Spatio-temporal patterns of Pyrenean exhumation revealed by inverse thermo-kinematic modeling of a large thermochronologic dataset

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Data Repository

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1.1 Thermo-kinematic modeling and inversion approach

We utilize the thermo-kinematic modeling code *Pecube* to evaluate our hypotheses. *Pecube* uses a finite-element method to solve the heat transport equation in 3D (Braun, 2003). It then tracks the paths and temperatures of rocks as they are advected through a surface topography. Given a tectonic and topographic scenario together with crustal and thermal parameters, *Pecube* will predict cooling ages for any thermochronometer. Pecube tests tectonic scenarios by imposing spatially and temporally variable rock uplift and a topographic evolution scenario. *Pecube* incorporates the Neighborhood Algorithm (Sambridge, 1999a, 1999b), allowing for direct inversion of thermochronology data. The inversion approach allows identifying a best-fit tectonic and topographic scenario within a predefined parameter space. To evaluate the fit of the model, predicted thermochronological ages are compared to observed ages using a reduced Chi-square calculation:

$$\mu = \sqrt{\frac{\sum_{i=1}^{n} \frac{(O_i - P_i)^2}{U_i^2}}{n}}$$

Where misfit (μ) represents the difference between observed (O_i) and predicted (P_i) thermochronologic ages, and incorporates published uncertainty on individual ages (U_i); n is the number of data. Each model run represents 10,080 forward models that converge on a combination of input parameters with the lowest calculated misfit. We then assess the inversion results by calculating the marginal posterior probability density function (PDF) of each inverted parameter, thus providing a Bayesian estimate of parameter resolution (Sambridge, 1999b; Valla et al., 2010; Glotzbach et al., 2011; Fillon and van der Beek, 2012).

1.2 Modeling of Miocene sediment blanketing (Figure DR1)

To incorporate the effects of Miocene sediment blanketing on thermochronometric ages we modify the source code to impose a minimum elevation in the same manner as Fillon and van der Beek (2012). We allow the minimum elevation to increase linearly between 34 and 23 Ma, simulating deposition in the valleys. The minimum elevation starts at 0 km at 34 Ma, and we invert for the thickness at 23 Ma and 10 Ma. The thicknesses at 23 Ma and 10 Ma are inverted separately, thus allowing for different values at these two times, searching between 0-2.5 km for the best fit. From 10 Ma to present, the minimum elevation decreases linearly back to 0 km, simulating incision. The sediment added has the same thermal properties as the modeled crust and is compensated with flexural isostasy.

1.3 Erosion calculations

To calculate eroded material through time, we combine the topographic evolution proposed by Curry et al. (2019) with our best-fit results from the suite of inversions, which provide rock uplift through time. If there was no topographic change (i.e. in topographic steady state), rock uplift (Ur) simply equals erosion (E). With topographic change ΔTopo (positive in case of topographic growth), Ur = E + ΔTopo (e.g., England and Molnar, 1990).

We calculate the rock uplift for each cell (~700 m^2) for each time bin of the inversion, and subtract the predicted topographic change. In this way we get a value for the amount of erosion for each cell at each time bin. To calculate the cumulative 1D erosion (Figure 3B, C in main text), we sum the cumulative erosion through time for each cell and report the mean value of erosion within the zone of interest.

1.4 Uncertainty introduced by topographic scenario

We use the first order topographic evolution proposed by Curry et al. (2019) to constrain the surface boundary conditions of our model (see Fig. DR1 below). Curry et al. (2019) used flexural modeling and basin reconstructions to estimate the change in the Pyrenean topographic load through time. The uncertainty this scenario introduces into our inferred rock uplift and exhumation rate is ±0.007-0.038 km/m.y., with the highest uncertainty (0.038 km/m.y.) during the late Eocene when there was rapid growth of topography (Table DR1, below). This uncertainty is calculated by propagating the uncertainty in surface uplift rate (in km/m.y.) onto our results, following again the simple equation Ur = E + ΔTopo (England and Molnar, 1990).

Table DR1: Calculation of uncertainty introduced by topographic scenario

Time (Ma)	Tau value from Curry et al. (2019) [proportion of modern topography]	Mean topographic elevation through time (m)	Uncertainty on mean topography (m)**
0	1	1469	150
23	1.1	1763	150
34	1	1396	150
38	0.8	1028	150
56	0.6	881	150

Time span (Ma)	Time (m.y.)	Delta mean (m)	Mean rate (m/my)	Tau 0.1 rate (m/m.y.)	Mean rate of topographic change (km/m.y.) **Used in model.	Uncertainty in topographic scenario (km/m.y.)
23-0	23	-294	-12.8	6.5	***-0.013***	***0.007***
34-23	11	367	33.4	13.6	***0.033***	***0.014***
38-34	4	367	91.8	37.5	***0.092***	***0.038***
56-38	18	147	8.2	8.3	***0.008***	***0.008***

** Uncertainty from Curry et al. (2019) is represented as 0.1 of Tau, which is a proportion of modern topography. The modern mean topography is 1469 in our study area, we use plus/minus 150 meters

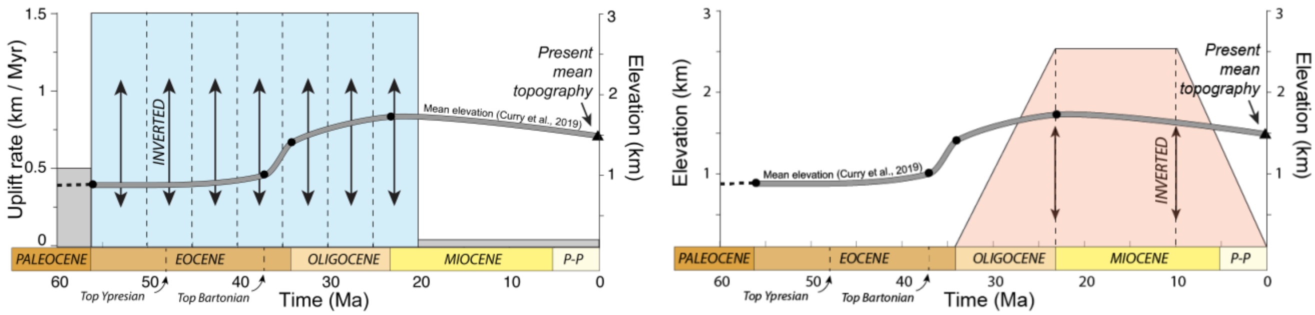

Figure DR1: Inversion set up. A) Time bins within which we invert for uplift rate, and range of values the inversion searches within. B) Sediment blanketing: Miocene sediment imposed (34-23 Ma) and removed (10-0 Ma) to simulate deposition and erosion of sediment in valleys. Gray line is mean swath elevation of the Pyrenees based on results of Curry et al. (2019). Double arrows indicate parameters that are inverted for.

