Exhumation sequence of the basement thrust units in the west-central Pyrenees. Constraints from apatite fission track analysis

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Sociedad Geológica de España

GEOGACETA, 60, 2016

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Secuencia de exhumación de las unidades cabalgantes de zócalo de los Pirineos centro-occidentales a partir del análisis de huellas de fisión en apatito

Pierre Labaume[1], Florian Meresse[1,2], Marc Jolivet[1,3] and Antonio Teixell[4]

[1]Géosciences Montpellier, Université de Montpellier, 34095 Montpellier, France. pierre.labaume@gm.univ-montp2.fr

[2]present address: CSTJF, Total, avenue Larribau, 64000 Pau, France. florian.meresse@total.com

[3]Géosciences Rennes, Université de Rennes 1, 34095 Rennes, France. marc.jolivet@univ-rennes1.fr

[4]Departament de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain. antonio.teixell@uab.es

ABSTRACT

Compilation of new and published apatite fission track data along a transect of the west-central Pyrenees shows that exhumation across the Partial Annealing Zone (~120–60°C) started during the mid Eocene in the North-Pyrenean Zone and migrated southward to reach the southern edge of the Axial Zone during the early Miocene. An early Miocene stage of exhumation is also detected in the northern part of the Axial Zone, indicating a late pop-up thrust reactivation of the Axial Zone.

Key-words: *Pyrenees, apatite fission tracks, exhumation.*

RESUMEN

La compilación de datos nuevos y pre-existentes de huellas de fisión en apatito a lo largo de un perfil de los Pirineos centro-occidentales muestra que la exhumación a través de la Partial Annealing Zone (~120–60°C) comenzó en el Eoceno medio en la Zona Norpirenaica, y fue migrando hacia el sur hasta alcanzar el borde meridional de la Zona Axial en el Mioceno inferior. Al norte de la Zona Axial se registra así mismo una marcada exhumación durante el Mioceno inferior, indicando una reactivación cabalgante en pop-up *de la Zona Axial.*

Palabras clave: *Pirineos, huellas de fisión en apatito, exhumación.*

Geogaceta, 60 (2016), 11-14
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Recepción: 2 de marzo de 2016
Revisión: 20 de abril de 2016
Aceptación: 20 de Mayo de 2016

Introduction

Low-temperature thermochronology has proven in the past decades an useful technique to unravel the relationships between the dynamics of thrusting and the erosional exhumation of the Pyrenees, often constituting the key to delineate or to date uplift and exhumation of Alpine thrust units within the Axial Zone basement (see Bosch *et al.*, 2016 and references therein). This study presents new apatite fission track (AFT) data from 9 samples collected along a transect in the west-central Pyrenees including the North Pyrenean Zone (NPZ) and the Axial Zone (AZ). These complement samples studied by Morris *et al.* (1998), Jolivet *et al.* (2007) and Bosch *et al.* (2016) (Fig. 1), and altogether provide new clues on the tectonic evolution of this segment of the chain.

Sampling and analytical methodology

New samples were collected in Variscan granite massifs (BS3, BS4, BS8, LP3, PM1, PM3) and veins (GV5), like all previously published samples, or in anatectic paragneisses (BB1, BB2). In the AZ, samples from the Bielsa granite and Gavarnie window are in the Bielsa thrust sheet, samples from the Balaïtous, Panticosa, Piau, Néouvielle and Bordères-Louron granites in the Gavarnie thrust sheet, samples from the Chiroulet granite in the Pierrefitte thrust sheet, while samples from the Lesponne granite are in the footwall of the north-directed Aygue-Rouye thrust. The Néouvielle massif is crossed by Alpine shear zones (Ingles *et al.*, 1999) corresponding to the eastern splays of the Eaux-Chaudes thrust but these have limited offset and cannot have driven exhumation. Samples from the Bagnères de Bigorre massif are in the NPZ. The sample set includes four sub-vertical profiles, in the Bielsa, Néouvielle, Balaïtous and Chiroulet massifs.

