001a; Wyns et al., 2003; Gandolfi et al., 2010). During these weathering phases, a weathering profile developed that, from bottom to top, encompasses bedrock, fissured zone, and alterites (or saprolite), subdivided into a laminated zone and loose saprolite. In plutonic rocks, the fissured zone is characterized by horizontal jointing due to the swelling of some minerals when hydrating, the most efficient one being biotite whose volume increases by 40% when it is transformed into chlorite or vermiculite (Wyns et al., 2004). The fissure density increases upwards, up to 1 fissure per 10 cm. The alterites consists of highly weathered minerals. In the bottom part (the laminated zone) it is laminated and the original rock structure is still observed, whereas in the upper part the rock is transformed into loose material. The very top of the profile is a planar surface that formed before further weathering, ensuring the necessary low-draining conditions that allow chemical weathering rather than physical erosion. The formation of a weathering profile implies a long duration, 5-10 Ma at least under such low-draining conditions (Wyns, 2002; Wyns et al., 2003). In Europe, excluding subsidence areas, saprolite thickness can reach several tens of metres, but usually less than 50 m thick (Migoñ and Lidmar-Bergström, 2001b; Wyns et al., 2003).

In the Pyrenees, the link between ancient weathering periods and planar surface development has never been investigated. Because plutons and gneisses are good protoliths for the development of weathering profiles, we focused our work on two of such well-developed planar surfaces at Bordères-

Louron in the Neste Valley and at Aston in the Ariège Valley, within the central and eastern Pyrenees, respectively (Figure 1).

## 2. Planar surfaces of the central and eastern Pyrenees

In the Nestes Valley, the 310-Ma-old Bordères-Louron pluton is exposed southeast of Arreau, the main village (Gleizes et al., 2006). It is centred on Bordères-Louron (0.38°E; 42.88°N), a village lying within the Louron Valley at 850 m asl. The granite intruded Early Carboniferous shale and limestone, and is unconformably overlain by Triassic sandstone and shale (Figure 2). Where preserved, planar surfaces appear mostly on top of the interfluvies, well above the main moraine systems and associated glacial deposits. Many villages are settled on the most prominent surface, as Lançon for at ~1100 m asl (Figure 2 and Figure 3). To the east and southeast, this main surface can be connected to smaller remnants, mostly located along the Louron Valley, for example around Ilhan and Ris villages, at similar elevations of 1100 and 1120 m asl, respectively (Figure 4). In addition to these sub-horizontal surfaces, the landscape exhibits a low-relief morphology up to 1360 m above Lançon village. Weathered rocks outcrop below every surfaces of the area.

The Aston area lies mostly south of the N120E-trending Ariège Valley for ~20 km between Tarascon and Ax-les-Thermes (1.7°E; 42.7°N), with a valley floor at ~500 m asl. It is characterized by 5-10 km wide planar surfaces, as already indicated by local names such as “plateau” or “pla”, the best known being the *Plateau de Beille* on which is built a Nordic skiing station (~1800 m asl). The main surface, which we called Aston surface, is developed at elevations between 1300 and 2100 m and gently dips north with an average slope of 3 to 5 degrees. The Aston planar surface developed over various lithologies, the most common being the Riète Gneiss formation (Figure 5A). A section parallel to the Ariège Valley, five kilometres to the south (Figure 5B), shows the different plateaus, separated by three valleys, defining a dissected low-relief surface. To the north of the Aston massif, near the Ariège Valley, the surface is associated to stepped surfaces at lower elevations: two levels are observed at 1700-1800 m and at 1300-1500 m. These surfaces are of similar origin as weathered rocks equally mantle them. The main step and some smaller offsets of these surfaces trend N110°, quite parallel to the North-Pyrenean Fault (Figure 5).

The Aston area is thus characterized by a ~10 x 20 sq. km set of related surfaces, whose morphology is a NW-trending low-relief glaciais that has been dissected since the development of these surfaces.