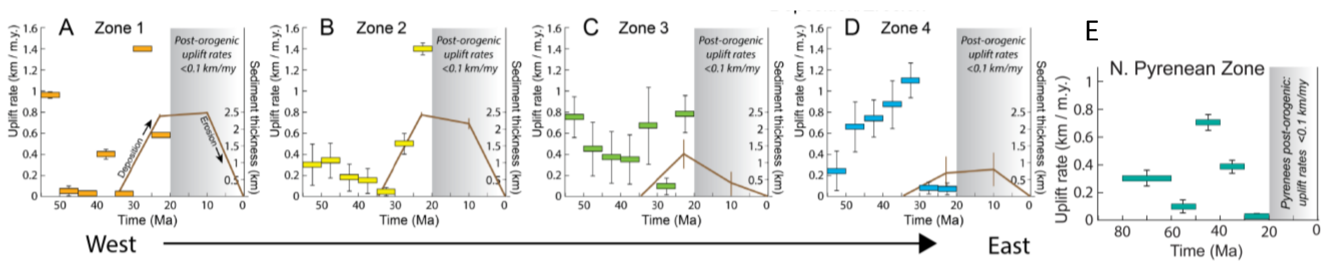

Figure DR2: Inversion results and uncertainties for best-fit model B (A-D) and North Pyrenean Zone (E). Inversion results for uplift rate through time, and thickness of sediment blanketing (brown lines in A-D, details in section DR1.2), organized by zone. Uncertainty bars correspond to the standard deviation of the marginal posterior probability density function of each inverted parameter, which provides a Bayesian estimate of parameter resolution.

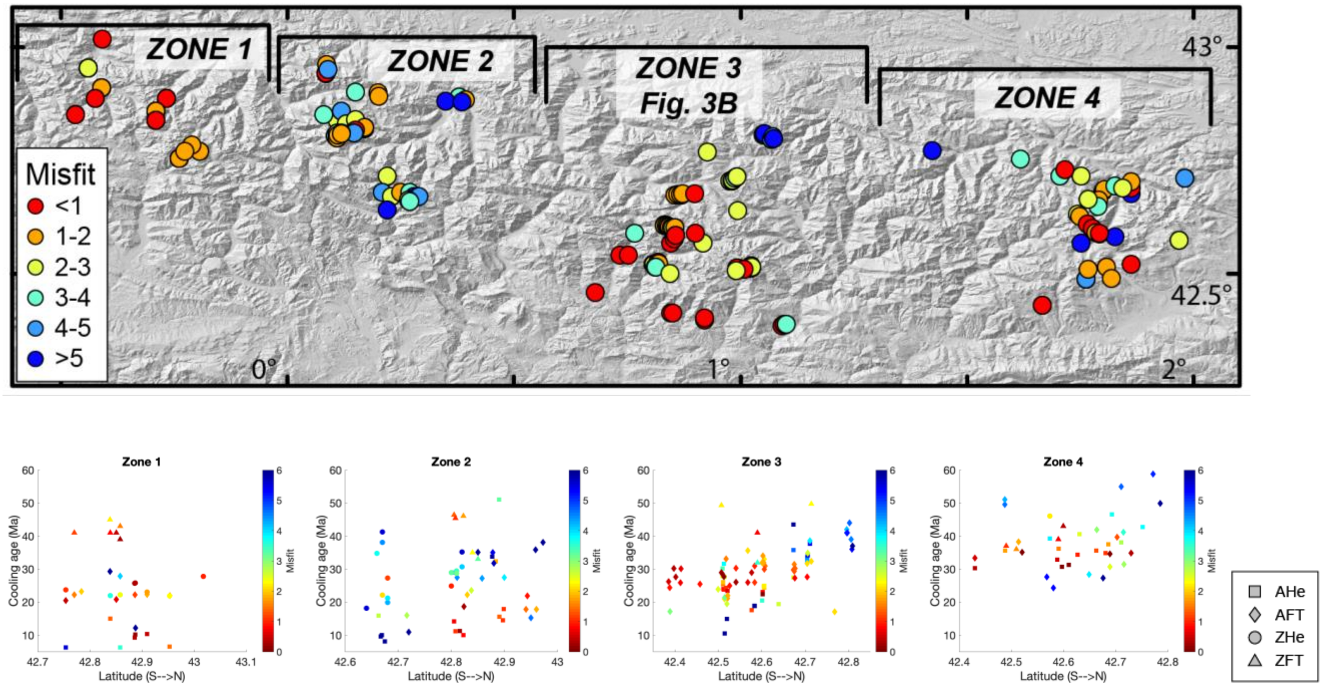

Figure DR3: Map of misfit and plots of north-south pattern of cooling ages for model B, separated by E-W zone and colored by misfit, symbols indicate different thermochronometers. Note the southward-younging ages in Zone 3 mentioned in the text, but lack of southward younging in other zones.