New AFT ages were obtained using the external detector method (Hurford and Green, 1983) with a zeta value of 343 ± 7 (FM) obtained on both Durango and Mount Dromedary standards. Errors on central ages are quoted at ± 2σ. Reverse modeling of AFT data has been performed to describe the sample time–temperature history across the partial annealing zone (PAZ), using the AFTSolve (Ketcham *et al.*, 2000) and the Ketcham *et al.* (1999) annealing model, with the D_{par} values used as kinetic parameter.

Fission track data for the 9 new samples are reported in Table I, and central ages of all samples are reported on the map in figure 1. The central ages *vs* elevation relationships are shown in figure 2 and new time-temperature models are in figure 3.

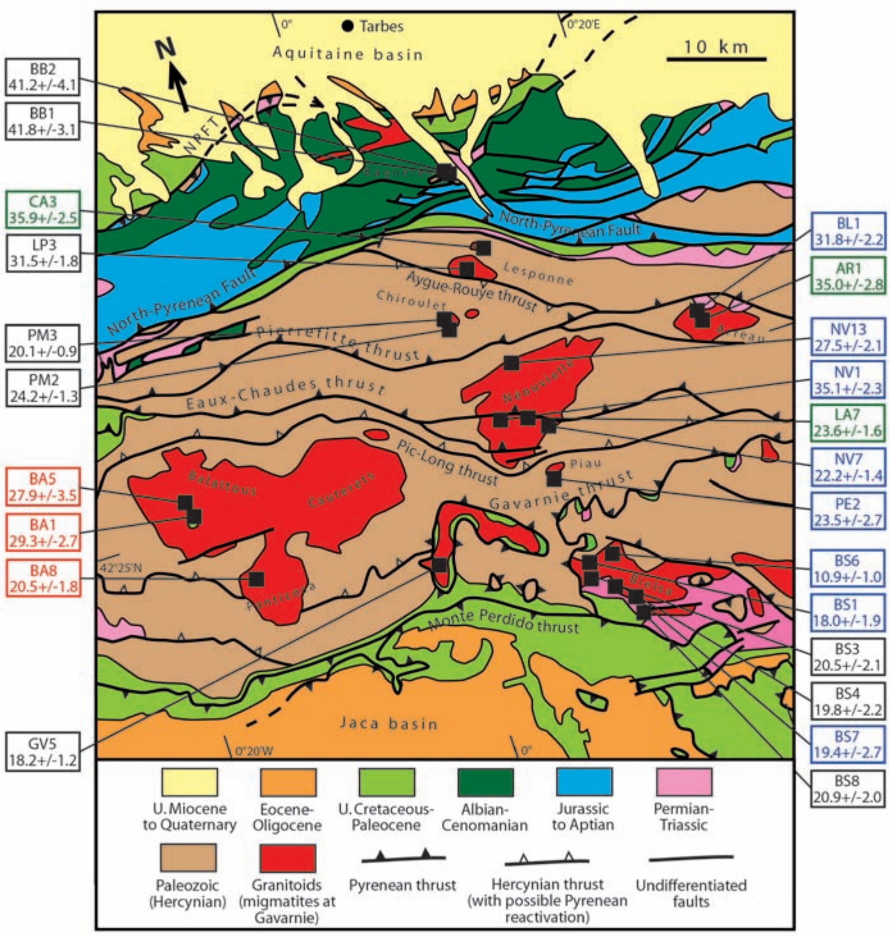

Fig. 1.- Geological map of the study area with location of the apatite fission track samples and their central ages in Ma. In black: this study; in red: Bosch et al. (2016); in blue: Jolivet et al. (2007); in green: Morris et al. (1998).

Fig. 1.- Mapa geológico del área de estudio con la localización de las muestras y sus edades centrales en Ma. Negro: este estudio; rojo: Bosch et al. (2016); azul: Jolivet et al. (2007); verde: Morris et al. (1998).

