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Mafic dykes from some plutons of the western Pyrenean Axial Zone (France, Spain): markers of the transition from late-Hercynian to early-Alpine events

by *François Debon*[1] and *Jean Louis Zimmermann*[2]

Abstract

A conspicuous swarm of mafic (and intermediate) dykes cross-cuts Hercynian plutons and Palaeozoic (meta)sedimentary country rocks of the western Pyrenean Axial Zone. These dominantly alkaline dykes are Saxonian in age (268 ± 7 Ma according to K–Ar isotope datings on kaersutite phenocrysts of four dykes). They mark the time where, as in other parts of the western Variscan, a sharp transition from orogenic calc-alkaline and aluminous magmatism to anorogenic alkaline magmatism occurred. Their contrasting geographical distribution along the Pyrenean range (Romeu, 1907) could suggest that the Axial Zone was simultaneously, at the end of the Hercynian orogeny, under transtension on the west and transpression on the east. An ascent of asthenospheric mantle, triggered by a reversal in the stress field, seems likely to account for the genesis of this Saxonian alkaline magmatism.

Keywords: alkaline magmatism, dyke, geochemistry, kaersutite, K–Ar dating, Permian geodynamics, Pyrenees.

Introduction

Hercynian plutons and pre-Permian Palaeozoic (meta)sedimentary series from the western part of the Pyrenean Axial Zone (Fig. 1) are cross-cut by a conspicuous swarm of dykes, dominantly mafic in composition (Bresson, 1903; Bresson and Carez, 1905; Romeu, 1907; Debon, 1972, 1975; Lamouroux, 1976). Such a magmatic event can be used as a major reference mark for the geodynamic evolution of the Axial Zone when (at least) its age and its typology – two hitherto ill-defined characteristics – are known.

Geological setting and typology

The dykes studied cross-cut the Cauterets, Panticosa and Néouvielle plutons as well as their country rocks (Fig. 1). They are made up of black or dark grey-green rocks with brown patina, thus strongly contrasting with the surrounding granitoids (Fig. 2) and light-coloured (meta)sedimentary formations (e.g. Vignemale marbles). Their thickness may vary greatly (from a few centimetres up to one decametre) as well as their length which can often exceed a kilometre. Usually, they are subvertical or north-dipping. Their prevailing trend, around N105°E (Fig. 3), parallels the present elongation of the Pyrenean Range, though variations between N80°E and N140°E exist (Bresson and Carez, 1905; Romeu, 1907; Debon, 1972; Lamouroux, 1976).

Due to actual textural and/or compositional variations, but also to semantic noise, these dykes have been given a diversity of names: labradorite, diabase, dolerite, lamprophyre, spessartite, basalt, andesite, microdiorite, etc. On the basis of petrography and chemistry (Tab. 1) of 28 samples taken from 26 dykes cutting through the Cauterets (21 dykes), Panticosa (1) and Néouvielle (3) plutons (Fig. 1) as also their Westphalian (?) surrounding "Sia Series" (1), two groups can be distinguished, viz. a dominant

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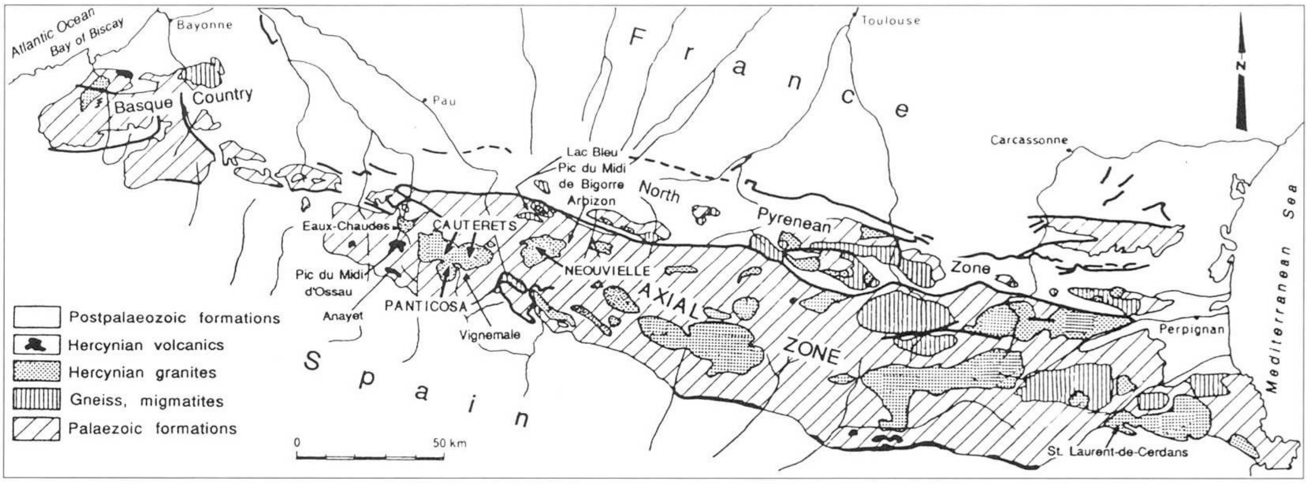

