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Long-Lasting Plutonism During Orogenic Cycles: Incremental Emplacement of the Variscan Bassiès Pluton (Central Pyrenees, France)

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ABSTRACT

Laser ablation U–Pb single zircon geochronology was applied to four peraluminous granite and granodiorite samples from the Bassiès pluton in the Central Pyrenees (France) yielding a wide range of concordant ages from early Carboniferous (Tournaisian, 351 Ma) to early Permian (Artinskian, 285 Ma). Emplacement of the Bassiès pluton occurred incrementally during the main Variscan deformation phase, with increased activities every 7–15 Myr and a peak at around 321 Ma. Evolution of the Bassiès pluton is more complex than the previously published single age of 312 Ma implied, underscoring the importance of synorogenic Variscan magmatism within the Axial Zone. Supported by geochronologic data from other plutons and gneiss domes, the notion that magmatism in the Axial Zone was confined to the late- to post-orogenic phase (315–295 Ma) is refuted. A possible thermal source for the long-lasting widespread plutonism in the Variscan crust is the TUZO mantle plume.

1 | Introduction

In contrast to other Phanerozoic orogens (e.g., Von Blanckenburg et al. 1998; Kalsbeek et al. 2001; Rosenberg 2004; Oliver et al. 2008), synorogenic plutonism in mid- and upper crustal levels of the Variscan orogen is widespread, suggesting an exceptional thermal structure. In the Pyrenean Axial Zone, more than 30 plutons cover approximately 20% of the area (Figure 1a). Timing of pluton emplacement provides important age constraints for the tectonometamorphic evolution of the Variscan Pyrenees (e.g., Mezger and Régnier 2016). Recent laser ablation U–Pb single zircon studies of plutons (Bossòst, Soulcem) and dikes intruding the Aston gneiss dome (Mezger and Gerdes 2016; Schnapperelle et al. 2020) have shown that the magmatic history of the Variscan Pyrenees extends beyond the previously proposed 15 Myr (e.g., Denèle et al. 2014).

A key area to study possible long-term magmatic activity in the Axial Zone is the Bassiès pluton whose shape and magnetic fabric suggest that it was emplaced prior to or early during the major Variscan deformation phase D_2 (Evans et al. 1997; Gleizes et al. 1997). A single U–Pb zircon ID-TIMS age of 312 ± 2 Ma has been interpreted as the emplacement age of the pluton (Paquette et al. 1997). However, the pluton's compositional zoning, leucogranite centre and granodiorite rim suggest multiple emplacement events or phases instead of one singular event. In this study, we apply whole rock geochemical analyses and laser ablation U–Pb geochronology on single zircons from four granitoid samples of the Bassiès pluton. The resulting range of zircon ages covers most of the Variscan orogeny from the Visean to the early Permian, raising the important question about the source for the long-term magmatic activity.