Discussion of apatite fission track results

The age-altitude plot of AFT data reveals relative vertical movements of the various massifs across the PAZ that are discussed considering three distinct sectors (Fig. 2).

Median AZ: Gavarnie and Pierrefitte thrust sheets. Samples show a clear age-altitude correlation. The Néouvielle and Balaïtous summit samples (NV1 and BA1) were exhumed rapidly during the Oligocene (beginning in the late Eocene for NV1 and ending in the early Miocene for BA1) as shown both by their central age difference with the corresponding valley samples (NV7 and BA5, respectively) and track length modelling (for NV1, see Jolivet *et al.*, 2007). The AFT ages of BA1 and BA5 appear in conflict with zircon (U-Th)/He (ZHe) ages around 22 Ma determined by Bosch *et al.* (2016). However, data modelling by these authors indicate a very rapid cooling of these samples between 30 and 20 Ma. All other samples from the Piau, Néouvielle, Balaïtous and Chiroulet massifs are located around 2000 m of altitude and show a clear age–altitude correlation with central ages spanning from the late Oligocene to early Miocene. This suggests that, after the initial rapid exhumation registered by the summit samples, the whole area behaved as a coherent block affected by slower exhumation.

Southern AZ: Bielsa thrust sheet. Samples only yield Miocene ages, younger than those from the median AZ at equivalent altitudes. The summit sample BS1 and samples BS3, BS4, BS7, BS8 and GV5, all located close to the tilted post-Variscan erosion surface, yield the same early Miocene age in spite of a 1500 m altitude difference, suggesting a post-cooling tilting (Jolivet *et al.*, 2007). By contrast, BS1 shows an age–altitude correlation with the BS6 valley sample in the core of the massif, which cooled during the late Miocene in spite of a higher altitude than BS7 and BS8.

Northern AZ and NPZ. Our two northernmost samples in the Axial Zone (LP3 and BL1, in the Lesponne and Bordère-Louron massifs, respectively) yield early Oligocene central ages, close to, although slightly younger than the Priabonian ages found by Morris *et al.* (1998) in the same massifs. These ages are similar to those of samples NV1 and BA1 located at the top of the Palaeozoic basement in the median AZ, but at much higher altitudes. Moreover, these ages contrast with the much younger, late Oligocene–early Miocene ages found immediately to the south at higher elevation (around 2000 m) at Chiroulet (PM2 and PM3) and north of Néouvielle (NV13). In particular, PM2 was exhumed 11 Myrs after LP3 although it is located 500 m higher and only 4 km southward. The age-altitude distribution between the median and northern parts of the AZ thus does not correspond to that expected in the case of valley erosion in a coherent block, but argues for an early Miocene uplift and erosion of the median AZ with respect to the northern part. In the NPZ, the mid Eocene central ages of samples BB1 and BB2, and the mid Eocene to early Oligocene cooling across the PAZ modelled for BB2, show that most exhumation of the NPZ occurred earlier than in the AZ in spite of a lower altitude.

Implications for the tectonic evolution of the west-central Pyrenees

The new results presented here complement those of Jolivet *et al.* (2007) in confirming the initial southward migration of exhumation across the PAZ along a profile of the west-central Pyrenees, similarly to the central Pyrenees (Fitzgerald *et al.*, 1999; Sinclair *et al.*, 2005).

The mid Eocene exhumation in the NPZ coincides with the deposition of the first conglomerates in the north-Pyrenean basin (Biteau *et al.*, 2006) and confirms that the onset of compressive deformation around 80 Ma predates the onset of deep erosion by several tens Myrs. This is coherent with ZHe data more to the west dating the onset of cooling in the NPZ around 50 Ma (Vacherat *et al.*, 2014; Bosch *et al.*, 2016).