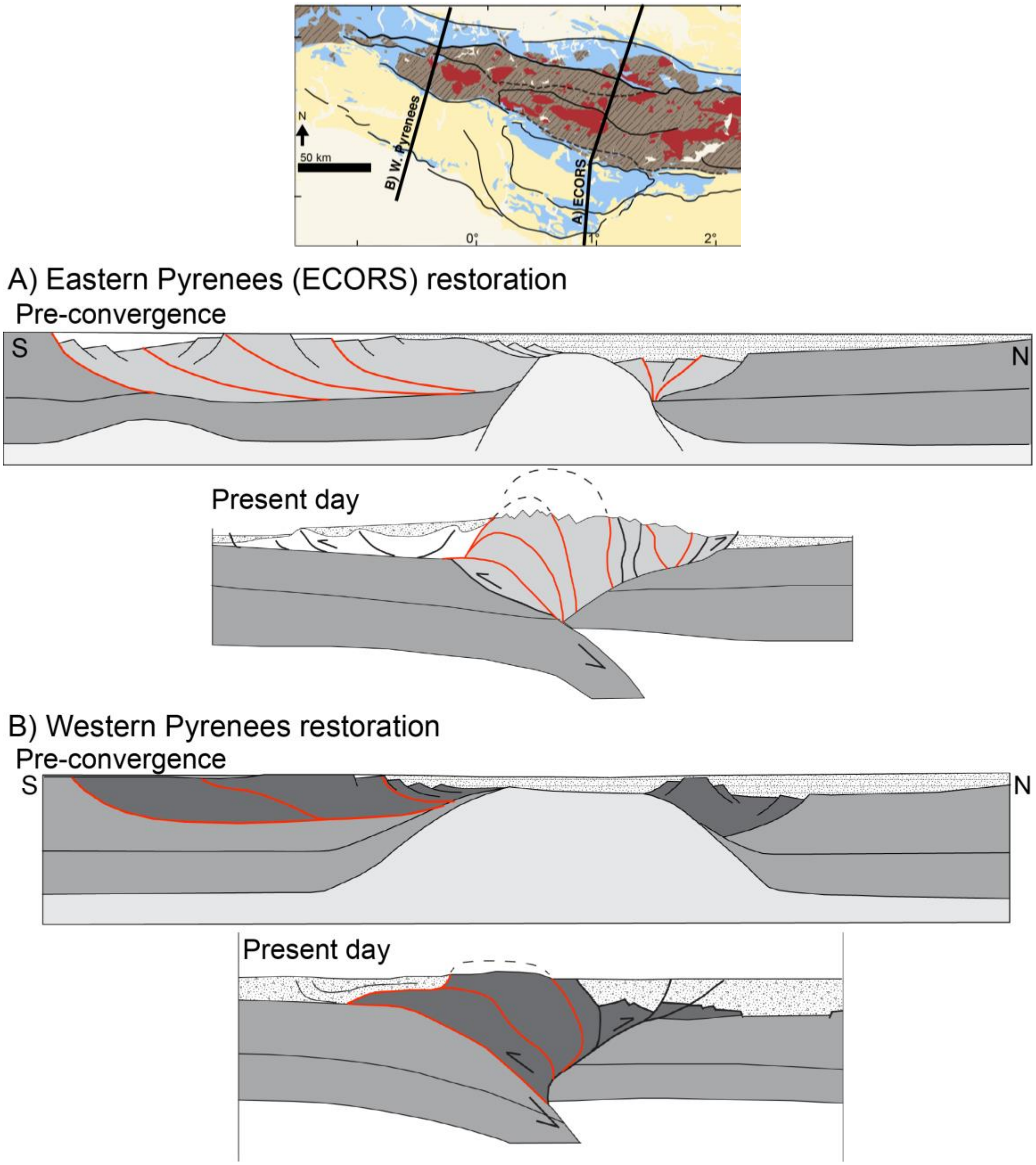

Figure DR4: Restored cross-sections and location map from A) eastern (our Zone 3) and B) western (our Zone 1) Pyrenees. Modified from Muñoz (1992), Sinclair et al. (2005), Jammes et al. (2014), Teixell et al. (2016).

Table DR2: Thermochronology data compilation

Longitude	Latitude	Elevation (meters)	AHe	AHe error	AFT	AFT error	ZHe	ZHe error	ZFT	ZFT error	EW Zone	Region	Sample type*	# Samples / # Grains	Reference
-0.44	42.953	677	6.6	0.8							Zone 1	Axial Zone	M-S	3 / 4	Bosch et al., 2016
-0.424	42.887	1066	10	6.1							Zone 1	Axial Zone	M-M	4 / 6	Bosch et al., 2016
-0.41	42.91	1208	10	3.0							Zone 1	Axial Zone	M-M	4 / 4	Bosch et al., 2016
-0.29	42.839	3147	15	3.4							Zone 1	Axial Zone	M-M	2 / 5	Bosch et al., 2016
-0.29	42.858	2080	6.3	1.0							Zone 1	Axial Zone	M-M	2 / 4	Bosch et al., 2016
-0.267	42.886	1417	9.3	5.6							Zone 1	Axial Zone	M-M	4 / 4	Bosch et al., 2016
-0.239	42.754	1614	6.3	0.5							Zone 1	Axial Zone	M-M	3 / 7	Bosch et al., 2016
0.106	42.804	2879	29	3.6							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.111	42.805	2707	14	2.6							Zone 2	Axial Zone	S-M	1 / 6	Fillon et al., in review
0.119	42.808	2423	11	0.9							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.151	42.816	2038	11	1.5							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.170	42.823	1864	10	1.8							Zone 2	Axial Zone	S-M	1 / 7	Fillon et al., in review
0.200	42.897	2032	15	3.0							Zone 2	Axial Zone	S-M	1 / 3	Fillon et al., in review
0.201	42.899	2013	18	6.2							Zone 2	Axial Zone	S-M	1 / 4	Fillon et al., in review
0.202	42.891	2135	16	2.9							Zone 2	Axial Zone	S-M	1 / 3	Fillon et al., in review
0.247	42.675	1532	8.1	1.0							Zone 2	Axial Zone	S-M	1 / 7	Fillon et al., in review
0.267	42.663	2528	16	1.3							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.28	42.669	2221	10	1.4							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.285	42.667	2209	9.6	1.7							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.368	42.877	1100	34	2.7							Zone 2	Axial Zone	S-S	1 / 1	Fillon et al., in review
0.379	42.890	779	51	12.1							Zone 2	Axial Zone	S-M	1 / 3	Fillon et al., in review
0.393	42.884	1209	32	10.9							Zone 2	Axial Zone	S-M	1 / 2	Fillon et al., in review
0.832	42.606	2735	24	1.4							Zone 3	Axial Zone	S-M	1 / 3	Metcalf et al., 2009
0.836	42.606	2605	25	1.5							Zone 3	Axial Zone	S-M	1 / 3	Metcalf et al., 2009
0.84	42.605	2495	25	1.4							Zone 3	Axial Zone	S-M	1 / 3	Metcalf et al., 2009
0.847	42.602	2210	23	1.4							Zone 3	Axial Zone	S-M	1 / 3	Metcalf et al., 2009
0.85	42.601	2080	21	0.5							Zone 3	Axial Zone	M-M	2 / 6	Metcalf et al., 2009
0.852	42.673	2090	44	3.5							Zone 3	Axial Zone	S-M	1 / 3	Metcalf et al., 2009
0.853	42.577	1620	18	3.9							Zone 3	Axial Zone	M-M	3 / 5	Metcalf et al., 2009
0.855	42.602	1945	22	1.4							Zone 3	Axial Zone	S-M	1 / 3	Metcalf et al., 2009
0.856	42.583	1680	19	0.5							Zone 3	Axial Zone	M-M	2 / 6	Metcalf et al., 2009
0.857	42.584	1780	19	0.4							Zone 3	Axial Zone	M-M	2 / 6	Metcalf et al., 2009
0.994	42.639	2120	19	1.3							Zone 3	Axial Zone	M-M	2 / 6	Metcalf et al., 2009
0.868	42.673	1480	28	2.2							Zone 3	Axial Zone	S-M	1 / 5	Gibson et al., 2007
0.869	42.673	1415	36	2.9							Zone 3	Axial Zone	M-M	2 / 11	Gibson, 2005 (Thesis)
0.976	42.705	2030	34	2.7							Zone 3	Axial Zone	M-M	3 / 21	Gibson et al., 2007
0.981	42.705	2200	32	2.6							Zone 3	Axial Zone	S-M	1 / 5	Gibson et al., 2007
0.983	42.706	2304	34	2.3							Zone 3	Axial Zone	S-M	1 / 7	Gibson et al., 2007
0.988	42.711	2440	38	3.0							Zone 3	Axial Zone	S-M	1 / 6	Gibson et al., 2007
0.993	42.513	2030	24	1.9							Zone 3	Axial Zone	M-M	2 / 26	Gibson et al., 2007
0.994	42.511	1920	25	2.0							Zone 3	Axial Zone	M-M	2 / 25	Gibson et al., 2007
1.001	42.51	2140	30	2.4							Zone 3	Axial Zone	S-M	1 / 8	Gibson et al., 2007
1.008	42.51	2250	28	2.3							Zone 3	Axial Zone	M-M	2 / 14	Gibson et al., 2007
1.013	42.512	2360	24	2.0							Zone 3	Axial Zone	S-M	1 / 5	Gibson et al., 2007
1.02	42.511	2440	26	2.0							Zone 3	Axial Zone	S-M	1 / 8	Gibson et al., 2007
1.024	42.518	2870	24	1.9							Zone 3	Axial Zone	S-M	3 / 20	Gibson et al., 2007
1.025	42.513	2650	32	2.5							Zone 3	Axial Zone	M-M	3 / 32	Gibson et al., 2007
1.025	42.514	2765	28	2.2							Zone 3	Axial Zone	M-M	2 / 13	Gibson et al., 2007
0.807	42.521	1750	23	2.0							Zone 3	Axial Zone	M-M	3 / 23	Gibson et al., 2007
0.808	42.52	1695	15	1.2							Zone 3	Axial Zone	M-M	2 / 23	Gibson et al., 2007
0.813	42.515	1150	11	1.0							Zone 3	Axial Zone	S-M	1 / 10	Gibson et al., 2007
1.618	42.752	1850	43	3.0							Zone 4	Axial Zone	M-M	3 / 9	Gunnel et al., 2009
1.666	42.43	1945	30	2.1							Zone 4	Axial Zone	M-M	4 / 8	Gunnel et al., 2009
1.98	42.711	2190	38	2.6							Zone 4	Axial Zone	M-M	3 / 9	Gunnel et al., 2009
1.763	42.488	2900	35	2.5							Zone 4	Axial Zone	M-M	2 / 4	Gunnel et al., 2009
1.744	42.631	2580	41	3.7							Zone 4	Axial Zone	M-M	2 / 20	Denèle, 2007 (PhD Thesis)
1.748	42.627	2783	34	3.1							Zone 4	Axial Zone	S-M	1 / 10	Denèle, 2007 (PhD Thesis)
1.766	42.61	2210	31	2.8							Zone 4	Axial Zone	M-M	2 / 20	Denèle, 2007 (PhD Thesis)
1.777	42.597	2000	31	2.8							Zone 4	Axial Zone	S-M	1 / 10	Denèle, 2007 (PhD Thesis)
1.785	42.591	1750	36	3.3							Zone 4	Axial Zone	M-M	2 / 20	Denèle, 2007 (PhD Thesis)
1.79	42.663	2250	36	3.2							Zone 4	Axial Zone	S-M	1 / 10	Denèle, 2007 (PhD Thesis)