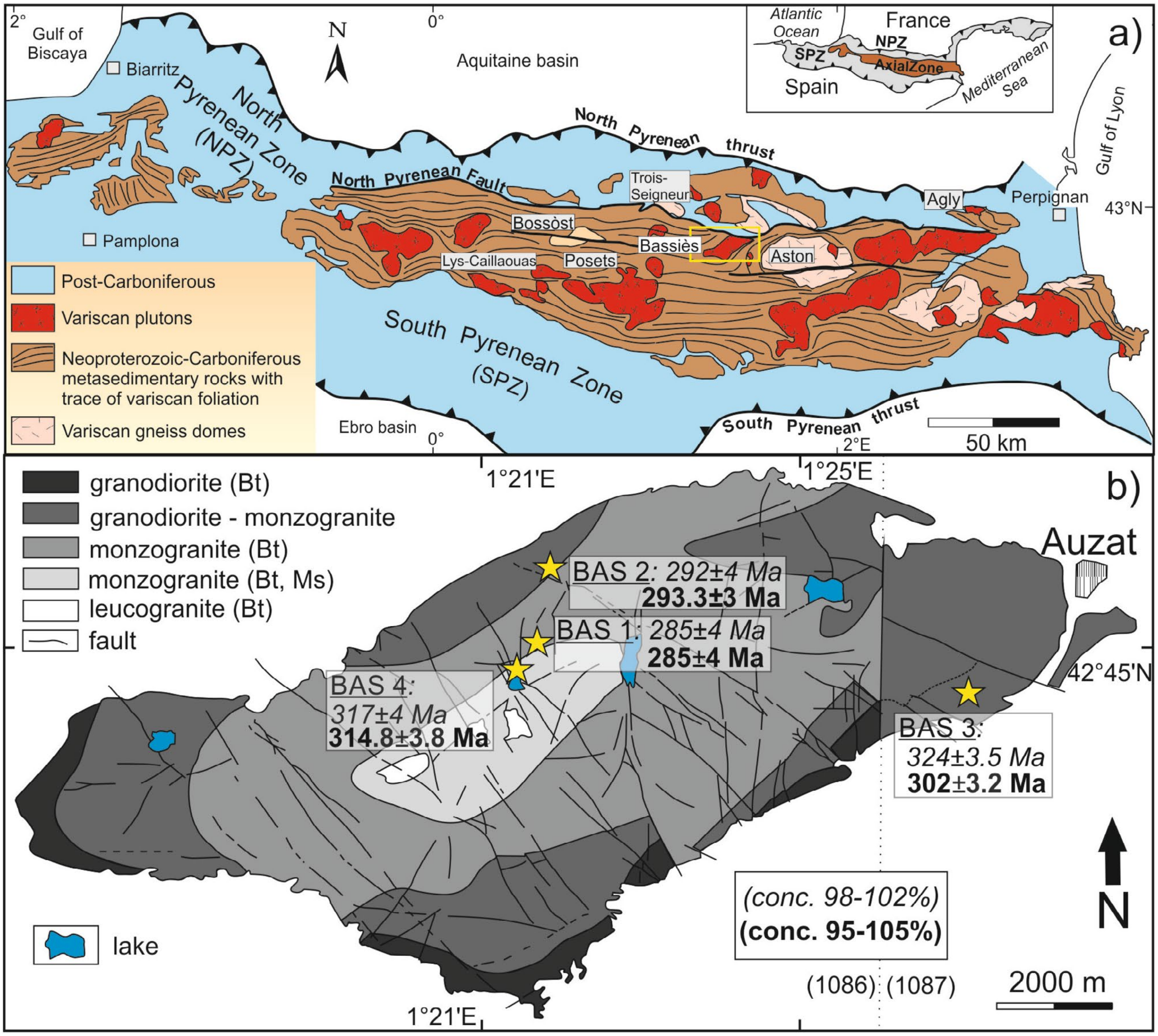

FIGURE 1 | (a) Major lithotectonic units of the Pyrenean Axial Zone (Baudin et al. 2008, modified after Mezger (2009)). Rectangle indicates location of Bassiès pluton. (b) Map of the Bassiès pluton showing compositional zonation and major faults. Modified after Colchem et al. (1997) and Casteras et al. (1969), BGRM maps 1086 and 1087. Note that there is no compositional zonation in map 1087. Stars indicate locations of analysed samples. For each sample, the youngest U–Pb zircon age is shown. Ages in italics indicate 98%–102%, bold indicates 95%–105% concordance. [Colour figure can be viewed at wileyonlinelibrary.com]

2 | Geologic Setting

The Variscan basement of the Pyrenees, the Axial Zone, contains three major lithotectonic units: (1) Ediacaran to Carboniferous metasedimentary rocks, (2) orthogneisses with Ordovician protolith ages, and (3) numerous Carboniferous to early Permian plutons.

The Bassiès pluton covers an area of approximately 90 km^2 in the Central Pyrenees and has the shape of an E-W oriented parallelogram (Figure 1). It intruded Ediacaran-Ordovician metasedimentary rocks resulting in a 1–2 km wide contact aureole (Evans et al. 1997). The pluton displays a magmatic zonation with leucogranite in the centre and successive zones of two-mica monzogranite, biotite monzogranite, and granodiorite at the margin (Figure 1b; Gleizes et al. 1991). The northern boundary of the pluton is defined by the Alpine North Pyrenean fault (Evans et al. 1997).

Evans et al. (1997) propose that the Bassiès pluton was emplaced in a sinistral strike-slip pull-apart setting between a regional D_1 compression and D_2 transpression. This tectonic transition has been linked to an increase in magmatic activity (e.g., Denèle et al. 2009; Cochelin et al. 2021). After crystallisation, the pluton and its contact aureole behaved as a rigid body within the surrounding metasedimentary rocks, resulting in its asymmetric shape and clockwise rotation during D_2 dextral transpression (Evans et al. 1997).

3 | Analytical Methods

Four samples collected from the monzogranite, granodiorite and granite zones outlined by the official BRGM geologic maps (Casteras et al. 1969; Colchem et al. 1997) were selected for single zircon U–Pb LA-ICPMS analyses (Figures 1; S1, S2 in Supporting Information). Modal and geochemical analyses show that the lithologic differences between the samples are minor, lying close together in the granite and granodiorite fields (Tables S1, S2; Figures S3, S4). Zircon grains were extracted by standard mineral separation procedures (File S1). Cathodoluminescence (CL)-imaging of zircons was used to select analytical spots (Figures S59–S83). Uranium, thorium and lead isotopes were analysed with a Thermo-Fisher-Scientific Element 2 XR double focused sector field ICP-MS coupled to a New Wave Research UP-193 nm ultraviolet laser system.

4 | Single Zircon U–Pb Results

Ages are calculated from analyses that lie within 95%–105% concordance and range from 285.0 ± 4.3 to 351.6 ± 7.5 Ma for all four samples (Table 1, Figures S5–S58). In addition, one Ordovician (455 ± 7.9 Ma) and one Neoproterozoic (625 ± 13 Ma) age were recorded. Descriptions of samples, petrological, geochemical and U–Pb data are listed in the Supporting Information (Figures S1–S82, Tables S1–S8).

BAS-1, a peraluminous s-type granodiorite/quartz monzonite (Figures S1–S4; Tables S1, S2; see also for following samples), yields the youngest age of all four samples, 285.0 ± 4.3 Ma (Table 1, Figure S8). The main concordant age cluster is at 320.8 ± 2.4 Ma. Additional clusters lie at 295.2 ± 2.7 Ma, 300.7 ± 4.5 Ma, 308.3 ± 2.6 Ma and 329.5 ± 3.4 Ma. The overall average age calculated from 28 analyses is 308.3 ± 5.4 Ma.

BAS-2, a peraluminous s-type granite near the northern margin of the pluton, yields a youngest zircon age at 293.3 ± 3.1 Ma (Figure S23). Three additional clusters occur at 305.5 ± 2.0 Ma, 317.6 ± 1.9 Ma and 329.9 ± 2.4 Ma. The average age from 34 analyses is 312.5 ± 4.4 Ma.

BAS-3, a peraluminous s-type granodiorite from the eastern rim of the pluton, has its youngest zircon age at 301.9 ± 3.2 Ma (Figure S37). Two additional clusters are at 319.4 ± 2.7 Ma and 329.3 ± 2.7 Ma. The average age from 17 analyses is 317.6 ± 6.1 Ma.

