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

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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.

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 Balaitous, 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 spays of the Eaux-Chaudes thrust but these have limited offset and cannot have driven exhumation. Samples from the Bagneres de Bigorre massif are in the NPZ. The sample set includes four sub-vertical profiles, in the Bielsa, Néouvielle, Balaitous 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 Dpar 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.
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 Baïlaitous 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, Baïlaitous 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).
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 coeval with the Eaux-Chaudes thrust and it may thus have been 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.

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 football 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 Balaitous 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 lowest 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).

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.

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