Fig. 1 Geological sketch map of the Pyrenees. After DEBON (1980) and BIXEL (1984, 1989), simplified.

mafic group and a subordinate intermediate group.

The *dominant group* (21 samples) comprises the most *mafic* dykes (SiO_2: range = 44.20–51.00%, average = 46.70%; weighted mafic mineral content: range = 51–64%, average = 56%). In addition to their mafic character, most of these dykes are distinguished by: (a) their fine-grained doleritic (diabasic) texture; (b) their mineralogical composition: calcic plagioclase (labrador, andesine) + pink titanaugite + opaques (pyrite according to ROMEU, 1907). Rare biotite and kaersutite may exist but quartz is always completely lacking. A very few dykes present a core loaded with prominent phenocrysts, several centimetres in size, of plagioclase and kaersutite (see hereafter and Fig. 4). On the other hand, all rocks have been affected at various degrees by retrogressive alteration-devitrification processes (chlorite, saussurite aggregates, white mica, epidote, leucoxene, etc.), and vesicles of millimetric size filled in with chlorite, calcite, zeolite etc. are sometimes present.

Such a development of secondary minerals usually rich in H_2O (or CO_2) is associated with high and various loss on ignition (L.I.) contents (range = 2.57–6.53%, average = 3.88%), and L.I. can be considered roughly proportional to the

Fig. 2 (a) Mafic dykes (λ) across the West Cauterets pluton. East cliff, about 120 m high, of the Crête du Diable. (b) Mafic dykes (λ) across the Néouvielle pluton. East face of the Pic du Néouvielle (3091 m) viewed from Ramoun (3011 m).

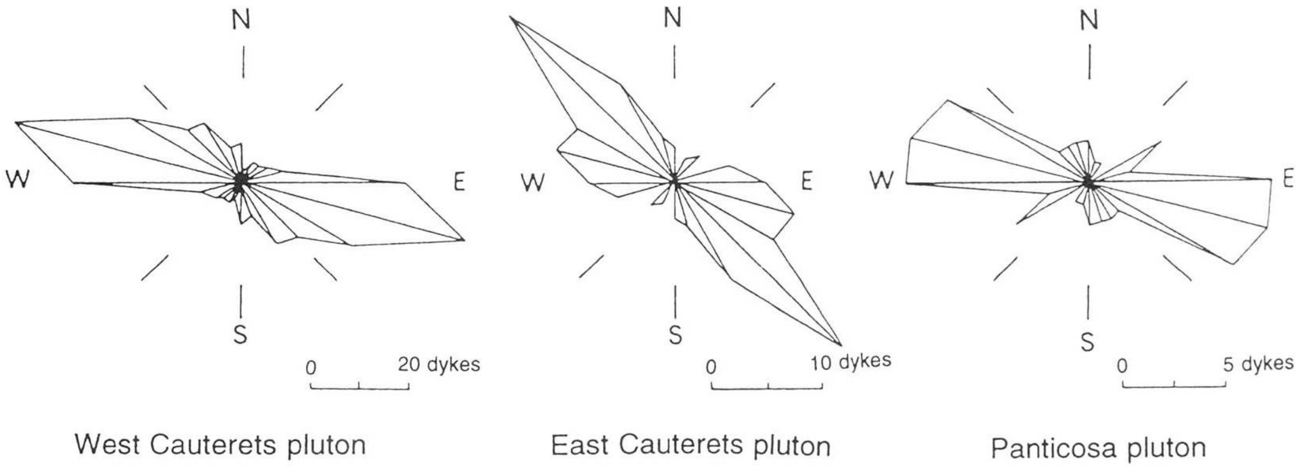

Fig. 3 Orientation of mafic and intermediate dykes of the Cauterets and Panticosa plutons. After DEBON (1972).