*** S-S = Single sample, single grain; S-M = Single sample, multiple grain; M-M = Multiple sample, multiple grain; M-S = Multiple sample, single grain; NR = Not Reported**

Longitude	Latitude	Elevation (meters)	AHe	AHe error	AFT	AFT error	ZHe	ZHe error	ZFT	ZFT error	EW Zone	Region	Sample type*	# Samples / # Grains	Reference
1.792	42.588	1450	33	3.0							Zone 4	Axial Zone	M-M	2 / 20	Denèle, 2007 (PhD Thesis)
1.8	42.681	1800	35	3.2							Zone 4	Axial Zone	M-M	2 / 20	Denèle, 2007 (PhD Thesis)
1.803	42.686	1550	38	3.4							Zone 4	Axial Zone	S-M	1 / 10	Denèle, 2007 (PhD Thesis)
1.827	42.693	900	47	4.2							Zone 4	Axial Zone	M-M	2 / 20	Denèle, 2007 (PhD Thesis)
1.968	42.574	2320	39	2.0							Zone 4	Axial Zone	M-M	2 / 20	Maurel et al., 2008
-0.267	42.886	1417			22	1.1					Zone 1	Axial Zone	S-M	1 / 24	Bosch et al., 2016
-0.290	42.839	3137			29	1.4					Zone 1	Axial Zone	S-M	1 / 20	Bosch et al., 2016
-0.290	42.858	2080			28	1.8					Zone 1	Axial Zone	S-M	1 / 20	Bosch et al., 2016
-0.239	42.754	1614			21	0.9					Zone 1	Axial Zone	S-M	1 / 20	Bosch et al., 2016
-0.424	42.887	1066			12	1.1					Zone 1	Axial Zone	S-M	1 / 15	Bosch et al., 2016
-0.410	42.910	1208			22	1.2					Zone 1	Axial Zone	S-M	1 / 22	Bosch et al., 2016
-0.440	42.953	677			22	1.6					Zone 1	Axial Zone	S-M	1 / 13	Bosch et al., 2016
0.085	42.941	1838			18	1.5					Zone 2	Axial Zone	S-M	1 / 8	Mouchene, 2016 (PhD thesis)
0.086	42.943	1669			22	2.1					Zone 2	Axial Zone	S-M	1 / 15	Mouchene, 2016 (PhD thesis)
0.087	42.961	1082			18	1.2					Zone 2	Axial Zone	S-M	1 / 20	Mouchene, 2016 (PhD thesis)
0.090	42.950	1420			15	1.0					Zone 2	Axial Zone	S-M	1 / 20	Mouchene, 2016 (PhD thesis)
0.35	42.88	900			32	2.2					Zone 2	Axial Zone	S-M	1 / 20	Jolivet et al., 2007
0.08	42.85	3100			35	2.3					Zone 2	Axial Zone	S-M	1 / 20	Jolivet et al., 2007
0.13	42.83	1900			22	1.4					Zone 2	Axial Zone	S-M	1 / 20	Jolivet et al., 2007
0.15	42.9	2100			28	2.1					Zone 2	Axial Zone	S-M	1 / 20	Jolivet et al., 2007
0.18	42.72	1400			11	1.1					Zone 2	Axial Zone	S-M	1 / 20	Jolivet et al., 2007
0.976	42.705	2030			32	2.8					Zone 3	Axial Zone	S-M	1 / 24	Sinclair et al., 2005
0.981	42.705	2200			28	2.4					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
0.983	42.706	2304			35	3.6					Zone 3	Axial Zone	S-M	1 / 24	Sinclair et al., 2005
0.988	42.711	2440			39	3.2					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
0.99	42.507	1750			29	3.1					Zone 3	Axial Zone	S-M	1 / 24	Sinclair et al., 2005
0.993	42.714	2635			32	2.8					Zone 3	Axial Zone	S-M	1 / 20	Sinclair et al., 2005
0.993	42.513	2030			28	2.5					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
1.008	42.51	2250			29	3.0					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
1.024	42.518	2870			33	3.4					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
0.807	42.521	1780			21	3.7					Zone 3	Axial Zone	S-M	1 / 17	Sinclair et al., 2005
0.808	42.52	1695			20	3.2					Zone 3	Axial Zone	S-M	1 / 17	Sinclair et al., 2005
0.813	42.515	1150			21	2.0					Zone 3	Axial Zone	S-M	1 / 24	Sinclair et al., 2005
1.092	42.386	1280			26	3.1					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
1.097	42.388	1085			24	3.9					Zone 3	Axial Zone	S-M	1 / 25	Sinclair et al., 2005
1.101	42.389	960			17	3.4					Zone 3	Axial Zone	S-M	1 / 9	Sinclair et al., 2005
0.832	42.608	2850			31	3.0					Zone 3	Axial Zone	S-M	1 / 19	Fitzgerald et al., 1999
0.832	42.606	2735			30	3.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.836	42.606	2605			33	3.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.84	42.605	2495			32	3.0					Zone 3	Axial Zone	S-M	1 / 22	Fitzgerald et al., 1999
0.843	42.603	2355			34	4.0					Zone 3	Axial Zone	S-M	1 / 9	Fitzgerald et al., 1999
0.846	42.568	1500			26	3.0					Zone 3	Axial Zone	S-M	1 / 19	Fitzgerald et al., 1999
0.847	42.602	2210			32	3.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.851	42.601	2080			32	2.0					Zone 3	Axial Zone	S-M	1 / 21	Fitzgerald et al., 1999
0.853	42.577	1620			29	3.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.855	42.602	1945			32	2.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.857	42.584	1400			26	2.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.857	42.584	1780			31	3.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
1.05	42.806	1340			39	3.0					Zone 3	Axial Zone	S-M	1 / 25	Fitzgerald et al., 1999
1.052	42.808	1460			36	2.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
1.053	42.809	1595			37	2.0					Zone 3	Axial Zone	S-M	1 / 25	Fitzgerald et al., 1999
1.068	42.796	2050			41	3.0					Zone 3	Axial Zone	S-M	1 / 25	Fitzgerald et al., 1999
1.069	42.796	2205			42	4.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
1.072	42.802	2483			44	4.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
1.073	42.797	2340			41	3.0					Zone 3	Axial Zone	S-M	1 / 18	Fitzgerald et al., 1999
0.812	42.514	1125			21	3.0					Zone 3	Axial Zone	S-M	1 / 5	Fitzgerald et al., 1999
0.818	42.526	1365			25	3.0					Zone 3	Axial Zone	S-M	1 / 20	Fitzgerald et al., 1999
0.819	42.522	1255			22	3.0					Zone 3	Axial Zone	S-M	1 / 19	Fitzgerald et al., 1999
0.855	42.673	2164			30	2.1					Zone 3	Axial Zone	S-M	1 / 24	Gibson et al., 2007
0.862	42.675	1880			32	2.7					Zone 3	Axial Zone	S-M	1 / 24	Gibson et al., 2007
0.867	42.675	1555			29	1.6					Zone 3	Axial Zone	S-M	1 / 23	Gibson et al., 2007