Sample	Latitude	Longitude	Elevation (m)	N	$\rho d \times 10^5$ (counted)	$\rho s \times 10^5$ (counted)	$\rho i \times 10^5$ (counted)	[U]	$P(\chi 2)$	Var (%)	FT age $\pm 2\sigma$	D_{par}	MTL $\pm$ 1σ (Tracks)
BS3	N42°41′3.6″	W0°08′34.4″	2050	19	12.4 (13562)	5.88 (161)	62.3 (1707)	68	100	2.8	20.5 ± 2.1	–	–
BS4	N42°39′53.8″	W0°11′05.5″	1450	23	11.31 (12540)	4.83 (113)	48.29 (1130)	53	100	0.3	19.8 ± 2.2	–	–
BS8	N42°38′16.0″	W0°12′54.0″	1020	16	11.75 (12540)	5.66 (189)	55.69 (1861)	50	100	4.4	20.9 ± 2.0	–	–
GV5	N42°43′59.8″	W0°00′32.5″	1388	18	12.34 (10996)	6.05 (245)	66.82 (2706)	64.3	97.53	0	18.2 ± 1.2	2	–
PM3	N42°56′53.2″	E0°05′00.8″	1650	20	13.46 (12632)	8.09 (626)	88.6 (6855)	70.34	93.76	0	20.1 ± 0.9	2	13.5 ± 2.3 (92)
PM2	N42°56′33.5″	E0°05′07.7″	1750	20	15.11 (14734)	6.4 (471)	68.5 (5022)	52.7	99.19	0	24.2 ± 1.3	2.2	13.1 ± 2.3 (69)
LP3	N42°59′01.4″	E0°07′16.4″	1226	20	15.41 (14734)	3.9 (399)	33.3 (3331)	24.55	92.35	0	31.5 ± 1.8	2	13.8 ± 1.9 (57)
BB1	N43°04′12.2″	E0°08′17.8″	557	20	12.03 (7978)	5.7 (246)	27.9 (1210)	29.66	78.7	0.01	41.8 ± 3.1	1.9	13.8 ± 1.8 (116)
BB2	N43°04′05.4″	E0°08′07.8″	641	16	12.79 (7978)	3.7 (127)	19.6 (673)	19.2	80.64	0	41.2 ± 4.1	1.8	13.8 ± 1.6 (65)

Table I.- Apatite fission track data of new samples.

Tabla I.- Datos de huellas de fisión en apatito de las muestras nuevas.

It suggests that the early compressive prism was a low-elevation, essentially submarine structure buried below continuous sedimentation, probably due to the fact that the first stages of the Pyrenean compression inverted a domain of previously highly thinned continental crust and exhumed mantle (e.g. Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010). At that time, the NPZ developed as a thrust pop-up and contributed to bury the northern edge of the AZ during the latest Cretaceous to earliest Tertiary. We infer that exhumation in the NPZ began after the exhumed mantle domain was subducted and the originally thinned crust had been sufficiently thickened to allow for full continental collision (Teixell *et al.*, 2016).

In the AZ, the earliest tectonic event dated in the study area is the early Eocene activity of the shear zones crossing the Néouvielle massif (Wayne and McCaig, 1998; Jolivet *et al.*, 2007). These correspond to the eastern termination of the Eaux-Chaudes thrust which activity is thus dated. There is no direct dating of the Pierrefitte thrust, but this thrust branches to the west in the Lakora thrust together with the Eaux-Chaudes thrust and it may thus have been active during the same period. However, activity of both thrusts did not result in hanging wall exhumation down to the AFT PAZ, as shown by the results on samples from the northern AZ being no older than the early Oligocene. This may be due to a limited offset and vertical uplift of these thrusts in the sampling area. Another possible explanation is that the NPF, the Pierrefitte thrust and the Eaux-Chaudes thrust were active coevally during the early–mid Eocene, forming a south-verging imbricate system in which only the uppermost unit, the NPZ, experienced exhumation at the end of this period.