amount of these minerals. Despite their high L.I. contents, several lines of evidence suggest that the original bulk chemistry of the mafic dykes remained almost unmodified by secondary processes: (1) When plotted in chemical-mineralogical diagrams (e.g. Fig. 5), the 21 samples are systematically scattered; they lie in the field of typical igneous compositions where they form a coherent association. (2) The magmatic typology deduced from their bulk chemistry coincides with the typology deduced from their primary mineralogy or from their little or non-mobile element (rare-earth) chemistry (see below). (3) There is no good correlation between L.I. and bulk chemistry, whatever the element considered (linear-correlation coefficients "r" are < 0.25, except for SiO_2; Tab. 2), including those elements very sensitive to alteration such as Na and Ca. Such a lack of correlation could indicate either that secondary processes were isochemical at the hand sample scale, or, on the contrary, that they thoroughly disturbed the original compositions through different and superimposed ways of element transfer. The latter possibility appears unlikely on account of the compositional coherence mentioned above. (4) In the same way, there is no good correlation between L.I. and the "aluminous index" A = Al – (K + Na + 2 Ca) (Tab. 2), despite its sensitiveness to alteration processes. On the whole, it seems that the observed alteration-devitrification features were dominantly associated with isochemical processes, excluding, however, some elements such as Ar (see below).

All the analysed mafic dykes but one are made up of metaluminous rocks which, according to their distribution in the R1R2 classification diagram of LA ROCHE et al. (1980; Fig. 5), display a broad compositional range: alkali gabbro (7 samples), (olivine) gabbro (4), syenogabbro (2), monzogabbro (3), syenodiorite (4), gabbrodiorite (1). Such compositions (Tab. 1) are typical of alkaline associations. High alkali ($[Na_2O + K_2O]$ averages 4.83%) and TiO_2 (1.87%, on average) contents and rare-earth data (Tab. 1; Fig. 6; e.g. CULLERS and GRAF, 1984) as well as minerals such as titanaugite or kaersutite strongly support this alkaline character. Data from literature indicate that similar compositions also characterize most of the dykes cross-cutting (meta)sedimentary Palaeozoic formations of the western Pyrenean Axial Zone (dykes of the Lac Bleu and Arbizon types of ROMEU [1907] and of the Pic du Midi de Bigorre area [FRANÇOIS, 1983]; Figs 1, 5; Tab. 1).

Four out of the investigated mafic dykes allowed us to find and extract amphibole pheno-

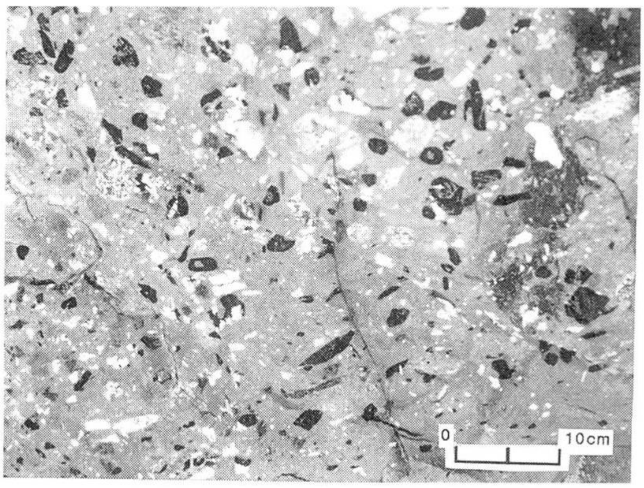

Fig. 4 Black kaersutite (sample KR29; Tab. 3, 4) and white plagioclase phenocrysts in a mafic dyke. Northwest surroundings of the Panticosa pluton (north of the Ibón Azul inferior).