*** S-S = Single sample, single grain; S-M = Single sample, multiple grain; M-M = Multiple sample, multiple grain; M-S = Multiple sample, single grain; NR = Not Reported**

Longitude	Latitude	Elevation (meters)	AHe	AHe error	AFT	AFT error	ZHe	ZHe error	ZFT	ZFT error	EW Zone	Region	Sample type*	# Samples / # Grains	Reference
0.872	42.677	1315			30	1.9					Zone 3	Axial Zone	S-M	1 / 22	Gibson et al., 2007
0.679	42.458	1250			26	3.1					Zone 3	Axial Zone	S-M	1 / 25	Gibson et al., 2007
0.846	42.414	1490			30	2.7					Zone 3	Axial Zone	S-M	1 / 24	Gibson et al., 2007
0.851	42.413	1580			26	3.6					Zone 3	Axial Zone	S-M	1 / 25	Gibson et al., 2007
0.92	42.398	1540			30	4.1					Zone 3	Axial Zone	S-M	1 / 39	Gibson et al., 2007
0.921	42.402	1490			28	3.7					Zone 3	Axial Zone	S-M	1 / 40	Gibson et al., 2007
1.980	42.711	2190			55	4.4					Zone 4	Axial Zone	S-M	1 / 20	Gunnel et al., 2009
1.705	42.715	1939			41	1.7					Zone 4	Axial Zone	S-M	1 / 20	Gunnel et al., 2009
1.618	42.785	1850			50	2.5					Zone 4	Axial Zone	S-M	1 / 20	Gunnel et al., 2009
1.423	42.772	1938			59	4.7					Zone 4	Axial Zone	S-M	1 / 20	Gunnel et al., 2009
1.763	42.488	2900			50	3.2					Zone 4	Axial Zone	S-M	1 / 18	Gunnel et al., 2009
1.763	42.488	2900			51	3.8					Zone 4	Axial Zone	S-M	1 / 20	Gunnel et al., 2009
1.862	42.521	2377			35	2.5					Zone 4	Axial Zone	S-M	1 / 11	Gunnel et al., 2009
1.666	42.43	1950			33	1.8					Zone 4	Axial Zone	S-M	1 / 19	Gunnel et al., 2009
-0.211	42.784	2449			23	1.6					Zone 1	Axial Zone	NR	NR	Herman et al., 2013
0.165	42.824	1977			19	1.3					Zone 2	Axial Zone	NR	NR	Herman et al., 2013
0.927	42.768	2490			17	4.5					Zone 3	Axial Zone	NR	NR	Herman et al., 2013
1.862	42.703	1122			40	4.2					Zone 4	Axial Zone	NR	NR	Herman et al., 2013
1.844	42.689	1331			31	1.5					Zone 4	Axial Zone	NR	NR	Herman et al., 2013
0.128	42.959	88			36	2.5					Zone 2	Axial Zone	S-M	1 / 16	Morris et al., 1998; Yelland, 1991
0.22	42.716	1020			16	1.5					Zone 2	Axial Zone	S-M	1 / 19	Morris et al., 1998; Yelland, 1991
0.917	42.568	1635			36	3.4					Zone 3	Axial Zone	S-M	1 / 15	Morris et al., 1998; Yelland, 1991
0.844	42.5	1718			24	1.3					Zone 3	Axial Zone	S-M	1 / 15	Morris et al., 1998; Yelland, 1991
1.862	42.676	1000			27	1.3					Zone 4	Axial Zone	S-M	1 / 10	Morris et al., 1998; Yelland, 1991
1.789	42.649	1143			28	1.7					Zone 4	Axial Zone	S-M	1 / 20	Morris et al., 1998; Yelland, 1991
1.752	42.716	935			32	1.1					Zone 4	Axial Zone	S-M	1 / 20	Morris et al., 1998; Yelland, 1991
1.862	42.689	900			35	1.8					Zone 4	Axial Zone	S-M	1 / 12	Morris et al., 1998; Yelland, 1991
1.716	42.73	1160			35	1.9					Zone 4	Axial Zone	S-M	1 / 14	Morris et al., 1998; Yelland, 1991
1.752	42.568	1980			28	1.5					Zone 4	Axial Zone	S-M	1 / 15	Morris et al., 1998; Yelland, 1991
-0.468	42.851	1660			21	1.5					Zone 1	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
-0.193	42.77	2693			22	1.5					Zone 1	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.147	42.973	1645			38	3.0					Zone 2	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.385	42.878	700			35	2.8					Zone 2	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.11	42.838	2110			24	1.6					Zone 2	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.12	42.858	2321			27	1.8					Zone 2	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.147	42.811	2227			28	1.9					Zone 2	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.899	42.676	2104			27	1.7					Zone 3	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.734	42.541	1141			26	2.9					Zone 3	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
0.752	42.541	1631			30	3.5					Zone 3	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
1.767	42.664	1812			42	2.2					Zone 4	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
1.826	42.581	2353			24	1.3					Zone 4	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
1.807	42.514	1852			38	2.2					Zone 4	Axial Zone	S-M	NR	Morris et al., 1998; Yelland, 1991
-0.267	42.886	1417					26	6.5			Zone 1	Axial Zone	S-M	1 / 4	Bosch et al., 2016
-0.29	42.839	3147					22	1.2			Zone 1	Axial Zone	S-M	1 / 3	Bosch et al., 2016
-0.29	42.858	2080					22	1.7			Zone 1	Axial Zone	S-M	1 / 3	Bosch et al., 2016
-0.239	42.754	1614					24	2.3			Zone 1	Axial Zone	S-M	1 / 2	Bosch et al., 2016
-0.424	42.887	1066					26	2.0			Zone 1	Axial Zone	S-M	1 / 3	Bosch et al., 2016
-0.41	42.91	1208					23	1.8			Zone 1	Axial Zone	S-M	1 / 3	Bosch et al., 2016
-0.44	42.953	677					22	1.7			Zone 1	Axial Zone	S-M	1 / 3	Bosch et al., 2016
-0.408	43.018	559					28	2.2			Zone 1	Axial Zone	S-M	1 / 2	Bosch et al., 2016
0.11	42.8	2879					29	1.7			Zone 2	Axial Zone	S-M	1 / 8	Pik et al., 2016
0.11	42.8	2754					25	1.5			Zone 2	Axial Zone	S-M	1 / 6	Pik et al., 2016
0.11	42.81	2707					29	1.8			Zone 2	Axial Zone	S-M	1 / 15	Pik et al., 2016
0.12	42.81	2423					29	1.7			Zone 2	Axial Zone	S-M	1 / 20	Pik et al., 2016
0.15	42.82	2038					31	1.8			Zone 2	Axial Zone	S-M	1 / 10	Pik et al., 2016
0.17	42.82	1864					35	2.1			Zone 2	Axial Zone	S-M	1 / 11	Pik et al., 2016
0.21	42.68	1099					20	1.2			Zone 2	Axial Zone	S-M	1 / 20	Pik et al., 2016
0.22	42.64	895					18	1.1			Zone 2	Axial Zone	S-M	1 / 26	Pik et al., 2016
0.23	42.67	1309					22	1.3			Zone 2	Axial Zone	S-M	1 / 15	Pik et al., 2016
0.25	42.68	1532					27	1.6			Zone 2	Axial Zone	S-M	1 / 24	Pik et al., 2016
0.27	42.66	2528					35	2.1			Zone 2	Axial Zone	S-M	1 / 20	Pik et al., 2016
0.27	42.68	1831					21	1.3			Zone 2	Axial Zone	S-M	1 / 3	Pik et al., 2016