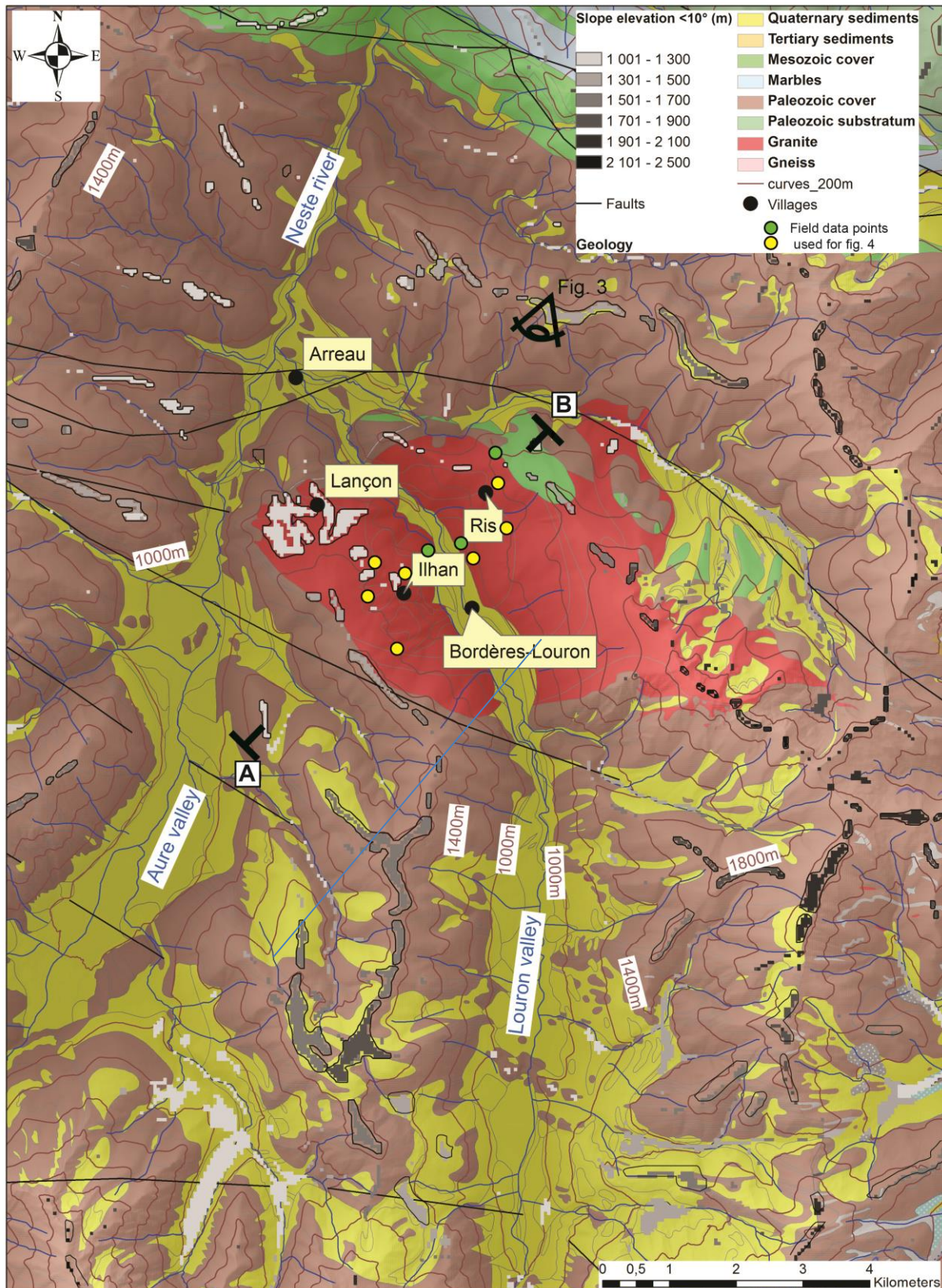


Figure 2: Simplified geological map of the Bordères-Louron area, derived from the 1/50 000 geological map (Barrère et al., 1984), showing the location and elevation of the computed surfaces (the DEM was created by IGN and has a resolution of 50 m). The colour gradient shows surfaces from light gray for low elevations to black for the high ones. A-B: location of the cross-section of Figure 4. View point symbol for Figure 3.



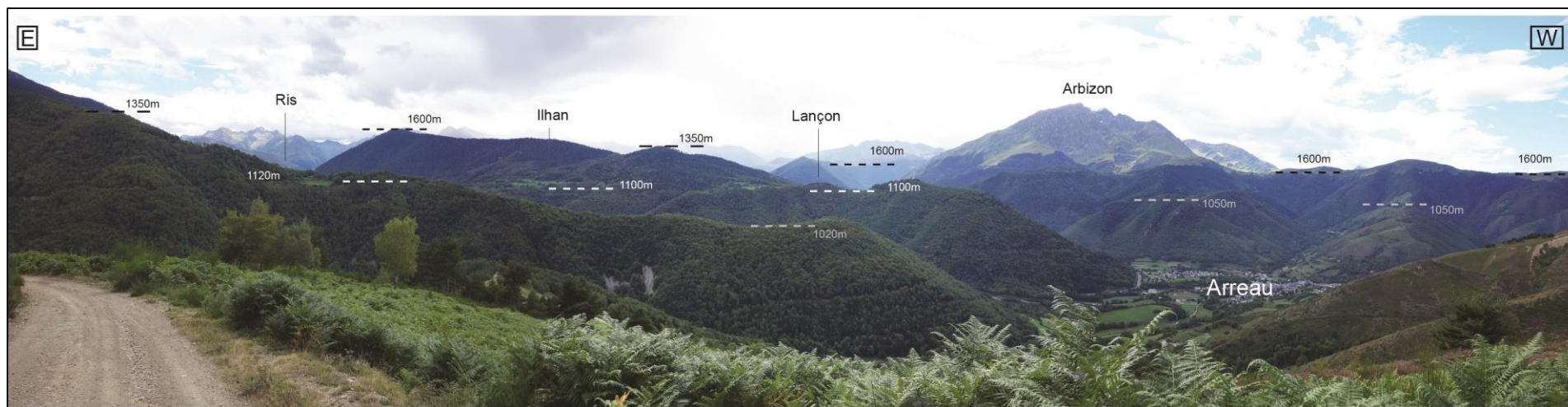


Figure 3: The Nestes Valley (including Aure and Luron rivers) observed from the NNE (View point shown on Figure 2).

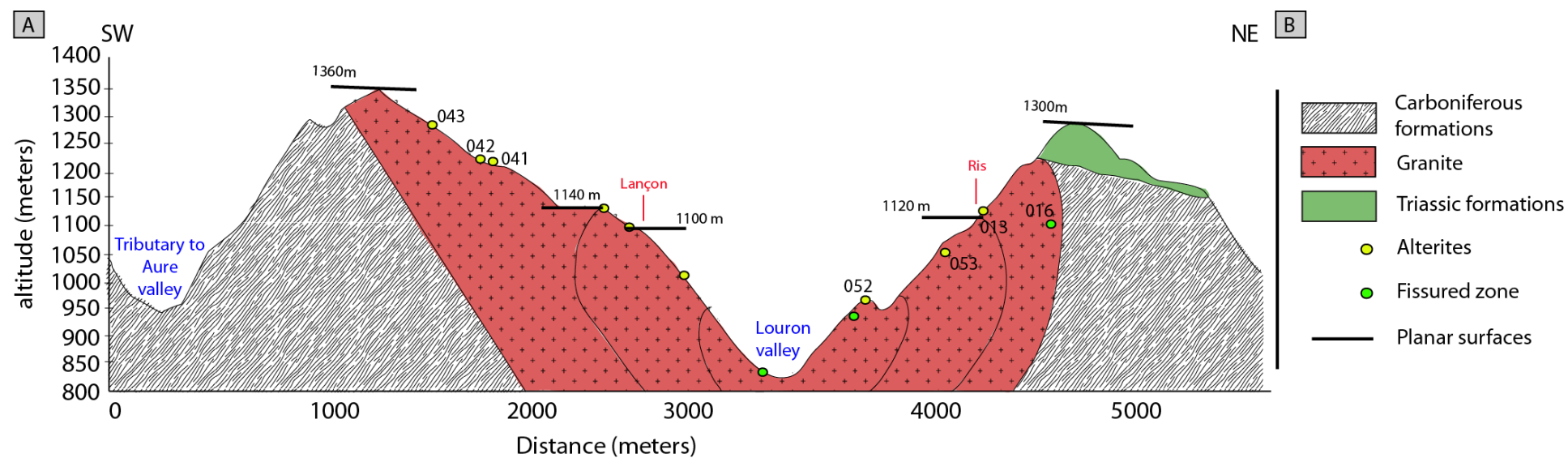


Figure 4: NE-SW geological cross-section across the Bordères-Louron granite, showing the elevations of the different surface levels, such as the main one at 1100 m asl. See location on Figure 2.