BAS-4, a peraluminous s-type granite from the centre of the pluton, has its youngest age at 314.8 ± 3.8 Ma (Figure S50). Two clusters lie at 325.5 ± 3.8 Ma and 342.2 ± 3.8 Ma and an additional single age of 351.6 ± 7.5 Ma. The average age from 12 analyses is 327.9 ± 8.3 Ma.

5 | Discussion of Age Data

U–Pb zircon analyses are commonly reported with 95%–105% concordance (Ludwig 1998), resulting in several age clusters that can be eliminated by constricting the concordance requirements to 98%–102% (Table 2). For all four samples, 91 analyses fall in the 95%–105% range; 38 analyses satisfy the 98%–102% concordance. The age spread in both concordance ranges is nearly identical. Individual samples display a range of zircon ages spanning 17–40 Myr, almost 65 Myr for all four samples

TABLE 1 | U–Pb zircon age groups of the Bassiès pluton.

Sample number				Age (Ma)[a]				Age (all data) (Ma)
Individual samples								
BAS 1	285.0 ± 4.3	295.2 ± 2.7	300.7 ± 2.6	308.3 ± 2.6	320.8 ± 2.6	329.8 ± 3.4	n.d.	308.3 ± 5.4
	(*n* = 2)[c]	(*n* = 5)	(*n* = 2)	(*n* = 6)	(*n* = 7)	(*n* = 4)		(*n* = 28)
BAS 2	n.d.[b]	293.3 ± 3.1	305.5 ± 2.0	n.d.	317.6 ± 1.9	329.9 ± 2.4	n.d.	312.5 ± 4.4
		(*n* = 4)	(*n* = 10)		(*n* = 12)	(*n* = 8)		(*n* = 34)
BAS 3	n.d.	n.d.	301.9 ± 3.2	n.d.	319.4 ± 2.7	329.3 ± 2.7	n.d.	317.6 ± 6.1
			(*n* = 4)		(*n* = 6)	(*n* = 1)		(*n* = 17)
BAS 4	n.d.	n.d.	n.d.	314.8 ± 3.8	325.5 ± 3.4	n.d.	342.2 ± 3.8	327.9 ± 8.3
				(*n* = 3)	(*n* = 4)		(*n* = 4)	(*n* = 12)
							351.6 ± 7.5	
							(*n* = 4)	
Bassiès average age group								
	285	**295**	**304**	**310**	**320**	**329**	**345**	

Note: Detailed information on location and complete analytical data sets are presented in Tables S3–S8 in the Supporting Information. Bold values: mean of grouped local maxima of age distributions.
[a]95%–105% concordance.
[b]n.d.: = no data.
[c]Number of analyses.

TABLE 2 | U–Pb zircon age groups of the Bassiès pluton (conservative).

Sample number	Age (Ma)[a]						Age (all data) (Ma)
Individual samples							
BAS 1	285.0 ± 4.3	298.7 ± 4.3	308.3 ± 2.6	n.d.[b]	323.9 ± 2.7	n.d.	307.9 ± 8.1
	(n = 2)[c]	(n = 2)	(n = 5)		(n = 6)		(n = 15)
BAS 2	n.d.	292.2 ± 4.1	n.d.	316.1 ± 2.6	n.d.	331.3 ± 3.3	315.0 ± 9.5
		(n = 2)		(n = 5)		(n = 4)	(n = 12)
BAS 3	n.d.	n.d.	n.d.	n.d.	324.5 ± 3.5	337.7 ± 7.1	324.7 ± 9.3
					(n = 4)	(n = 1)	(n = 5)
BAS 4	n.d.	n.d.	n.d.	317.6 ± 3.9	n.d.	334.7 ± 5.2	323.0 ± 10
				(n = 3)		(n = 2)	(n = 5)
Bassiès average age group							
	285	**295**	**308**	**316**	**324**	**333**	

Note: Detailed information on location and complete analytical data sets are presented in Tables S3–S8 in the Supporting Information. Bold values: mean of grouped local maxima of age distributions.
[a]98%–102% concordance.
[b]n/a: = no data.
[c]Number of analyses.

combined, from 351 to 285 Ma (Figure 2, Figures S5–S58). The ages are not evenly distributed but seem to form clusters at 7–15 Myr intervals (Table 1; Figures 2, 3).

The wide range of clustered zircon ages, structural data and compositional zonation of the Bassiès pluton imply a complex emplacement history (Evans et al. 1997; Gleizes et al. 1997). Zircons with older cores and younger rims (Figure 2g,h) indicate that the Bassiès pluton is not the result of a single intrusive event as the ID-TIMS age of 312 Ma obtained from one monzogranite sample suggested (Paquette et al. 1997). Instead, we propose that the Bassiès pluton was assembled over several ten million years as a succession of smaller intrusions. Thus, the youngest zircon ages of ~285 Ma represent the final magmatic pulses and not the emplacement age of the pluton.

Prolonged emplacements of plutons have been documented by geochronologic studies in the North American Cordillera and the western European Variscides. Large plutons of the Sierra Nevada Batholith were assembled over periods of 7–12 Myr (Coleman et al. 2004, 2016; Davis et al. 2012; Frazer et al. 2014). The Montes de Toledo batholith in the Central Iberian Zone is composed of three different granitoid series that were emplaced between 316 and 297 Ma, over a period of 19 Myr (Merino Martínez et al. 2014). Coleman et al. (2004) consider magma crystallisation over such time periods too long for individual plutons to exist as magma chambers. Instead, they propose that such plutons were assembled as a series of incrementally emplaced intrusions.