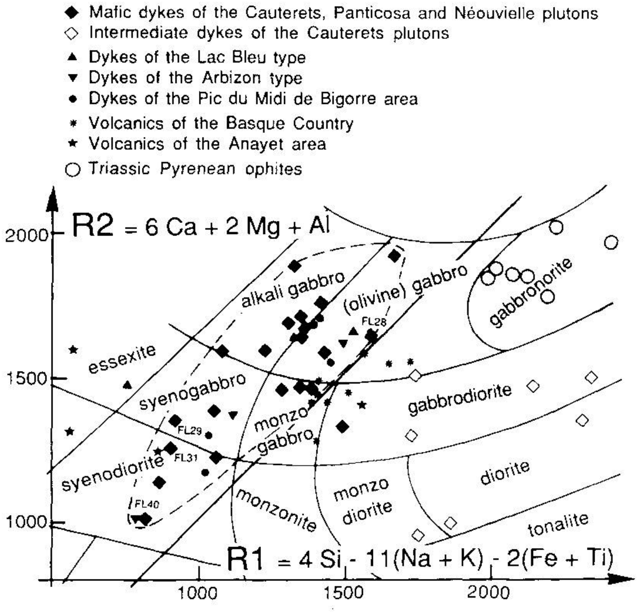

Fig. 5 Distribution of the dykes studied in the R1R2 diagram. Numbers FL28, FL29, FL31 and FL40 indicate the mafic dykes from which kaersutite phenocrysts have been extracted (Tab. 3, 4). For comparison, other mafic dykes of the Axial Zone (Arbizon, Lac Bleu, Pic du Midi de Bigorre), Upper Permian Pyrenean volcanics (Basque Country, Anayet area), and sills or dykes of Triassic Pyrenean ophites are also shown. Data and other explanations as in table 1. R1R2 diagram according to LA ROCHE et al. (1980).

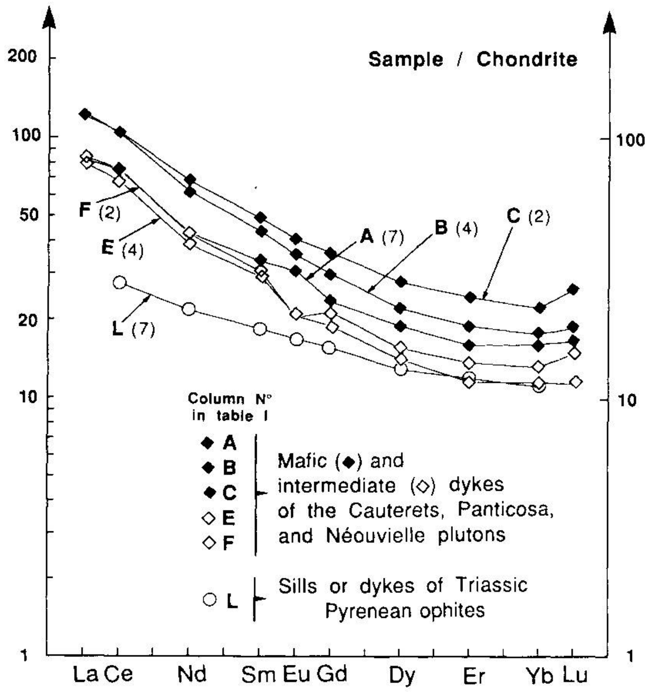

Fig. 6 Mean REE patterns of the dykes studied. For comparison, an average pattern of sills or dykes of Triassic Pyrenean ophites is also shown. Data (Tab. 1) normalised to chondritic values of EVENSEN et al. (1978). In parentheses, number of analysed samples.

crysts (Fig. 4). Following LEAKE's (1978) nomenclature and according to their chemical composition (Tab. 3), the phenocrysts belong to the calcic amphibole group and, on the basis of their high Ti content (Ti ions in formula > 0.50) and Mg/(Mg + Fe^{2+}) ratio (> 0.50), are classified as *kaersutites* sensu stricto. Such kaersutite phenocrysts are well known in alkaline dykes (e.g. Monteregian and White Mountain suites; BÉDARD, 1988). Despite the geographical scattering and compositional diversity of the dykes they come from (Tab. 3; Fig. 5), the extracted phenocrysts exhibit a remarkable uniformity in composition (Tab. 3). This suggests that mafic dykes originate from the same original magma within which kaersutite phenocrysts crystallized at depth, before differentiations responsible for their compositional diversity occurred (G. BANZET, pers. comm.). This early crystallization of kaersutite phenocrysts is also supported by the lack of positive correlation in the Mg/(Mg + Fe) ratio between amphibole and whole rock (Tab. 3), contrary to what has been observed elsewhere (BÉDARD, 1988). Owing to their chemical variations the mafic dykes cannot represent members of a unique evolutionary series. Therefore, their original magma probably dissociated into several batches that differentiated independently from each other.