*** S-S = Single sample, single grain; S-M = Single sample, multiple grain; M-M = Multiple sample, multiple grain; M-S = Multiple sample, single grain; NR = Not Reported**

0.28	42.67	2221					41	2.5			Zone 2	Axial Zone	S-M	1 / 19	Pik et al., 2016
0.29	42.67	2209					38	2.3			Zone 2	Axial Zone	S-M	1 / 13	Pik et al., 2016
1.968	42.574	2320					46	3.7			Zone 4	Axial Zone	S-M	1 / 2	Maurel et al., 2008
-0.226	42.77	2449							41	4.1	Zone 1	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
0.08	42.85	2700							33	3.3	Zone 2	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
0.15	42.84	2700							35	3.5	Zone 2	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
0.111	42.805	2707							46	2.5	Zone 2	Axial Zone	S-M	1 / 24	Fillon et al., in review
0.119	42.808	2423							45	2.3	Zone 2	Axial Zone	S-M	1 / 23	Fillon et al., in review
0.17	42.823	1864							46	2.0	Zone 2	Axial Zone	S-M	1 / 48	Fillon et al., in review
0.993	42.714	2635							50	3.1	Zone 3	Axial Zone	S-M	1 / 20	Sinclair et al., 2005
0.99	42.507	1750							49	2.6	Zone 3	Axial Zone	S-M	1 / 20	Sinclair et al., 2005
0.767	42.59	1700							32	3.2	Zone 3	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
0.901	42.59	1700							41	4.1	Zone 3	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
1.768	42.51	2000							36	3.6	Zone 4	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
1.818	42.49	2000							37	3.7	Zone 4	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
1.777	42.6	2000							43	4.3	Zone 4	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
1.792	42.59	2000							39	3.9	Zone 4	Axial Zone	S-M	NR	Yelland, 1991 (PhD thesis)
0.267	42.663	2528							161	16	Zone 2	Axial Zone	S-M	1 / 15	Fillon et al., in review
0.247	42.675	1532							143	7.7	Zone 2	Axial Zone	S-M	1 / 33	Fillon et al., in review
0.813	42.515	1150							104	7.0	Zone 3	Axial Zone	S-M	1 / 16	Sinclair et al., 2005
1.105	42.391	805							159	33	Zone 3	Axial Zone	S-M	1 / 3	Sinclair et al., 2005