In the Pyrenean Axial Zone, long-term pluton assemblages have not been recognised, although recent U–Pb zircon studies of the Lys-Caillaouas dome and Posets pluton reported extended age ranges of 20 Myr (Lopez-Sanchez et al. 2019; Esteban et al. 2021). Felsic dikes that intruded the orthogneiss core of the Aston dome in the central Axial Zone record Variscan zircon ages spanning > 70 Myr (Schnapperelle et al. 2020). Although not constrained by geochronology, an anisotropy of magnetic susceptibility (AMS) study of the Saint-Laurent–La Jonquera pluton suggests synkinematic sequential or incremental emplacement of multiple granitoid sheets during D_2 dextral transpression (Olivier et al. 2016). In the North Pyrenean Zone, U–Pb zircon geochronology of the Agly and Trois Seigneurs massifs record age ranges of 37 Myr and 40 Myr, respectively (Vanardois et al. 2022; Connop et al. 2024).

Geochronological studies of Pyrenean intrusions analysed a very small number of samples ($n \leq 3$) that may not be representative of the intrusion history. Prior to 2000, analyses were performed as ID-TIMS, which resulted in single dates that were interpreted as emplacement ages. Considering a complex pluton assemblage (e.g., Coleman et al. 2004), we suggest these ages record only a snapshot of the emplacement history of a Variscan pluton. Though the plutons in the Pyrenean Axial Zone are smaller in size (15–660 km^2) than the Sierra Nevada and Montes de Toledo batholiths (1200–2000 km^2), a similar long assemblage period on the order of tens of Myr can be assumed. Zircon cores within Bassiès pluton samples are 20 Ma older than their rims (Figure 2g,h). These grains display oscillatory zoning without xenocrystic cores, that is, no overgrowth on older grains from assimilated wall-rocks or detrital zircons (Figures 2g,h, S59–S83).

The current consensus that Variscan magmatism of the Pyrenean Axial Zone is confined to a narrow 20 Myr period during the latest Carboniferous–earliest Permian (Denèle et al. 2014, and references therein) does not concur with the results of our study. Instead, we propose that magmatism was already widespread during the early Carboniferous. The zircon ages of granitoids from the Bassiès pluton span more than 65 Myr beginning in the Tournaisian. Mezger and Gerdes (2016) reported similar early Variscan ages (339–336 Ma) from the Bossòst and Soulcem