The *subordinate group* (7 samples) is composed of the dykes of *intermediate* composition (SiO_2: range = 51.80–57.39%, average = 54.50%; weighted mafic mineral content: range = 37–51%, average = 44%; Tab. 1). These dykes are made up of fine-grained (micro)granular rocks, more or less porphyritic, at times displaying a lamprophyric texture (elongated prismatic amphibole), usually quartz-bearing and including: plagioclase ± brown olive-green amphibole ± rare kaersutite, biotite and opaque, with, in addition, a variable proportion of chlorite, saussurite aggregates, epidote, leucoxene and calcite. Following the R1R2 diagram (Fig. 5), their compositional ranges vary from gabbrodioritic (4 samples) to dioritic (2) and monzodioritic (1).

On the basis of both petrographic and chemical criteria, the subordinate intermediate group is rather easily distinguishable from the dominant mafic doleritic one (e.g. Figs 5, 6; Tab. 1). However, field, mineralogical and chemical (e.g. Fig. 6) similarities as well as transitional types (ROMEU, 1907) exist between the two groups, thus supporting their probable relationship and identity in age.

Tab. 1 Mean chemical composition of various Pyrenean dykes, sills, and volcanics.
Symbols as in figures 5 and 6. Rock type defined according to sample distribution in the R1R2 classification diagram of La Roche et al. (1980; Fig. 5). Abbreviations: Alkgo alkali gabbro, D diorite, Essex essexite, God gabbrodiorite, Gon gabbronorite, Mzd monzodiorite, Mzgo monzogabbro, Olgo (olivine) gabbro, Syd syenodiorite, Sygo syenogabbro. The prefix "micro" has to be added to the different petrographic names. n = number of analysed samples. Fe_2O_3t = total iron as ferric oxide; L.I. = loss on ignition. Trace element and REE contents in ppm. Columns A–F: mafic (A–D) and intermediate (E, F) dykes of the Cauterets, Panticosa, and Néouvielle plutons (Debon, 1972, 1975, and new data. Analysis by emission spectrometry; K. Govindaraju, CRPG, Nancy); G, H: dykes of the Lac Bleu (G) and Arbizon (H) types (Romeu, 1907; Fig. 1); I: dykes of the Pic du Midi de Bigorre area (François, 1983; Fig. 1); J, K: Upper Permian volcanism (fifth episode of Bixel, 1984, 1988) from the Basque Country (J) and Anayet area (K) (Bixel, ibid.; Cabanis and Le Fur-Balouet, 1989; Fig. 1), excluding samples with a positive alumina index; L: sills or dykes of Triassic ophites (Alibert, 1985).