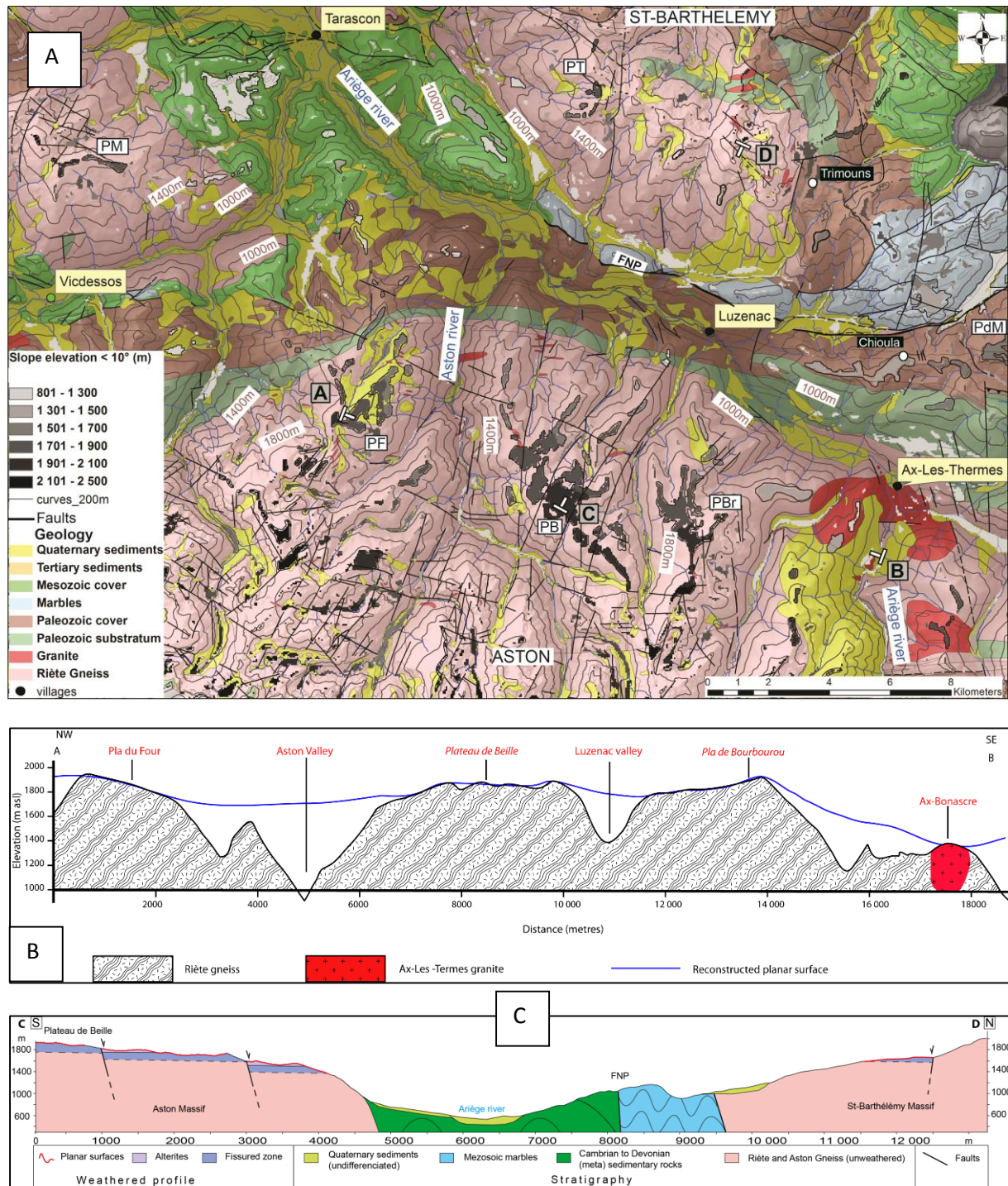


Figure 5: A): Simplified geological map of the Aston area, derived from the 1/50 000 geological map (Destombes et al., 1969), and location of the surfaces (colour gradient from light gray for low elevations to black for high ones). PB: Plateau de Beille; PF: Pla du Four; PBr: Pla de Bourbourou; PdM: Pla du Mont; PT: Pla de Tabé; PM: Pla de Madame. A-B: location of the cross-section. B) NW-SE cross section from Pla du Four to Ax-Bonascre. The thalwegs are made by planar surfaces used to define the envelope surface. This surface is interrupted by incised valleys like the Aston one. The surface deflection between Pla de Bourbourou and Ax-Bonascre is concomitant with a step. C) N-S cross-section from the Plateau de Beille to the St-Barthélémy summit, showing the stepped surfaces and preserved alterites controlled by normal faults (not mapped on figure 5A) on both sides of the Ariège River (see text for further explanations.).

### 3. Weathering

In both study areas, the planar surfaces are developed over significantly weathered rocks that are directly exposed. On granitic and gneissic rocks, the weathered profiles exhibit a common organization

of the successive weathered horizons (Figure 6). In addition to macroscopic study of the weathered profiles, X-ray and microscopic observations on samples taken from the fissured zone indicate the presence of supergene minerals like goethite or lepidocrocite on both sites.

In the Bordères-Louron area, the planar surfaces developed on any lithologies and are all associated with unconsolidated alterites (Figure 4). This is consistent with the 1/50 000 geological map (Barrère et al., 1984). Over the Bordères granite, the surfaces developed on top of unconsolidated quartz alterites (Figure 6). Fissured granite is observed at the bottom of Louron Valley, about 300 m below the planar surfaces (Figure 4).