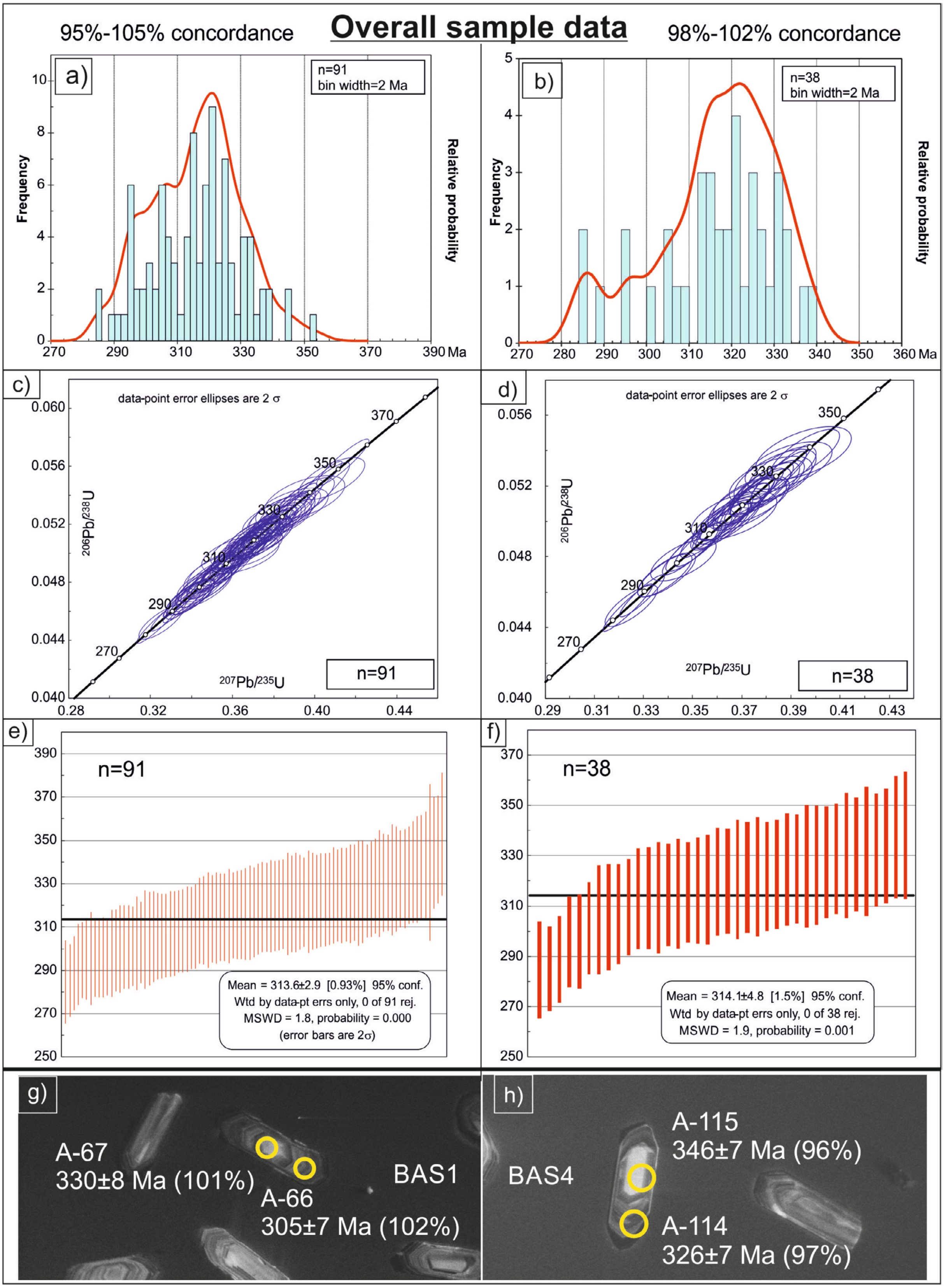

FIGURE 2 | Combined single zircon U–Pb analyses of four Bassiès pluton granitoids. Left column presents ages within 95%–105% concordance, right column within 98%–102% concordance. (a, b) Histograms and probability density plots (bin width = 2 Ma). (c, d) $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$ concordia diagrams. (e, f) Weighted averages ages. Black horizontal lines indicate mean ages. (g, h) Cathodoluminescence images of zircons from samples BAS 1 and BAS 4 with different core and rim ages. Diameter of analytical spots is 30 μm. Percentage of concordance is given. See text for discussion. [Colour figure can be viewed at wileyonlinelibrary.com]

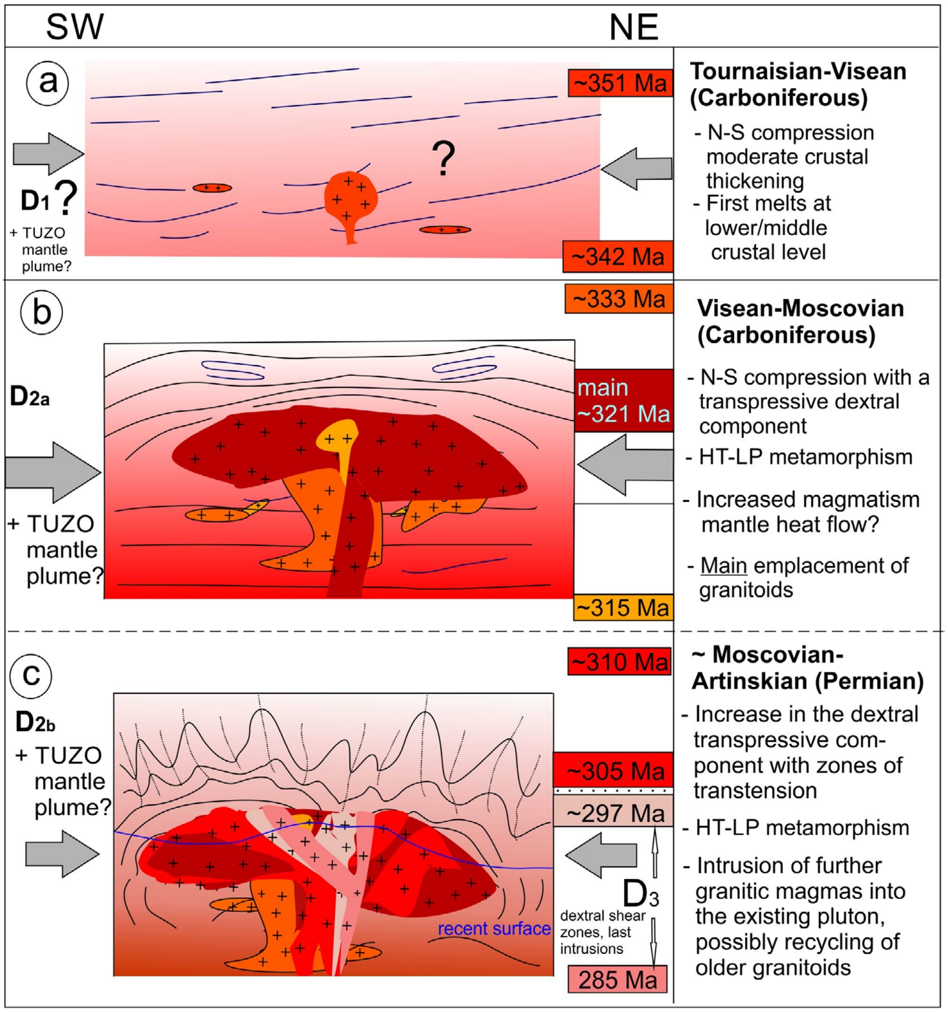

FIGURE 3 | Schematic not-to-scale evolution model of the Bassiès pluton from the early Carboniferous to the earliest Permian displayed in SW–NE oriented cross-sections. The colours of intrusions refer to the main magmatic events shown on the right. D_1, D_2, D_3 refer to the main Variscan deformation periods. Grey arrows represent compression. See text for discussion. [Colour figure can be viewed at wileyonlinelibrary.com]

granites, situated within gneiss domes of the central Pyrenees. Another granitic sample from the Soulcem intrusion yields concordant zircon ages ranging from 361 to 302 Ma (Schnapperelle et al. 2020).

6 | Evolution of the Bassiès Pluton

Tournaisian and early Visean zircon ages indicate that the earliest magmatic phase of the Bassiès pluton coincides with crustal thickening that led to the Variscan D_1 deformation (Figure 3a). Little is known about D_1, but it did not seem to have resulted in a significantly thickened crust with partial melting and magma production at its base (De Hoÿm de Marien et al. 2019).

The number of zircon ages increases from 333 Ma on and reaches a maximum at 321 Ma, which is interpreted as the main magmatic pulse of the Bassiès pluton (Figure 3b). It corresponds with a change in the tectonic setting in the Axial Zone from mainly N-S compression to dextral transpression (D_{2a}), accompanied by widespread HT-LP and local HT-MP metamorphism in the Axial Zone (Carreras and Cappella 1994; Druguet 2001; Mezger et al. 2004; Denèle et al. 2009).