	MAFIC DYKES				INTERM. DYKES		MISCELLANEOUS DYKES			BASQUE	ANAYET	OPHITES
Column N°	A	B	C	D	E	F	G	H	I	J	K	L
Symbol	◆	◆	◆	◆	◇	◇	▲	▼	●	✻	★	○
Rock type	Alkgo Olgo	Sygo Mzgo	Syd	God	God	Mzd D	Alkgo Olgo Essex	Olgo Sygo Syd	Olgo Sygo Syd	Olgo Mzgo God	Syd God Essex	Gon
n	11	5	4	1	4	3	3	3	5	9	4	7
SiO_2	45.60	48.32	46.63	51.00	53.38	55.97	46.55	48.67	46.71	48.07	43.88	50.16
Al_2O_3	17.30	17.04	16.63	14.80	17.23	16.46	17.44	19.10	16.93	17.57	17.56	14.67
Fe_2O_3t	10.24	10.25	11.70	10.59	8.10	6.80	10.86	10.59	10.72	9.78	10.37	10.77
MnO	0.17	0.17	0.20	0.21	0.13	0.10	–	–	0.18	0.16	0.16	0.19
MgO	6.70	5.47	6.26	6.89	5.55	5.71	7.19	5.29	6.05	6.94	5.99	7.78
CaO	9.53	7.56	4.91	6.50	7.65	4.52	8.21	6.41	7.78	7.22	6.99	11.20
Na_2O	3.24	3.89	3.56	4.14	2.64	2.67	3.45	3.81	3.69	3.25	4.76	1.94
K_2O	0.93	1.46	2.48	0.53	1.69	2.61	1.47	1.86	0.95	1.10	0.13	0.70
TiO_2	1.71	1.88	2.29	1.81	0.86	0.70	2.37	2.13	2.06	2.02	2.03	1.08
P_2O_5	0.44	0.64	0.68	–	0.24	0.21	–	–	–	0.43	0.40	0.09
L.I.	4.00	3.22	4.45	3.68	2.44	4.05	3.99	3.41	4.50	3.90	7.80	1.05
TOTAL	99.87	99.88	99.79	100.15	99.89	99.80	101.53	101.27	99.57	100.44	100.06	99.63
n	3	3	2	–	2	3	–	–	3	8	4	7
Ba	180	344	539	–	452	540	–	–	262	315	89	148
Be	1.5	2.2	2.8	–	1.5	1.9	–	–	–	–	–	–
Co	36	25	28	–	21	12	–	–	–	34	39	–
Cr	148	77	62	–	217	212	–	–	66	143	134	275
Cu	55	43	31	–	34	24	–	–	< 14	–	–	–
Ga	28	29	32	–	21	18	–	–	–	–	–	–
Nb	< 14	29	39	–	10	< 7	–	–	–	–	–	6
Ni	68	42	45	–	57	30	–	–	49	56	62	127
Rb	43	43	109	–	59	101	–	–	35	23	< 3	–
Sc	32.6	27.0	22.9	–	21.6	27.0	–	–	–	28.8	31.8	–
Sr	383	629	457	–	277	262	–	–	465	448	705	–
Th	< 6	7	< 6	–	5	6	–	–	–	6.2	1.9	1.3
V	180	178	156	–	106	154	–	–	223	–	–	–
Y	32.1	35.5	45.8	–	24.3	26.3	–	–	–	–	–	–
Zn	81	75	99	–	77	79	–	–	–	–	–	–
Zr	171	259	273	–	126	140	–	–	–	251	216	77
n	7	4	2	–	4	2	–	–	–	8	4	7
La	20.04	30.29	29.47	–	19.35	20.53	–	–	–	34.20	18.08	–
Ce	47.71	66.01	66.87	–	43.31	48.15	–	–	–	–	–	17.56
Nd	20.30	29.30	32.20	–	18.31	20.02	–	–	–	–	–	10.24
Sm	5.14	6.70	7.52	–	4.48	4.69	–	–	–	–	–	2.83
Eu	1.77	2.04	2.35	–	1.19	1.18	–	–	–	1.98	1.61	0.98
Gd	4.76	6.06	7.32	–	3.84	4.34	–	–	–	–	–	3.18
Dy	4.79	5.58	7.04	–	3.57	3.94	–	–	–	–	–	3.26
Er	2.63	3.12	4.04	–	1.91	2.26	–	–	–	–	–	1.97
Yb	2.65	2.90	3.65	–	1.89	2.17	–	–	–	–	–	1.83
Lu	0.42	0.47	0.66	–	0.29	0.38	–	–	–	–	–	–

Tab. 2 Linear correlation coefficient "r" between loss on ignition and bulk chemistry in the mafic dyke group (21 samples).
A = Al – (K + Na + 2 Ca) is a classical index (SHAND, 1927) used to define the more or less aluminous character of an igneous rock.

SiO_2	–0.50
Al_2O_3	–0.10
Fe_2O_3t	0.06
MnO	0.05
MgO	0.23
CaO	–0.12
Na_2O	0.01
K_2O	–0.10
TiO_2	–0.01
P_2O_5	–0.22
A = Al – (K + Na + 2 Ca)	0.18

Chronological data

According to ROMEU (1907), the dykes studied exclusively intersect plutonic or (meta)sedimentary formations of Palaeozoic age and are unknown among Permian pebbles. In particular, they can cross-cut (DEBON, 1972) the NW–SE to NNW–SSE dyke swarm associated with the Lower Permian volcanism of the Pic du Midi d'Ossau (Fig. 1; BIXEL, 1984) that has been dated by U–Pb on zircons at 278 ± 5 Ma – 272 ± 3 Ma (INNOCENT, 1989; BRIQUEU and INNOCENT, 1993; INNOCENT et al., 1993). On the other hand, because they can be disrupted and displaced (Fig. 2) or even, in a few cases, foliated, they pre-date Alpine deformations (DEBON, 1972; LAMOUROUX, 1976). On the whole, their emplacement age is bracketed by a very precise upper limit and a poorly constrained lower limit.