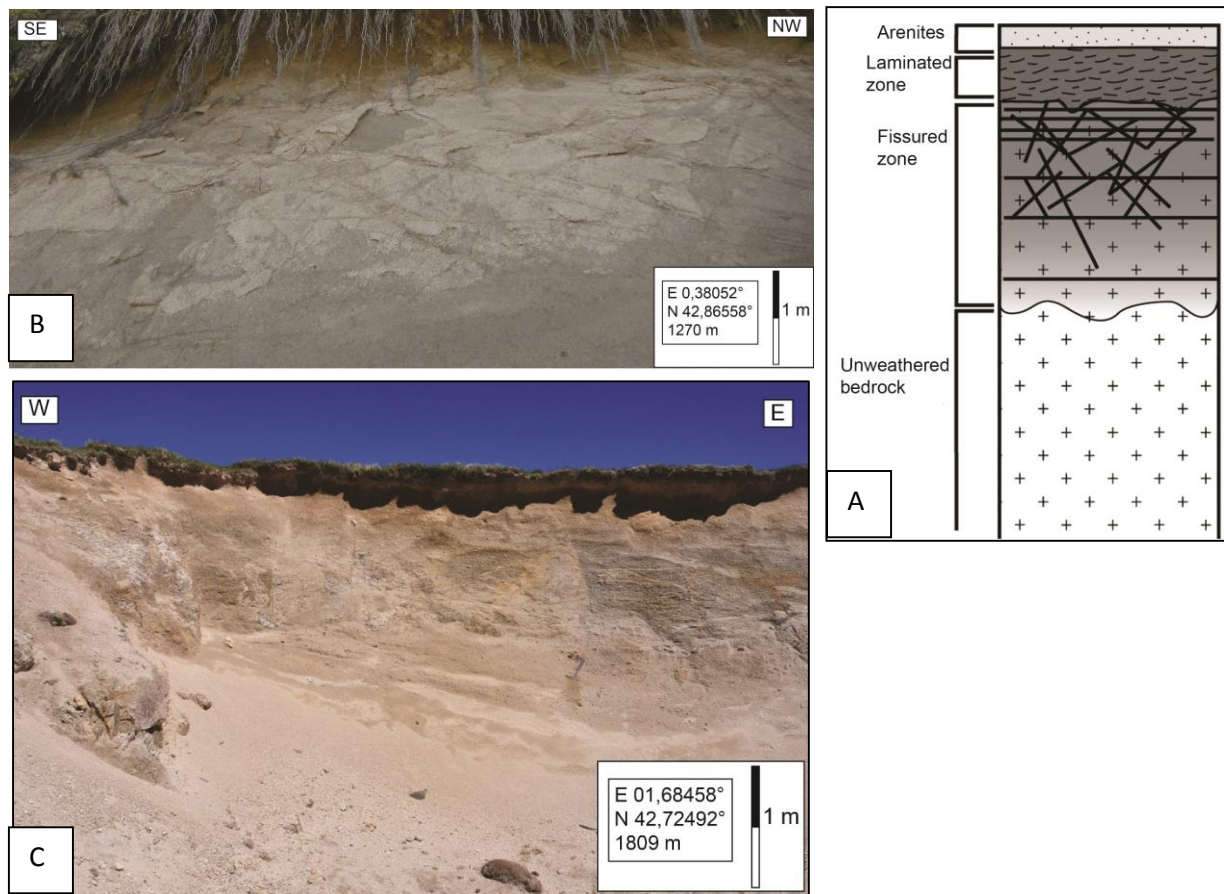


Figure 6: A) Sketch of a granite weathering profile. The arenites and the laminated zone define the unconsolidated alterite unit. The fissured zone is about twice as thick as the unconsolidated alterite. Photographs show unconsolidated alterites of the weathered profile: B) Under the planar surface at Lançon in Bordères-Louron granite; C) Under the Plateau de Beille of the Aston massif in Riète gneiss formation.

Under the Aston surface, we found both the alterites at the ski station (1800 m asl) and a fissured horizon dipping gently to the north at the summit of the surface (~1900 m asl) (Figure 6 and Figure 7). This indicates more pronounced denudation since the weathering period than in the Bordères-Louron area. Part of the denudation occurred during the Quaternary by glacial dynamics until at least 1450 m asl, where glacier presence is proved by glacial deposits overlying the laminated zone of the Riète Gneiss (Delmas, 2009). However, the glacier may have reached an elevation of 1900 m asl (Delmas et al., 2012).



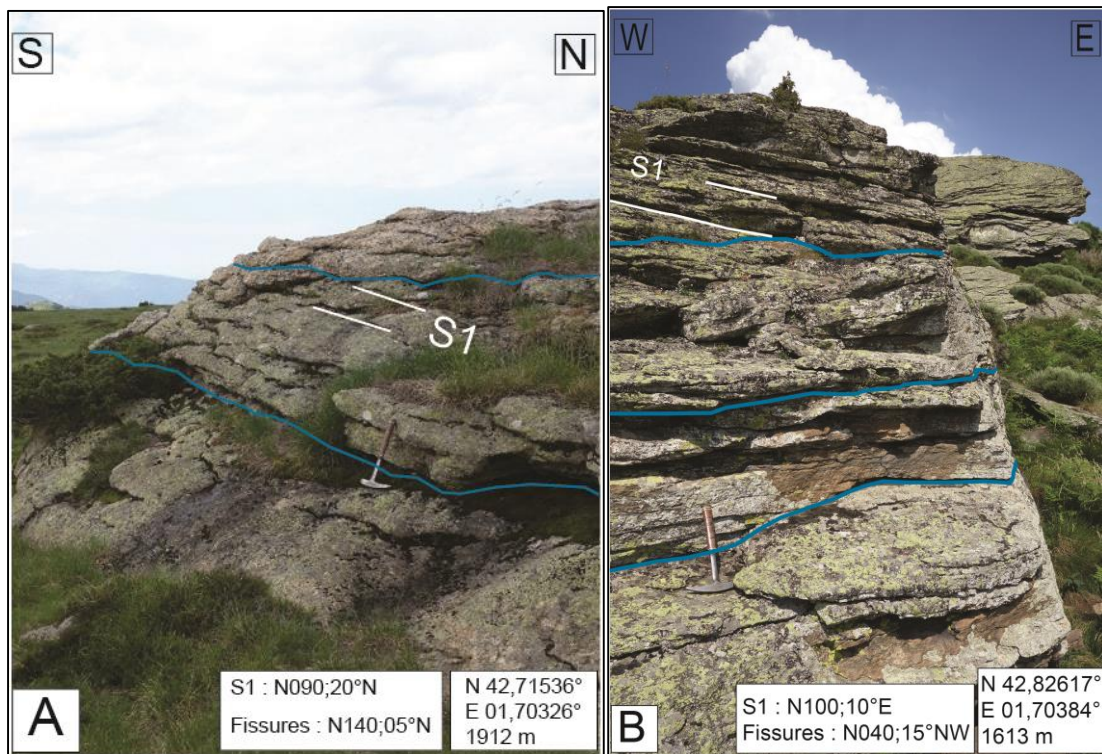


Figure 7: A) Fissured horizon under the Aston surface at Plateau de Beille (1900 m asl). B) Fissured horizon in the gneissic rocks of the south-western flank of St Barthélémy (1600 m asl). Open fissures are underlined by thick lines, foliation (S1) is represented by white lines.

Observation of landscape together with the analysis of the weathering profile indicate that the Aston surface extends to the northern side of the Ariège Valley. We clearly observed surface remnants both in the south-western St Barthelemy massif flank, where a fissured horizon in gneiss gently dips northward (Figure 7), and on its south-eastern flank around Trimouns and Chioula. On the northern flank of the Aston massif, the surface is lowered by N110-trending faults towards the Ariège River (Figure 5C and Figure 8). North of the river, the surface is affected by south-dipping faults but crosses the North-Pyrenean fault without offset. Normal faults cross-cut the weathering profile, preserving alterites on the lowered fault block (Figure 5C).