Subsequent magmatic pulses at 315 and 305 Ma occurred under the increasingly transpressive deformation phase D_{2b} associated with local orogen-parallel extension of the middle crust in the Axial Zone (Figure 3c). In the Bassiès pluton, granitoid intrusions became dominant. The youngest zircon ages (299 and 285 Ma) are coeval with the last Variscan deformation phase D_3, which was dominated by dextral shear zones throughout the Axial Zone (Carreras 2001; Denèle et al. 2009; Mezger et al. 2012).

7 | Source of Long-Lasting Magmatism

Evidence for widespread magmatism in the Pyrenean Axial Zone starting in the early Carboniferous is mounting, but its origin remains unclear. For northwest Iberia, Gutierrez-Alonso et al. (2018) postulate that subduction of the Gondwana margin led to partial melting of a thickened crust and subsequent Visean magmatism. Lopez-Sanchez et al. (2019) propose a similar process for the Axial Zone without providing additional evidence. Thermobarometric modelling of metasedimentary rocks and migmatites from the eastern Axial Zone (Canigou massif, Roc de Frausa) yielded peak pressures of 6.5–7.5 kbar for M_1

metamorphism, indicating a thickened crust that could have undergone thermal weakening (Aguilar et al. 2015; De Hoÿm de Marien et al. 2019). However, such medium-pressure metamorphism has been recorded only locally.

High-pressure assemblages that record a significantly thickened crust are absent in the Pyrenean Axial Zone. Likewise, the Axial Zone does not contain eclogites or blueschists that could provide evidence of an intracontinental subduction zone as proposed by Kroner and Romer (2013). Only the latest post-304 Ma magmatic phase can be attributed to northwestward subduction of the Western Paleotethys oceanic lithosphere underneath Pangaea, synchronous with D_3 transpressional shearing (Druguet et al. 2014; Pereira et al. 2014).

Although the direct cause for long-term sustained magmatism starting in the early Carboniferous or before is still elusive, a possible source could be a thermal anomaly caused by a mantle plume, which was originally proposed by Simancas et al. (2006) for SW Iberia in the early Carboniferous. Torsvik et al. (2014) and Franke et al. (2017) suggest that the TUZO mantle plume likely underlaid northern Gondwana starting in the Ordovician and lasted at least until the Permian.

8 | Conclusions

Single zircon U–Pb ages from granitoids of the Bassiès pluton in the Central Pyrenean Axial Zone span a nearly continuous range from 351 to 285 Ma, covering most of the evolution of the Pyrenean Variscan orogeny. Age clusters indicate discrete magmatic pulses every 7–15 Myr, with the main emplacement taking place at around 321 Ma. The implications of this wide age range recorded in one pluton reflecting almost the complete range reported from Variscan magmatism in the Pyrenees are twofold: (1) The Bassiès pluton was not emplaced during one single event at 312 Ma but was assembled by incremental intrusions over a long period (~65 Myr) during the Variscan deformation phases D_1, D_2, and possibly D_3. (2) Widespread magmatism in the Axial Zone already occurred during the Tournaisian, corroborating studies of other Pyrenean plutons and gneiss domes. The source of early Variscan magmatism remains elusive. A long-lived mantle plume (TUZO) situated underneath northern Gondwana could have provided the thermal anomaly that initiated early Carboniferous magmatic activity and sustained until the development of regular late-orogenic magmatism and postorogenic extension.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

References

Aguilar, C., M. Liesa, P. Štípská, K. Schulmann, J. A. Muñoz, and J. M. Casas. 2015. "P–T–t–d Evolution of Orogenic Middle Crust of the Roc de Frausa Massif (Eastern Pyrenees): A Result of Horizontal Crustal Flow and Carboniferous Doming?" *Journal of Metamorphic Geology* 33: 273–294. https://doi.org/10.1111/jmg.12120.

Baudin, T., A. Barnolas, I. Gil, and S. Martin Alfageme. 2008. "Carte Géologique des Pyrénées à 1/400000 (Socle) BRGM-ITGE. Orléans, France."

Carreras, J. 2001. "Zooming on Northern Cap de Creus Shear Zones." *Journal of Structural Geology* 23: 1457–1486.

Carreras, J., and I. Cappella. 1994. "Tectonic Levels in the Palaeozoic Basement of the Pyrenees: A Review and a New Interpretation." *Journal of Structural Geology* 16: 1509–1524.

Casteras, J., J.-P. Destombes, and E. Raguin. 1969. "Carte Géologique de Vicdessos 1/50.000 Carte XXI-48 et Notice Explicative (1087). BRGM. Orléans, France."

Cochelin, B., Lemirre, Y. Denèle, and M. de Saint Blanquat. 2021. "Strain Partitioning Within Bending Orogens, New Insights From the Variscan Belt (Chiroulet-Lesponne Domes, Pyrenees)." *Tectonics* 40: 1–30. https://doi.org/10.1029/2020TC006386.

Colchem, M., Y. Ternet, E. J. Debroas, et al. 1997. "Carte Géologique France (1/50.000), Feuille Aulus-les-Bains (1086). BRGM. Orléans, France."

Coleman, D. S., W. Gray, and A. F. Glazner. 2004. "Rethinking the Emplacement and Evolution of Zoned Plutons: Geochronologic Evidence for Incremental Assembly of the Tuolumne Intrusive Suite, California." *Geology* 32: 433–436. https://doi.org/10.1130/G20220.1.

Coleman, D. S., R. D. Mills, and M. J. Zimmerer. 2016. "The Pace of Plutonism." *Elements* 12: 97–102. https://doi.org/10.2113/gselements.12.2.97.