NORTH PYRENEAN ZONE

Longitude	Latitude	Elevation (meters)	AHe	AHe error	AFT	AFT error	ZHe	ZHe error	ZFT	ZFT error	EW Zone	Region	Sample type*	# Samples / # Grains	Reference
1.44	42.831	2199	43	3.5								NPZ	S-M	1 / 4	Vacherat et al., 2016
1.44	42.827	2068	34	2.7								NPZ	S-M	1 / 4	Vacherat et al., 2016
1.441	42.824	1915	40	3.2								NPZ	S-M	1 / 5	Vacherat et al., 2016
1.439	42.821	1772	38	3.0								NPZ	S-S	1 / 1	Vacherat et al., 2016
1.436	42.818	1700	33	2.7								NPZ	S-M	1 / 4	Vacherat et al., 2016
1.437	42.813	1598	51	4.1								NPZ	S-M	1 / 3	Vacherat et al., 2016
1.442	42.805	1459	36	2.9								NPZ	S-M	1 / 4	Vacherat et al., 2016
1.247	42.86	552	44	3.5								NPZ	S-M	1 / 1	Vacherat et al., 2016
1.177	42.934	451	35	2.8								NPZ	S-M	1 / 4	Vacherat et al., 2016
1.214	42.908	493	34	3.0								NPZ	S-M	1 / 3	Vacherat et al., 2016
1.533	42.965	488	47	4.4								NPZ	S-M	1 / 3	Vacherat et al., 2016
1.133	42.933	1048			55	3.0						NPZ	S-M	1 / 25	Fitzgerald et al., 1999
1.202	42.943	815			50	3.0						NPZ	S-M	1 / 25	Fitzgerald et al., 1999
1.214	42.933	950			49	3.0						NPZ	S-M	1 / 24	Fitzgerald et al., 1999
1.215	42.94	645			49	2.0						NPZ	S-M	1 / 25	Fitzgerald et al., 1999
1.202	42.878	500			34	1.6						NPZ	S-M	1 / 17	Morris et al., 1998
1.551	42.959	455			106	5.3						NPZ	S-M	1 / 20	Morris et al., 1998
1.312	42.838	945			38	1.9						NPZ	S-M	1 / 25	Morris et al., 1998
1.147	42.905	520			40	1.7						NPZ	S-M	1 / 15	Morris et al., 1998
1.422	42.811	1604			35	2.2						NPZ	NR	NR	Yelland, 1991 (PhD thesis)
0.073	43.068	645			42	2.4						NPZ	NR	NR	Yelland, 1991 (PhD thesis)
1.679	42.824	1113			43	3.0						NPZ	NR	NR	Yelland, 1991 (PhD thesis)
1.385	43.027	426			118	12						NPZ	NR	NR	Yelland, 1991 (PhD thesis)
0.375	42.982	626			35	2.3						NPZ	S-M	1 / 21	Mouchene, 2016 (PhD thesis)
0.595	42.957	677			38	6.0						NPZ	S-M	1 / 12	Mouchene, 2016 (PhD thesis)
1.440	42.831	2199			47	4.7						NPZ	S-M	1 / 20	Vacherat et al., 2016
1.440	42.827	2068			37	2.2						NPZ	S-M	1 / 22	Vacherat et al., 2016
1.441	42.824	1915			46	4.0						NPZ	S-M	1 / 20	Vacherat et al., 2016
1.439	42.821	1772			38	2.4						NPZ	S-M	1 / 27	Vacherat et al., 2016
1.436	42.818	1700			35	2.4						NPZ	S-M	1 / 31	Vacherat et al., 2016
1.437	42.813	1598			42	1.9						NPZ	S-M	1 / 20	Vacherat et al., 2016
1.941	42.805	1459			42	3.4						NPZ	S-M	1 / 27	Vacherat et al., 2016
1.247	42.860	552			39	1.9						NPZ	S-M	1 / 20	Vacherat et al., 2016
1.177	42.934	451			44	2.1						NPZ	S-M	1 / 56	Vacherat et al., 2016
1.214	42.908	493			39	1.8						NPZ	S-M	1 / 31	Vacherat et al., 2016
1.533	42.964	488			75	7.0						NPZ	S-M	1 / 29	Vacherat et al., 2016

*** S-S = Single sample, single grain; S-M = Single sample, multiple grain; M-M = Multiple sample, multiple grain; M-S = Multiple sample, single grain; NR = Not Reported**

Longitude	Latitude	Elevation (meters)	AHe	AHe error	AFT	AFT error	ZHe	ZHe error	ZFT	ZFT error	EW Zone	Region	Sample type*	# Samples / # Grains	Reference
1.44	42.831	2199					89	18				NPZ	S-M	1 / 2	Vacherat et al., 2016
1.44	42.827	2068					68	17				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.441	42.824	1915					78	16				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.439	42.821	1772					60	3.8				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.436	42.818	1700					68	4.2				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.247	42.86	552					35	16				NPZ	S-M	1 / 2	Vacherat et al., 2016
1.177	42.934	451					60	18				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.214	42.908	493					43	7.0				NPZ	S-M	1 / 2	Vacherat et al., 2016
1.533	42.965	488					41	23				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.396	42.908	981					55	15				NPZ	S-M	1 / 3	Vacherat et al., 2016
1.364	42.838	1500					36	5.8				NPZ	S-M	1 / 3	Vacherat et al., 2016
-0.275	43.103	439					44	5.0				NPZ	S-M	1 / 3	Bosch et al., 2016
-0.252	43.152	317					220	55				NPZ	S-M	1 / 3	Bosch et al., 2016
-0.320	43.069	778					36	3.0				NPZ	S-M	1 / 3	Bosch et al., 2016
-0.234	43.119	367					38	4.1				NPZ	S-M	1 / 3	Bosch et al., 2016
-0.287	43.172	266					205	60				NPZ	S-M	1 / 3	Bosch et al., 2016
-0.408	43.018	559					28	2.3				NPZ	S-M	1 / 2	Bosch et al., 2016
1.44	42.831	2199							153	18		NPZ	S-M	1 / 9	Vacherat et al., 2016
1.44	42.827	2068							106	7.9		NPZ	S-M	1 / 19	Vacherat et al., 2016
1.441	42.824	1915							109	7.4		NPZ	S-M	1 / 27	Vacherat et al., 2016
1.439	42.821	1772							101	5.7		NPZ	S-M	1 / 32	Vacherat et al., 2016
1.436	42.818	1700							105	5.7		NPZ	S-M	1 / 38	Vacherat et al., 2016
1.247	42.86	552							169	19		NPZ	S-M	1 / 12	Vacherat et al., 2016
1.177	42.934	451							156	10		NPZ	S-M	1 / 27	Vacherat et al., 2016
1.214	42.8745	493							135	14		NPZ	S-M	1 / 8	Vacherat et al., 2016
1.533	42.965	488							168	29		NPZ	S-M	1 / 7	Vacherat et al., 2016
1.396	42.908	981							90	5.9		NPZ	S-M	1 / 26	Vacherat et al., 2016

*** S-S = Single sample, single grain; S-M = Single sample, multiple grain; M-M = Multiple sample, multiple grain; M-S = Multiple sample, single grain; NR = Not Reported**

Thermochronology references: (Fillon et al., *in review*; Yelland, 1991; Morris et al., 1998; Fitzgerald et al., 1999; Sinclair et al., 2005; Denèle, 2007; Gibson et al., 2007; Jolivet et al., 2007; Maurel et al., 2008; Gunnell et al., 2009; Metcalf et al., 2009; Herman et al., 2013; Bosch et al., 2016; Mouchené, 2016; Pik et al., 2016; Vacherat et al., 2016)

Table DR3. Model parameters

Parameter	Value	Unit
Crustal density	2800	kg/m^3
Mantle density	3300	kg/m^3
Young's modulus	10^{11}	Pa
Poisson's ratio	0.3	
Thermal diffusivity	25	km^2/Myr
Crustal thickness	45	km
Basal crustal temperature	810	°C
Sea level temperature	10	°C
Atmospheric lapse rate	4	°C/km
Crustal heat production	0.95	μW/m^3
Elastic plate thickness	20	km

SUPPLEMENTAL REFERENCES

Bosch, G. V., Teixell, A., Jolivet, M., Labaume, P., Stockli, D., Domènech, M., and Monié, P., 2016, Timing of Eocene–Miocene thrust activity in the Western Axial Zone and Chaînons Béarnais (west-central Pyrenees) revealed by multi-method thermochronology: Comptes Rendus Geoscience, v. 348, p. 246–256, doi:10.1016/j.crte.2016.01.001.