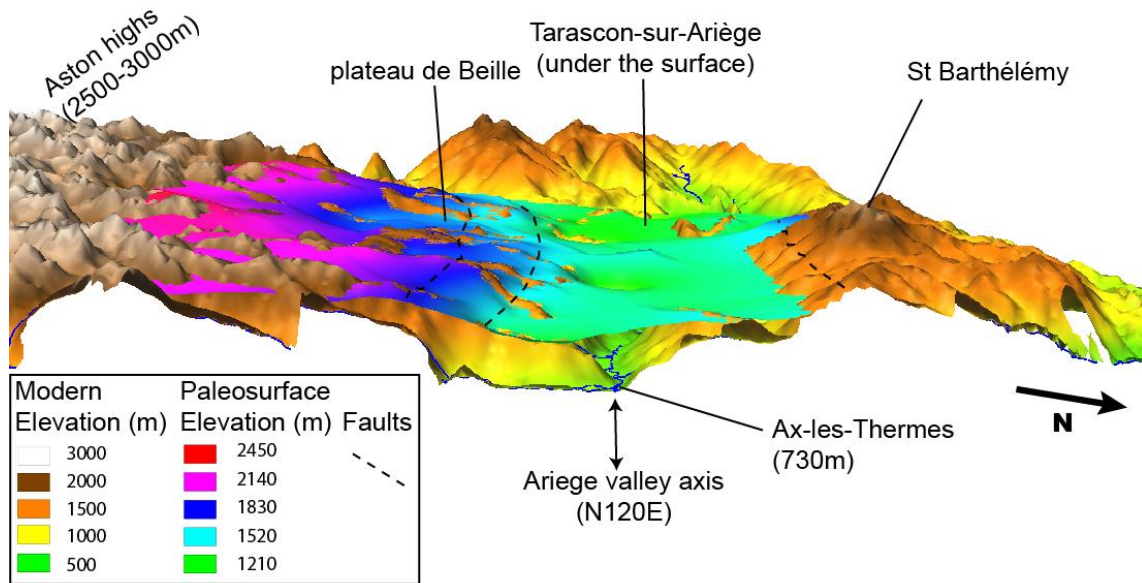


Figure 8: 3D view of the modern Ariège Valley between Ax-les-Thermes and Tarascon, and the reconstructed paleo-weathering surface. At Ax-les-Thermes, the current Ariège river level is 700 m below the reconstructed surface.

## 4. Discussion

### Estimating the age of the surfaces

Theoretically, the best method for dating weathering stages is to date supergene minerals, e.g. cryptomelane (Beauvais et al., 2008) or goethite (Shuster et al., 2005), or paleomagnetic dating (e.g. Ricordel-Prognon et al., 2010). However, up to now none of these methods was successful in our study area, and we have to use published ages obtained from surrounding sites for discussing the formation age of the surfaces.

For many granite plutons in the Pyrenees, fission tracks and (U-Th)/He dating on apatites indicate major cooling between 40 and 30 Ma ago (Fitzgerald et al., 1999; Gunnell et al., 2009; Jolivet et al., 2007a; Morris et al., 1998; Sinclair et al., 2005). These low-temperature thermochronological ages correspond to periods of significant denudation that preceded the weathering. Moreover, micro-mammalian assemblages in superficial rock fissures within the surfaces in the eastern Pyrenees (Madres and Agly massifs), show that little erosion occurred since 26 Ma (Gunnell et al., 2009).

Based on (U-Th)/He dating on zircons and apatites, the Aston massif underwent major denudation at 32-40 Ma (Denèle, 2007). South of the Aston massif, the Hospitalet massif yields younger ages, 28-34 Ma (Denèle, 2007), suggesting a slightly faster denudation and relative motion related to tectonic deformation along the Merens fault separating the two massifs. The Hospitalet ages indicate that denudation probably lasted until 28 Ma ago. To the south-east, the Canigou and Mont-Louis massifs show the similar range of cooling ages with a denudation rate slowing down around 21 Ma ago (Maurel et al., 2002). Northwest of the Aston massif, analyses indicate consistent ages in the Arize and Trois Seigneurs massifs, with youngest (U-Th)/He Oligocene ages on apatites (Vacherat, 2014).

Thermochronological data are also available from the southern flank of the central Pyrenees. The Maladeta massif shows a paleosurface associated with a weathering profile (Ortuño, 2008; Ortuño et al., 2013). Pollen collected within small basins showed the surface predates the Vallesian (11.1-



8.7 Ma). Low-T thermochronology indicates rapid denudation that decreased after 30 Ma (Fillon, 2012; Fitzgerald et al., 1999; Gibson et al., 2007; Sinclair et al., 2005); Fillon, 2012). This Eocene-Oligocene denudation episode led to infilling of the valleys, about 9 Ma ago (Fitzgerald et al., 1999; Fillon and van der Beek, 2012).

To sum up, the weathering profiles associated to the surfaces may have developed between the Eocene-Oligocene and the late Miocene (Calvet, 1996; Hautmann and Lippolt, 2000; Migoñ and Lidmar-Bergström, 2001b), and thus seem to be related to the Pyrenean orogeny. This agrees with the earlier interpretation by Hautmann and Lippolt (2000), who considered that Neogene weathering episodes were controlled tectonically rather than climatically. Development of the weathering surfaces seems to have ended around 10 Ma ago, and their subsequent disappearance was probably driven by incision and relief rejuvenation, as is shown by the Pliocene deposits filling the valleys in the northern Pyrenean piedmont (Monod et al., GARVEMIP working group, 2014).

### Reconstructing the planar paleosurface

Our work allows reconstructing the geometry of the surfaces (Figure 5 and Figure 8). The Aston surface has a relatively simple geometry, while the Bordères-Louron surface is slightly more complicated. We thus mainly focus our interpretation on the first one for which more data are available. The reconstructed surfaces top intermediate interfluvies and are connected with the foothills of the highest reliefs (see for example the southern boundary of the Aston surface, Figure 8 and Figure 9). In our interpretation, these piedmont surfaces correspond to an episode of relief (difference in elevation between talwegs and crests) decrease, and were later incised by deep valleys, partly of glacial origin. Our reconstructed surface for the Aston area shows low relief, resembling a gently dipping wide glaciais between some higher ground. The latter was smooth and shaped during a period of relief decrease, probably corresponding to the reworking of higher surfaces (Gunnell et al., 2009). On the basis of the low-temperature thermochronology data (Denèle, 2007; Maurel, 2003; Morris et al., 1998), we suggest that these reliefs were less than 1000 m above the piedmont, as a greater height seems impossible. Our reconstruction fits Goron's (1937) observations, who noted that these surfaces are at about 1200 m on the north side of the range, well above the current piedmont elevation, implying either infilling of the piedmont basin or uplift of the range after their development.