A K–Ar isotopic investigation of four mafic dykes of the Cauterets-Panticosa plutons was carried out. In addition to kaersutite datings, whole rock analyses were also performed for comparison (Tab. 4).

Alteration-devitrification processes mentioned above are most probably responsible for the large scatter of whole rock datings (from 62 to 124 Ma). The existence of strong disturbances in the K-Ar system of altered dolerites has been pointed out by different authors (e.g. DALRYMPLE et al., 1975, for diabase dykes in Liberia; MONTIGNY et al., 1982, for Triassic Pyrenean ophites) and, as it could be expected, the dykes studied conform to the usual rule. Their whole rock datings have no geological significance, and they cannot be used for determining the dyke emplacement age.

Dates obtained on kaersutite phenocrysts from the same four dykes vary from 266 ± 10 Ma to 271 ± 9 Ma (Tab. 4). Given the analytical uncertainties, they are identical, and cluster round 268 ± 7 Ma. They differ from the dates yielded by whole rock analysis of the dykes they come from in being both remarkably concordant among themselves and much older. As far as the kaersutite system remained closed to loss or gain of radiogenic argon, they are likely to indicate the dyke emplacement age. In addition to the well-known high retentivity of amphibole for argon (e.g. HART, 1964; ONSTOTT and PEACOCK, 1987), such a loss can be discarded owing to the ages obtained and the above field constraints. Contamination of amphibole with excess argon is a rather frequent phenomenon (e.g. RODDICK and FARRAR, 1971) that seems, however, unlikely in the present case. As shown by HARRISON and MCDOUGALL (1980), excess argon is mostly distributed near the margins of crystals. Our argon measurements were done after an initial outgassing at 300 °C for 15 hours, fitted to minimize the eventual excess argon adsorbed or entrapped at the grain boundaries. Because external overpressures responsible for gain of argon in minerals are aleatory processes, the quantity of excess argon is rarely identical among the different crystals of a given formation, even when crystals belong to the same mineral species (e.g. MONTIGNY, 1985). Such an inhomogeneous distribution of the excess argon is out of keeping with the nice concordance of the four kaersutite dates. In addition, when plotted in K–Ar isochron diagrams, the four kaersutites yield regression lines whose characteristics (correlation coefficient, intercept, age, M.S.W.D.; Tab. 5; Fig. 7) indicate that neither apparent gain nor loss of radiogenic argon occurred.

Following ROMEU (1907) and field constraints, the dykes studied were hitherto implicitly considered as Palaeozoic. The emplacement age given by kaersutite phenocrysts (ca. 268 Ma, i.e. Saxonian according to the time scale of HAQ and VAN EYSINGA, 1987) fully agrees with this assumption. In addition, such an age is consistent with another K-Ar date, also obtained on kaersutite, for a mafic dyke cutting through the St. Laurent-de-Cerdans pluton (Fig. 1), in Eastern Pyrenees (282 ± 11 Ma; BAUBRON, in AUTRAN et al., in press).

Discussion

In the Pyrenean framework, the dykes studied are distinguished unambiguously by their Saxonian age and dominantly alkaline character from the mostly calc-alkaline or aluminous first four episodes of the Stephanian-Permian volcanism (e.g. BIXEL, 1984, 1988, 1989; CABANIS and LE FUR-BA-

Tab. 3 Chemical composition of kaersutite phenocrysts (KR) and their host mafic dykes (FL). Host plutons or series and surrounding rocks of the dykes refer to DEBON (1972, 1975). Samples used for dyke analysis taken from fine-grained margins. Rock type defined as in table 1. Analysis by ICP emission spectrometry (K. GOVINDARAJU, CRPG, Nancy) except for FeO and F (M. VERNET, CRPG). Fe_2O_3t = total iron as ferric oxide, L.I. = loss on ignition; H_2O^+ content approximated by calculation. Kaersutite structural formula based upon 24 oxygen equivalents; ions in formula arranged according to LEAKE's (1978) classification.