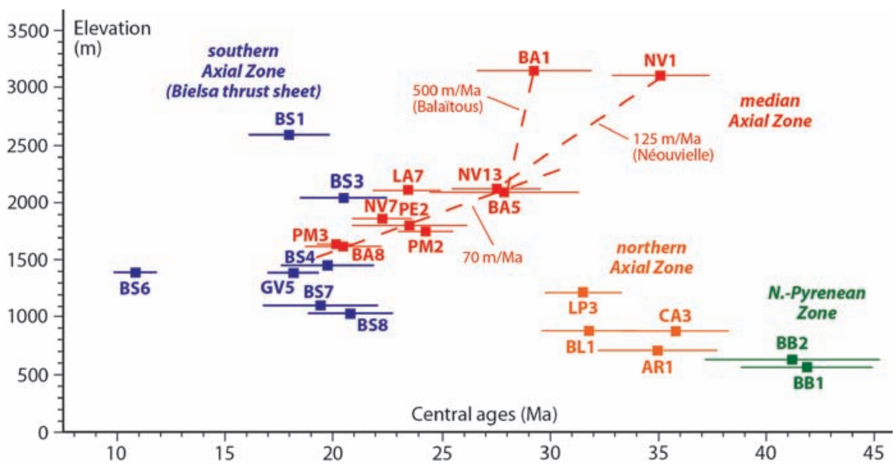

Fig. 2.- Apatite fission track central ages vs. elevation, grouped by structural domains, with estimation of the mean denudation rates for the median Axial Zone (the colours refer to the different structural domains; location of the samples and references of sample origin are in figure 1).

Fig. 2.- Edades centrales de huellas de fisión vs. elevación de las muestras, agrupadas por dominios estructurales. Se incluye estimación de las tasas de exhumación de la Zona Axial media (los colores se refieren a los diferentes dominios estructurales; la localización de las muestras y las referencias de su origen se muestran en la figura 1).

Exhumation across the PAZ of samples from the northern and median AZ (LP3 at Lesponne, BL1 at Bordères-Louron, NV1 at the Néouvielle summit) during the latest Eocene–early Oligocene is interpreted as resulting from uplift of the Gavarnie thrust sheet above its footwall ramp (Jolivet *et al.*, 2007). This interpretation is consistent with the dating of the Gavarnie thrust activity to the Priabonian–early Oligocene by growth strata in the Jaca basin (Teixell, 1996). More to the west in the median AZ, AFT and ZHe results on the Balaïtous samples attest a younger, Oligocene exhumation that can be related to the Guarga thrust activity dated to this period in the Jaca basin (Teixell, 1996; Bosch *et al.*, 2016).

The youngest exhumation episode occurred in the early Miocene in the southern AZ, in the lowermost part of the Gavarnie thrust sheet and underlying Bielsa thrust sheet. These units were finally tilted southwards (and westward in the Gavarnie window area) after cooling. As an alternative to an out-of-sequence onset of the Bielsa thrust proposed by Jolivet *et al.* (2007), we may infer a piggyback sequence for the Gavarnie, Bielsa and Guarga thrusts, the cooling being due to the end of activity of the latter thrust during the early Miocene (Teixell, 1996) and the tilting to a late deformation of the Bielsa thrust hanging wall not necessarily related to the main thrust slip phase. The late Miocene cen-