Such perched piedmont surfaces allow estimating the subsequent denudation that affected this area of the Pyrenees. The denudation was twofold: on the surfaces it corresponds to surface lowering, while in valleys it corresponds to incision after the surface developed. First, the weathered rocks below the surface remnants indicate that saprolite stripping is not complete and less than 50 m; this value of 50 m thus is an upper boundary for surface lowering by weathering since their formation (and probably before incision as discussed below). Second, we measured the incision to be 200-250 m in the Louron Valley (Figure 4) and 850 m in the Ariege and Aston valleys (see Figures Figure 5 and Figure 9). In the Aston area, the average incision can be measured as the difference between the current DEM and the reconstructed surface, i.e. about 300 m.

Consequently, if we consider an age of ~10 Ma for the surfaces, the upper boundary for an average denudation rate is around 5 m/Ma for the surfaces themselves (without incision), a value typical for low-erosion areas as indicated by cosmogenic nuclides (Portenga and Bierman, 2011) and by modern fluxes (Summerfield and Hulton, 1994). For the entire Aston area, the denudation rate must be about 350 m (300 m of average incision and 50 m of weathered-surface lowering). This corresponds to

35 m/Ma and maybe much more (up to 300 m/Ma), if we consider valley carving as having occurred mostly during the last 1 Ma, similarly to the data for Alpine valleys (Valla et al., 2011).

Surface remnants are found all through the Pyrenees, but the present work is too preliminary to prove that they all have a similar history to that shown on Figure 9, as suggested by Goron (1937). For instance, the Aston surface may be older than the Borderes one, since it has recorded more denudation. However, close to the study areas, the Canigou (to the south-east) and Maladeta (to the south) massifs seem to have undergone a similar evolution: strong denudation ending in the Oligocene, making place for surface- and weathering-profile development before incision after the Miocene (e.g., Gunnell et al., 2009; Ortuño et al., 2013). The latter incision would have been triggered by uplift (Calvet and Gunnell, 2008) or piedmont infilling by regressive erosion (Babault et al., 2005).

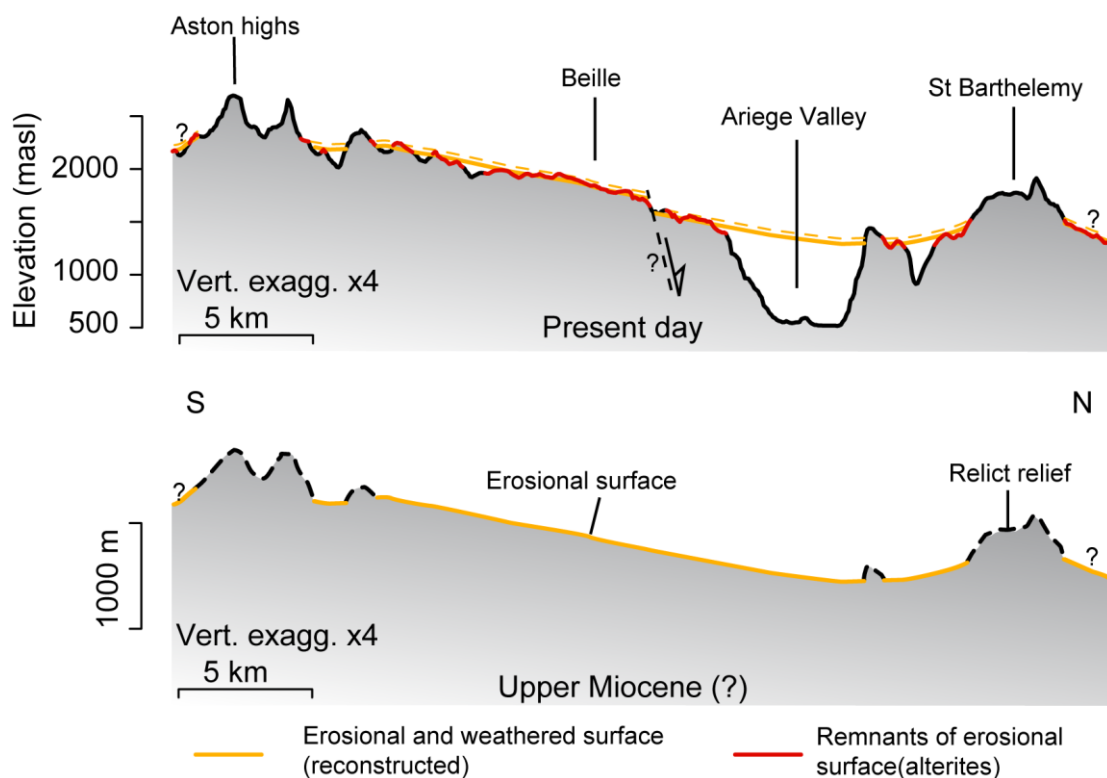


Figure 9: Surface development and incision: the example of Aston/Plateau de Beille. By the end of Miocene, an erosional surface associated with a weathered surface (alterites) shaped the valleys between remnants of relief built during the Pyrenean orogeny (unknown in dashed lines). Since the Miocene, this surface has been denudated by no more than 50 m (dashed yellow line) and partially dissected by incision.

### Surface faulting

In our study area, the Aston surface is deformed by normal faults with facet-like morphologies, oriented N110, thus paralleling some of the main tectonic boundaries, though as yet no visible striation on the fault surfaces was seen. The north-dipping high-angle faults expose a fissured zone in the footwall and unconsolidated alterites in the hanging wall. This structure is found from the summit of the Aston surface to the river level, giving the Ariège Valley a graben shape. Interestingly, Ortuño et al. (2013) describe a similar weathered surface from the Maladeta (assigned to Vallesian, cf. before), offset of around 440 m by the N100-trending normal Maladeta fault. Thus, a N110 normal faulting in Aston is considered possible (offset of about 150 m). The structure described here is consistent with post-Miocene extension in the Pyrenees, as already proposed by earlier studies dealing with active



tectonics (Lacan, 2008; Ortuño, 2008; Lacan and Ortuño, 2012), normal focal mechanisms (Chevrot et al., 2011) and digital models (Vernant et al., 2013).