Connop, C. H., A. J. Smye, J. M. Garber, and M. Tushar. 2024. "Heat Sources for Variscan High-Temperature Low-Pressure Metamorphism." *Journal of Metamorphic Geology* 42: 867–907. https://doi.org/10.1111/jmg.12775.

Davis, J. W., D. S. Coleman, J. T. Gracely, R. Gaschnig, and M. Stearns. 2012. "Magma Accumulation Rates and Thermal Histories of Plutons of the Sierra Nevada Batholith, CA." *Contributions to Mineralogy and Petrology* 163: 449–465. https://doi.org/10.1007/s00410-011-0683-7.

De Hoÿm de Marien, L., B. Le Bayon, P. Pitra, J. Van Den Driessche, M. Poujol, and F. Cagnard. 2019. "Two-Stage Variscan Metamorphism in the Canigou Massif: Evidence for Crustal Thickening in the Pyrenees." *Journal of Metamorphic Geology* 37: 863–888. https://doi.org/10.1111/jmg.12487.

Denèle, Y., P. Barbey, E. Deloule, E. Pelleter, P. Olivier, and G. Gleizes. 2009. "Middle Ordovician U–Pb Age of the Aston and Hospitalet Orthogneissic Laccoliths: Their Role in the Variscan Evolution of the Pyrenees." *Bulletin de La Sociète Geologique de France* 180: 209–216. https://doi.org/10.2113/gssgfbull.180.3.209.

Denèle, Y., B. Laumonier, J.-L. Paquette, P. Olivier, G. Gleizes, and P. Barbey. 2014. "Timing of Granite Emplacement, Crustal Flow and Gneiss Dome Formation in the Variscan Segment of the Pyrenees." *Geological Society, London, Special Publications* 405: 265–287. https://doi.org/10.1144/SP405.5.

Druguet, E. 2001. "Development of High Thermal Gradients by Coeval Transpression and Magmatism During the Variscan Orogeny: Insights

From the Cap de Creus (Eastern Pyrenees).” *Tectonophysics* 332: 275–293. https://doi.org/10.1016/S0040-1951(00)00261-4.

Druguet, E., A. Castro, M. Chichorro, M. F. Pereira, and C. Fernández. 2014. “Zircon Geochronology of Intrusive Rocks From Cap de Creus, Eastern Pyrenees.” *Geological Magazine* 151: 1095–1114. https://doi.org/10.1017/S0016756814000041.

Esteban, J. J., J. Cuevas, J. M. Tubía, A. Hilario, A. Larionov, and S. Sergeev. 2021. “Posets Pluton: A Geochronological Piece in the Puzzle of the Axial Zone of the Pyrenees.” *Geological Magazine* 158: 2264–2270. https://doi.org/10.1017/S0016756821000686.

Evans, N. G., G. Gleizes, D. Leblanc, and J.-L. Bouchez. 1997. “Hercynian Tectonics in the Pyrenees: A New View Based on Structural Observations Around the Bassiès Granite Pluton.” *Journal of Structural Geology* 19: 195–208. https://doi.org/10.1016/S0191-8141(96)00080-6.

Franke, W., L. R. M. Cocks, and T. H. Torsvik. 2017. “The Palaeozoic Variscan Oceans Revisited.” *Gondwana Research* 48: 257–284. https://doi.org/10.1016/j.gr.2017.03.005.

Frazer, R. E., D. S. Coleman, and R. D. Mills. 2014. “Zircon U–Pb Geochronology of the Mount Givens Granodiorite: Implications for the Genesis of Large Volumes of Eruptible Magma.” *Journal of Geophysical Research: Solid Earth* 139: 2907–2924. https://doi.org/10.1002/2013JB010716.

Gleizes, G., D. Leblanc, and J. L. Bouchez. 1991. “Le Pluton Granitique de Bassiès (Pyrénées Ariégoises) Zonation, Structure et Mis en Place.” *Comptes Rendus de L'académie Des Sciènces Paris* 312: 755–762.

Gleizes, G., D. Leblanc, and J. L. Bouchez. 1997. “Variscan Granites of the Pyrenees Revisited: Their Role as Syntectonic Markers of the Orogen.” *Terra Nova* 9: 38–41. http:doi/10.1046/j.1365-3121.1997.d01-9.x.

Gutierrez-Alonso, G., J. Fernández Suárez, A. Lopez-Carmona, and A. Gärtner. 2018. “Exhuming a Cold Case: The Early Granodiorites of the Northwest Iberian Variscan Belt—A Visean Magmatic Flare-Up?” *Lithosphere* 10: 194–216. https://doi.org/10.1130/L706.1.

Kalsbeek, F., H. F. Jepsen, and A. P. Nutman. 2001. “From Source Migmatites to Plutons: Tracking the Origin of Ca. 435 ma S-Type Granites in the East Greenland Caledonian Orogen.” *Lithos* 57: 1–21. https://doi.org/10.1016/S0024-4937(00)00071-2.

Kroner, U., and R. L. Romer. 2013. “Two Plates—Many Subduction Zones: The Variscan Orogeny Reconsidered.” *Gondwana Research* 24: 298–329. https://doi.org/10.1016/j.gr.2013.03.001.

Lopez-Sanchez, M. A., J. Garcia-Sansegundo, and F. J. Martinez. 2019. “The Significance of Early Permian and Early Carboniferous U–Pb Zircon Ages in the Bossòst and Lys-Caillaouas Granitoids (Pyrenean Axial Zone).” *Geological Journal* 54: 2048–2063. https://doi.org/10.1002/gj.3283.

Ludwig, K. R. 1998. “On the Treatment of Concordant Uranium-Lead Ages.” *Geochimica et Cosmochimica Acta* 62: 665–676. https://doi.org/10.1016/S0016-7037(98)00059-3.