Braun, J., 2003, Pecube: a new finite-element code to solve the 3D heat transport equation including the effects of a time-varying, finite amplitude surface topography: Computers & Geosciences, v. 29, p. 787–794, doi:10.1016/S0098-3004(03)00052-9.

Curry, M.E., van der Beek, P., Huismans, R.S., Wolf, S.G., and Muñoz, J.-A., 2019, Evolving paleotopography and lithospheric flexure of the Pyrenean Orogen from 3D flexural modeling and basin analysis: Earth and Planetary Science Letters, v. 515, p. 26–37, doi:10.1016/j.epsl.2019.03.009.

Denèle, Y., 2007, Formation des dômes gneissiques hercyniens dans les Pyrénées : exemple du massif de l'Aston-Hospitalet [Ph.D. Thesis]: Université de Toulouse Paul Sabatier.

England, P., and Molnar, P., 1990, Surface uplift, uplift of rocks, and exhumation of rocks: Geology, v. 18, p. 1173–1177, doi:10.1130/0091-7613(1990)018<1173:SUUORA>2.3.CO;2.

Fillon, C., and van der Beek, P., 2012, Post-orogenic evolution of the southern Pyrenees: constraints from inverse thermo-kinematic modelling of low-temperature thermochronology data: Basin Research, v. 24, p. 418–436, doi:10.1111/j.1365-2117.2011.00533.x.

Fillon, C., Mouthereau, F., Calassou, S., Pik, R., Bellahsen, N., Gautheron, C., Stockli, D., Mouchene, M., and van der Beek, P., *in review*, Extensional control on contrasted post-orogenic exhumation of the Pyrenees and its foreland

Fitzgerald, P.G., Muñoz, J.A., Coney, P.J., and Baldwin, S.L., 1999, Asymmetric exhumation across the Pyrenean Orogen; implications for the tectonic evolution of a collisional orogen: Earth and Planetary Science Letters, v. 173, p. 157–170.

Gibson, M., Sinclair, H.D., Lynn, G.J., and Stuart, F.M., 2007, Late- to post-orogenic exhumation of the

Central Pyrenees revealed through combined thermochronological data and modelling: Basin Research, v. 19, p. 323–334, doi:10.1111/j.1365-2117.2007.00333.x.

Glotzbach, C., van der Beek, P.A., and Spiegel, C., 2011, Episodic exhumation and relief growth in the Mont Blanc massif, Western Alps from numerical modelling of thermochronology data: Earth and Planetary Science Letters, v. 304, p. 417–430, doi:10.1016/j.epsl.2011.02.020.

Gunnell, Y., Calvet, M., Brichau, S., Carter, A., Aguilar, J.-P., and Zeyen, H., 2009, Low long-term erosion rates in high-energy mountain belts: Insights from thermo- and biochronology in the Eastern Pyrenees:, doi:10.1016/j.epsl.2008.12.004.

Herman, F., Seward, D., Valla, P.G., Carter, A., Kohn, B., Willett, S.D., and Ehlers, T.A., 2013, Worldwide acceleration of mountain erosion under a cooling climate: Nature, v. 504, p. 423–426, doi:10.1038/nature12877.

Jammes, S., Huismans, R.S., and Muñoz, J.A., 2014, Lateral variation in structural style of mountain building: controls of rheological and rift inheritance: Terra Nova, v. 26, p. 201–207, doi:10.1111/ter.12087.

Jolivet, M., Labaume, P., Monié, P., Brunel, M., Arnaud, N., and Campani, M., 2007, Thermochronology constraints for the propagation sequence of the south Pyrenean basement thrust system (France-Spain): Tectonics, v. 26, doi:10.1029/2006TC002080.

Maurel, O., Moniè, P., Pik, R., Arnaud, N., Brunel, M., and Jolivet, M., 2008, The Meso-Cenozoic thermo-tectonic evolution of the Eastern Pyrenees: an 40Ar/39Ar fission track and (U–Th)/He thermochronological study of the Canigou and Mont-Louis massifs: International Journal of Earth Sciences, v. 97, p. 565–584, doi:10.1007/s00531-007-0179-x.

Metcalf, J.R., Fitzgerald, P.G., Baldwin, S.L., and Muñoz, J.-A., 2009, Thermochronology of a convergent orogen: Constraints on the timing of thrust faulting and subsequent exhumation of the Maladeta Pluton in the Central Pyrenean Axial Zone: Earth and Planetary Science Letters, v. 287, p. 488–503, doi:10.1016/j.epsl.2009.08.036.

Morris, R.G., Sinclair, H.D., and Yelland, A.J., 1998, Exhumation of the Pyrenean orogen: implications for sediment discharge: Basin Reseach, v. 10, p. 69–85, doi:10.1046/j.1365-2117.1998.00053.x.

Mouchené, M., 2016, Evolution post-orogenique du systeme couple piemont/bassin versant : le ḿega-cone alluvial de Lannemezan et son bassin versant au Nord des Pyrenees [Ph.D. Thesis]: Université Grenoble Alpes.

Muñoz, J.A., 1992, Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section, *in* McClay, K.R. ed., Thrust Tectonics, London, Chapman & Hall, p. 235–246.

Pik, R., Zimmerman, L., Bellahsen, N., Vacherat, A., Ternois, S., Mouthereau, F., and Ford, M., 2016, Damages dependent sensitivity of Zircon (U-Th)/He ages to thermal processes: the case of Pyrenean samples, *in* Geophysical Research Abstracts, EGU General Assembly, doi: 10.24396/ORDAR-52.

Sambridge, M., 1999a, Geophysical inversion with a neighbourhood algorithm—I. Searching a parameter space: Geophysical Journal International, v. 138, p. 479–494, doi:10.1046/j.1365-246X.1999.00876.x.

Sambridge, M., 1999b, Geophysical inversion with a neighbourhood algorithm—II. Appraising the ensemble: Geophysical Journal International, v. 138, p. 727–746, doi:10.1046/j.1365-246x.1999.00900.x.

Sinclair, H.D., Gibson, M., Naylor, M., and Morris, R.G., 2005, Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes: American Journal of Science , v. 305, p. 369–406, doi:10.2475/ajs.305.5.369.

Teixell, A., Labaume, P., and Lagabrielle, Y., 2016, The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario: Comptes Rendus Geoscience, v. 348, p. 257–267, doi:10.1016/j.crte.2015.10.010.

Vacherat, A. et al., 2016, Rift-to-collision transition recorded by tectonothermal evolution of the northern Pyrenees: Tectonics, v. 35, p. 907–933, doi:10.1002/2015TC004016.

Valla, P.G., Herman, F., van der Beek, P.A., and Braun, J., 2010, Inversion of thermochronological age-elevation profiles to extract independent estimates of denudation and relief history — I: Theory and conceptual model: Earth and Planetary Science Letters, v. 295, p. 511–522, doi:10.1016/j.epsl.2010.04.033.

Yelland, A.J., 1991, Thermo-tectonics of the Pyrenees and Provence from fission track studies [Ph.D. Thesis]: University of London.