## Conclusions

We describe planar surfaces associated with highly weathered rocks in the Pyrenees, based on the examples in the Bordères-Louron (central Pyrenees) and Aston (eastern Pyrenees) areas. We conclude that these surfaces are post-orogenic and developed between 30 Ma and 10 Ma ago. After that, they were abandoned during rejuvenation of the relief, involving either regional uplift or large-scale regressive erosion. These surfaces, which are found throughout the Pyrenees, represent outstanding morphological markers for analysing the post-orogenic processes, notably the question of the extensional tectonics that seem to have occurred recently.

## Acknowledgements

This work has been carried out with the support of RGF (Référentiel Géologique de la France) funding. Additional funding was provided by the POTAPYR project. VR and JC are grateful to D. Beziat, M. Thibault and D. Guillaume for optical and DR-X determinations of lepidocrocite and goethite. We thank M. Calvet, S. Carretier and C. Gautheron for fruitful discussions. We thank the two reviewers P. Lacan, JF. Ritz and the Associate Editor Y. Lagabrielle for thorough and constructive reviews that contribute to improve the manuscript. Dr H.M. Kluijver edited the English of the manuscript.

## References

- Babault, J., Van den Driessche, J., Bonnet, S., Castelltort, S., Crave, A., 2005. Origin of the highly elevated Pyrenean peneplain. *Tectonics* 24.
- Barrère, P., Bouquet, C., Debroas, E.-J., Péliissonnier, H., Peybernès, B., Soulé, J.-C., Souquet, P., Ternet, Y., 1984. Carte géologique et notice explicative de la feuille Arreau à 1/50 000. BRGM, 63 p.
- Beauvais, A., Ruffet, G., Hénocque, O., Colin, F., 2008. Chemical and physical erosion rhythms of the West African Cenozoic morphogenesis: The <sup>39</sup>Ar-<sup>40</sup>Ar dating of supergene K-Mn oxides. *J. Geophys. Res. Earth Surf.* 113, n/a–n/a. doi:10.1029/2008JF000996
- Calvet, M., 1996. Morphogenèse d'une montagne méditerranéenne : les Pyrénées orientales, Thèse Doct Etat. Doc. - BRGM 255, 1177.
- Calvet, M., Gunnell, Y., 2008. Planar landforms as markers of denudation chronology: an inversion of East Pyrenean tectonics based on landscape and sedimentary basin analysis. *Geol. Soc. Lond. Spec. Publ.* 296, 147–166. doi:10.1144/SP296.10
- Calvet, M., Gunnell, Y., Farines, B., 2015. Flat-topped mountain ranges: Their global distribution and value for understanding the evolution of mountain topography. *Geomorphology* 241, 255–291. doi:10.1016/j.geomorph.2015.04.015
- Chevrot, S., Sylvander, M., Delouis, B., 2011. A preliminary catalog of moment tensors for the Pyrenees. *Tectonophysics* 510, 239–251. doi:10.1016/j.tecto.2011.07.011
- Delmas, M., 2009. Chronologie et impact géomorphologique des glaciations quaternaires dans l'est des Pyrénées (phdthesis). Université Panthéon-Sorbonne - Paris I.
- Delmas, M., Calvet, M., Gunnell, Y., Braucher, R., Boulès, D., 2012. Les glaciations quaternaires dans les Pyrénées ariégeoises : approche historiographique, données paléogéographiques et chronologiques nouvelles. *Quat. Rev. Assoc. Fr. Pour l'étude Quat.* 61–85. doi:10.4000/quaternaire.6091
- Denèle, Y., 2007. Formation des dômes gneissiques hercyniens dans les Pyrénées : exemple du massif de l'Aston-Hospitalet (phd). Université de Toulouse, Université Toulouse III - Paul Sabatier.

- De Sitter, L.U., 1952. Pliocene uplift of Tertiary mountain chains. *Am. J. Sci.* 250, 297–307. doi:10.2475/ajs.250.4.297
- Destombes, J.P., Raguin, E., Casteras, M., Paris, J.P., 1969. Carte géologique de la feuille Vicdessos à 1/50 000. BRGM.
- Farines, B., Calvet, M., Gunnell, Y., 2015. The summit erosion surfaces of the inner Betic Cordillera: Their value as tools for reconstructing the chronology of topographic growth in southern Spain. *Geomorphology, Patterns and rates of Cenozoic landscape change in orogenic and post-orogenic settings* 233, 92–111. doi:10.1016/j.geomorph.2014.11.019
- Fillon, C., 2012. Variations spatio-temporelles dans l'exhumation Cénozoïque de la chaîne Pyrénéo-catabrienne : couplages entre tectonique et processus de surface (phdthesis). Université de Grenoble.
- Fillon, C., van der Beek, P., 2012. Post-orogenic evolution of the southern Pyrenees: constraints from inverse thermo-kinematic modelling of low-temperature thermochronology data. *Basin Res.* 24, 418–436. doi:10.1111/j.1365-2117.2011.00533.x
- Fitzgerald, P.G., Muñoz, J.A., Coney, P.J., Baldwin, S.L., 1999. Asymmetric exhumation across the Pyrenean orogen: implications for the tectonic evolution of a collisional orogen. *Earth Planet. Sci. Lett.* 173, 157–170. doi:10.1016/S0012-821X(99)00225-3
- Gandolfi, J., Wyns, R., Damy, P., 2010. Diagnostic des potentialités aquifères des formations de socle en région Midi-Pyrénées. Phase 1 : secteur "Massif Central" (No. BRGM/RP-58808-FR).
- Gibson, M., Sinclair, H.D., Lynn, G.J., Stuart, F.M., 2007. Late- to post-orogenic exhumation of the Central Pyrenees revealed through combined thermochronological data and modelling. *Basin Res.* 19, 323–334. doi:10.1111/j.1365-2117.2007.00333.x
- Gleizes, G., Crevon, G., Asrat, A., Barbey, P., 2006. Structure, age and mode of emplacement of the Hercynian Bordères-Louron pluton (Central Pyrenees, France). *Int. J. Earth Sci.* 95, 1039–1052. doi:10.1007/s00531-006-0088-4
- Goron, L., 1937. Les unités topographiques du Pays ariégeois : Le rôle des cycles d'érosion tertiaires et des glaciations quaternaires dans leur morphologie. *Rev. Géographique Pyrén. Sud-Ouest* 8, 300–334. doi:10.3406/rgpso.1937.4268
- Gunnell, Y., Calvet, M., Brichau, S., Carter, A., Aguilar, J.-P., Zeyen, H., 2009. Low long-term erosion rates in high-energy mountain belts: Insights from thermo- and biochronology in the Eastern Pyrenees. *Earth Planet. Sci. Lett.* 278, 208–218. doi:10.1016/j.epsl.2008.12.004
- Hautmann, S., Lippolt, H.J., 2000. <sup>40</sup>Ar/<sup>39</sup>Ar dating of central European K–Mn oxides — a chronological framework of supergene alteration processes during the Neogene. *Chem. Geol.* 170, 37–80. doi:10.1016/S0009-2541(99)00241-7
- Jolivet, M., Labaume, P., Monié, P., Brunel, M., Arnaud, N., Campani, M., 2007a. Thermochronology constraints for the propagation sequence of the south Pyrenean basement thrust system (France-Spain). *Tectonics* 26, TC5007. doi:10.1029/2006TC002080
- Jolivet, M., Ritz, J.-F., Vassallo, R., Larroque, C., Braucher, R., Todbileg, M., Chauvet, A., Sue, C., Arnaud, N., Vicente, R.D., Arzhanikova, A., Arzhanikov, S., 2007b. Mongolian summits: An uplifted, flat, old but still preserved erosion surface. *Geology* 35, 871–874. doi:10.1130/G23758A.1
- Lacan, P., 2008. Activité Sismotectonique Plio-Quaternaire de l'Ouest des Pyrénées. Université de Pau et des Pays de l'Adour.
- Lacan, P., Ortuño, M., 2012. Active Tectonics of the Pyrenees: A review. *J. Iber. Geol.* 38, 9–30. doi:10.5209/rev\_JIGE.2012.v38.n1.39203
- Maurel, O., 2003. L'exhumation de la Zone Axiale des Pyrénées orientales : Une approche thermo-chronologique multi-méthodes du rôle des failles. (phdthesis). Université Montpellier II - Sciences et Techniques du Languedoc.
- Maurel, O., Brunel, M., Monié, P., 2002. Exhumation cénozoïque des massifs du Canigou et de Mont-Louis (Pyrénées orientales, France). *Comptes Rendus Geosci.* 334, 941–948. doi:10.1016/S1631-0713(02)01834-5