Merino Martínez, E. M., C. Villaseca, D. Orejana, C. Pérez-Soba, E. Belousova, and T. Andersen. 2014. “Lithos Tracing Magma Sources of Three Different S-Type Peraluminous Granitoid Series by In Situ U–Pb Geochronology and Hf Isotope Zircon Composition: The Variscan Montes de Toledo Batholith (Central Spain).” *Lithos* 200: 273–298. https://doi.org/10.1016/j.lithos.2014.04.013.

Mezger, J. E. 2009. “Transpressional Tectonic Setting During the Main Variscan Deformation: Evidence From Four Structural Levels in the Bossóst and Aston-Hospitalet Mantled Gneiss Domes, Central Axial Zone, Pyrenees.” *Bulletin de la Societe Geologique de France* 180: 199–207. https://doi.org/10.2113/gssgfbull.180.3.199.

Mezger, J. E., and A. Gerdes. 2016. “Early Variscan (Visean) Granites in the Core of Central Pyrenean Gneiss Domes: Implications From Laser Ablation U–Pb and Th-Pb Studies.” *Gondwana Research* 29: 181–198. https://doi.org/10.1016/j.gr.2014.11.010.

Mezger, J. E., C. W. Passchier, and J.-L. Régnier. 2004. “Metastable Staurolite–Cordierite Assemblage of the Bossòst Dome: Late Variscan Decompression and Polyphase Metamorphism in the Axial Zone of the Central Pyrenees.” *Comptes Rendus Geoscience* 336: 827–837. https://doi.org/10.1016/j.crte.2003.12.024.

Mezger, J. E., and J.-L. Régnier. 2016. “Stable Staurolite-Cordierite Assemblages in K-Poor Metapelitic Schists in Aston and Hospitalet Gneiss Domes of the Central Pyrenees (France, Andorra).” *Journal of Metamorphic Geology* 34: 167–190. https://doi.org/10.1111/jmg.12177.

Mezger, J. E., S. Schnapperelle, and C. Rölke. 2012. “Evolution of the Central Pyrenean Mérens Fault Controlled by Near Collision of Two Gneiss Domes.” *Hallesches Jahrbuch* 34: 11–29.

Oliver, G. J. H., S. A. Wilde, and Y. Wan. 2008. “Geochronology and Geodynamics of Scottish Granitoids From the Late Neoproterozoic Break-Up of Rodinia to Palaeozoic Collision.” *Journal of the Geological Society* 165: 661–674. https://doi.org/10.1144/0016-76492007-105.

Olivier, P., E. Druguet, L. M. Castaño, and G. Gleizes. 2016. “Granitoid Emplacement by Multiple Sheeting During Variscan Dextral Transpression: The Saint-Laurent—La Jonquera Pluton (Eastern Pyrenees).” *Journal of Structural Geology* 82: 80–92. https://doi.org/10.1016/j.jsg.2015.10.006.

Paquette, J.-L., G. Gleizes, D. Leblanc, and J.-L. Bouchez. 1997. “Le Granite de Bassiès (Pyrénées): un Pluton Syntectonique d'âge Westphalien. Géochronologie U–Pb sur zircons.” *Comptes Rendus de l'Académie des Sciences. Série 2. Sciences de la Terre et Des Planètes* 324: 387–392.

Pereira, M. F., A. Castro, M. Chichorro, et al. 2014. “Chronological Link Between Deep-Seated Processes in Magma Chambers and Eruptions: Permo-Carboniferous Magmatism in the Core of Pangaea (Southern Pyrenees).” *Gondwana Research* 25: 290–308. https://doi.org/10.1016/j.gr.2013.03.009.

Rosenberg, C. L. 2004. “Shear Zones and Magma Ascent: A Model Based on a Review of the Tertiary Magmatism in the Alps.” *Tectonics* 23: 1–21. https://doi.org/10.1029/2003TC001526.

Schnapperelle, S., J. E. Mezger, M. Stipp, M. Hofmann, A. Gärtner, and U. Linnemann. 2020. “Polyphase Magmatic Pulses Along the Northern Gondwana Margin: U–Pb Zircon Geochronology From Gneiss Domes of the Pyrenees.” *Gondwana Research* 81: 291–311. https://doi.org/10.1016/j.gr.2019.11.013.

Simancas, J. F., R. Carbonell, F. Gonzáles Lodeiro, et al. 2006. “Transpressional Collision Tectonics and Mantle Plume Dynamics: The Variscides of Southwestern Iberia.” *Geological Society, London, Memoirs* 32: 345–354. https://doi.org/10.1144/GSL.MEM.2006.032.01.21.

Torsvik, T. H., R. Voo, P. V. Van Der Doubrovine, K. Burke, and B. Steinberger. 2014. “Deep Mantle Structure as a Reference Frame for Movements in and on the Earth.” *PNAS* 111: 8735–8740. https://doi.org/10.1073/pnas.1318135111.

Vanardois, J., P. Trap, F. Roger, et al. 2022. “Flow of the Partially Molten Crust in the Variscan Foreland Revealed by U–Th–Pb Dating of Metamorphism, Magmatism and Deformation (Agly Massif, Eastern Pyrenees).” *International Journal of Earth Sciences* 111: 2101–2128. https://doi.org/10.1007/s00531-022-02229-7.

Von Blanckenburg, F., H. Kagami, A. Deutsch, et al. 1998. “The Origin of Alpine Plutons Along the Periadriatic Lineament.” *Schweizerische Mineralogische und Petrographische Mitteilungen* 78: 55–66. https://doi.org/10.5169/seals-59274.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.