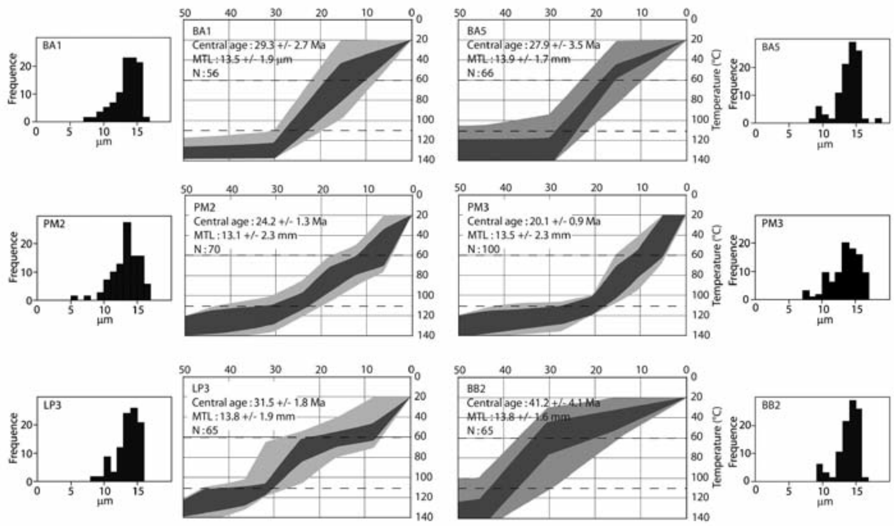

Fig. 3. Reverse time–temperature modelling of apatite fission track data (see methodology in the text). MTL: measured mean track length, N: number of tracks measured. Dark-grey area: envelope of all the possible temperature–time curves falling within a ± 1σ error interval from the best fit curve. Light-grey area: envelope of all the curves falling within a ± 2σ interval. Only the area between 110 and 60 °C (Partial Annealing Zone) is representative.

Fig.- 3.- Modelización inversa tiempo–temperatura a partir de los datos de las huellas de fisión (ver el texto para la metodología utilizada). MTL: longitud media medida de las huellas; N: número de huellas medidas. En gris oscuro se muestra la envolvente de las curvas temperatura–tiempo que caen en el intervalo de error ± 1σ respecto a la curva mejor ajustada. En gris claro se muestra la envolvente de las curvas que caen en el intervalo ± 2σ. Solo es representativa el área entre 110 y 60 °C (zona de borrado térmico parcial).

tral age of sample BS6 in the core of the Bielsa massif, the youngest AFT age known in the Pyrenean AZ, is interpreted as due to valley incision.

Results also show that aside from the general southward migration of the exhumation across the AZ, the age-altitude relationships between the Chiroulet and Lesponne samples indicate an early Miocene tectonic uplift of the median AZ with respect to the northernmost part, possibly related to a late activation of the north-verging Aigue-Rouye thrust. More to the east, equivalent thrusts may explain the similar age-altitude pattern between the north of the Néouvielle massif (NV13) and the Bordère-Louron massif (BL1). This argues for a late tectonic uplift of the whole median and southern parts of the AZ, corresponding to a pop-up basement structure activated coevally with, or slightly after, the end of shortening at the Pyrenean mountain fronts.

Conclusions

This study confirms a southward migration of the exhumation across the west-central Pyrenees, with the following major characteristics: (i) The first stages of Pyrenean compression, during which the continental crust recovered its original thickness after a previous thinning stage, did not involve significant exhumation; (ii) From the mid Eocene (~ 40 Ma), exhumation across the AFT PAZ begun in the NPZ which was probably thrust as a pop-up; (iii) Exhumation migrated southward in the northern AZ during the late Eocene–early Oligocene when continental collision activated the Gavarnie thrust in the Iberian plate, followed by the Bielsa and Guarga thrusts in piggy-back sequence. Exhumation slowed down during the late Oligocene–early Miocene in the median and southern AZ which then behaved as a coherent structural block; (iv) The late stages of Pyrenean compression involved the pop-up reactivation of the median and southern AZ, leading to the post-cooling tilting of the southern edge of the AZ and an early Miocene cooling in the northern AZ possibly related to reactivation of a north-vergent thrust.

Acknowledgements

This work was funded by the DYETI program of the INSU-CNRS, France and project CGL2010-15416 of the MINECO, Spain. We thank Luis Barbero and Jaume Vergés for their reviews of the original manuscript.

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