- Migoń, P., Lidmar-Bergström, K., 2001a. Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. *Earth-Sci. Rev.* 56, 285–324. doi:10.1016/S0012-8252(01)00068-X
- Migoń, P., Lidmar-Bergström, K., 2001b. Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. *Earth-Sci. Rev.* 56, 285–324. doi:10.1016/S0012-8252(01)00068-X
- Monod, B., le groupe de travail GARVEMIP, 2014. Carte Géologique numérique à 1/250 000 de la région Midi-Pyrénées. Notice technique. (No. BRGM/RP-63650-FR). BRGM.
- Morris, R.G., Sinclair, H.D., Yelland, A.J., 1998. Exhumation of the Pyrenean orogen: implications for sediment discharge. *Basin Res.* 10, 69–85. doi:10.1046/j.1365-2117.1998.00053.x
- Ortuño, M., 2008. Deformación activa en el Pirineo Central: la falla Norte de la Maladeta y otras fallas activas. Universitat de Barcelona.
- Ortuño, M., Martí, A., Martín-Closas, C., Jiménez-Moreno, G., Martinetto, E., Santanach, P., 2013. Palaeoenvironments of the Late Miocene Prüdo Basin: implications for the uplift of the Central Pyrenees. *J. Geol. Soc.* 170, 79–92. doi:10.1144/jgs2011-121
- Pierre, G., 1989. Les altérites fossilisées par des coulées de lave : valeur paléoclimatique et implications géomorphologiques ; l'exemple de l'Auvergne, de l'Aubrac et du Velay. (phdthesis). Panthéon-Sorbonne - Paris I.
- Portenga, E.W., Bierman, P.R., 2011. Understanding Earth's eroding surface with  $^{10}\text{Be}$ . *GSA Today* 21, 4–10. doi:10.1130/G111A.1
- Ricordel-Prognon, C., Lagroix, F., Moreau, M.-G., Thiry, M., 2010. Lateritic paleoweathering profiles in French Massif Central: Paleomagnetic datings. *J. Geophys. Res. Solid Earth* 115, B10104. doi:10.1029/2010JB007419
- Scott, G.R., 1975. Cenozoic Surfaces and Deposits in the Southern Rocky Mountains. *Geol. Soc. Am. Mem.* 144, 227–248. doi:10.1130/MEM144-p227
- Shuster, D.L., Vasconcelos, P.M., Heim, J.A., Farley, K.A., 2005. Weathering geochronology by (U-Th)/He dating of goethite. *Geochim. Cosmochim. Acta* 69, 659–673. doi:10.1016/j.gca.2004.07.028
- Sinclair, H.D., Gibson, M., Naylor, M., Morris, R.G., 2005. Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes. *Am. J. Sci.* 305, 369–406. doi:10.2475/ajs.305.5.369
- Summerfield, M.A., Hulton, N.J., 1994. Natural controls of fluvial denudation rates in major world drainage basins. *J. Geophys. Res. Solid Earth* 99, 13871–13883. doi:10.1029/94JB00715
- Vacherat, A., 2014. Inversion d'une marge hyper-amincie. Contexte thermo-cinématique et interactions tectonique-érosion au Nord des Pyrénées (PhD Thesis). Université Pierre et Marie Curie, Paris, France.
- Valla, P.G., Shuster, D.L., van der Beek, P.A., 2011. Significant increase in relief of the European Alps during mid-Pleistocene glaciations. *Nat. Geosci.* 4, 688–692. doi:10.1038/ngeo1242
- Vernant, P., Hivert, F., Chéry, J., Steer, P., Cattin, R., Rigo, A., 2013. Erosion-induced isostatic rebound triggers extension in low convergent mountain ranges. *Geology* 41, 467–470. doi:10.1130/G33942.1
- Wyns, R., 2002. Climat, eustatisme, tectonique : quels contrôles pour l'altération continentale ? Exemple des séquences d'altération cénozoïques en France. *Bull Inf Géol Bass Paris* 39, 5–16.
- Wyns, R., Baltassat, J.M., Lachassagne, P., Legchenko, A., Vairon, J., Mathieu, F., 2004. Application of proton magnetic resonance soundings to groundwater reserve mapping in weathered basement rocks (Brittany, France). *Bull. Soc. Geol. Fr.* 175, 21–34. doi:10.2113/175.1.21
- Wyns, R., Quesnel, F., Simon-Coinçon, R., Guillocheau, F., Lacquement, F., 2003. Major weathering in France related to lithospheric deformation. *Geol. Fr., Special conference on Paleoweathering and paleosurfaces in the Ardennes-Eifel region, Preizerdau, Luxembourg*, 14-17/05/2003 79–87.