	KAERSUTITE-	HOST DYKE	KAERSUTITE-	HOST DYKE	KAERSUTITE-	HOST DYKE	KAERSUTITE-	HOST DYKE
Sample N°	KR28	FL28	KR29	FL29	KR31	FL31	KR40	FL40
Host pluton	Panticosa		–		West Cauterets		West Cauterets	
Host series	–		Sia		–		–	
Surroundings	Quartzgabbrodiorite (3gqB)		Quartzite & Metapelite (hS)		Adamellite (1gA)		Granodiorite (1gdB)	
Locality	South of Ibón Azul superior		North of Ibón Azul inferior		Lacs de Cambalès		East of Crête du Diable	
Sampling point	Outcrop		Scree		Outcrop		Outcrop	
X	2° 35' 09" W		2° 34' 36" W		2° 33' 22" W		2° 36' 26" W	
Coordinates Y	42° 46' 59" N		42° 47' 31" N		42° 49' 57" N		42° 49' 55" N	
Z	2540 m		2370 m		2310 m		2620 m	
Rock type	–	Olgo	–	Sygo	–	Syd	–	Syd
Column N° in table 1		A		B		C		C
SiO_2	39.25	45.92	39.45	47.77	39.40	47.27	38.98	47.14
Al_2O_3	13.61	16.89	13.63	17.26	13.71	16.98	13.91	16.60
Fe_2O_3t	14.73	11.46	13.46	10.19	13.75	11.35	14.44	11.78
[FeO]	[12.37]	–	[11.73]	–	[11.54]	–	[12.33]	–
MnO	0.17	0.17	0.15	0.16	0.17	0.20	0.16	0.13
MgO	10.85	6.73	11.50	4.25	11.33	5.48	11.10	6.45
CaO	11.00	9.10	11.16	7.45	11.46	6.15	10.60	3.40
Na_2O	2.58	2.63	2.41	4.10	2.31	3.52	2.52	2.67
K_2O	1.16	0.96	1.08	2.16	0.98	2.82	1.08	4.34
TiO_2	5.84	1.67	6.27	2.25	6.25	2.22	6.23	2.31
P_2O_5	0.20	0.51	0.20	0.81	0.15	0.68	0.19	0.68
L.I.	0.43	3.74	0.49	3.25	0.29	3.05	0.59	4.19
[H_2O^+]	[1.66]	–	[1.64]	–	[1.45]	–	[1.83]	–
[F]	[0.14]	–	[0.15]	–	[0.12]	–	[0.13]	–
TOTAL	99.82	99.78	99.80	99.65	99.80	99.72	99.80	99.69
Si	5.89	–	5.89	–	5.90	–	5.83	–
Al	2.11	–	2.11	–	2.10	–	2.17	–
Al	0.30	–	0.29	–	0.32	–	0.28	–
Ti	0.67	–	0.70	–	0.70	–	0.70	–
Fe^{3+}	0.11	–	0.05	–	0.10	–	0.08	–
Mg	2.43	–	2.56	–	2.53	–	2.47	–
Fe^{2+}	1.49	–	1.40	–	1.35	–	1.47	–
Fe^{2+}	0.06	–	0.07	–	0.09	–	0.07	–
Mn	0.02	–	0.02	–	0.02	–	0.02	–
Ca	1.77	–	1.79	–	1.84	–	1.70	–
Na	0.15	–	0.12	–	0.05	–	0.21	–
Na	0.60	–	0.58	–	0.62	–	0.52	–
K	0.22	–	0.21	–	0.19	–	0.20	–
OH	1.66	–	1.63	–	1.45	–	1.83	–
F	0.07	–	0.07	–	0.06	–	0.06	–
Mg/(Mg + Fet)	0.59	0.54	0.63	0.45	0.62	0.49	0.60	0.52
Mg/(Mg + Fe^{2+})	0.61	–	0.64	–	0.64	–	0.62	–

Tab. 4 K–Ar isotope data for kaersutite phenocrysts and their host mafic dykes.
K content determined by atomic absorption (M. VERNET, CRPG , Nancy). ^{40}Ar measured by isotopic dilution using a ^{38}Ar spike and a THN 205E mass spectrometer. $^{40}Ar^*$ calculated with $\lambda_\beta = 4.962 \times 10^{-10} a^{-1}$, $\lambda\gamma = 0.581 \times 10^{-10} a^{-1}$, $^{40}K = 0.01167\%$ K. Other explanations as in table 3.

Sample N°	Paired materials	Analysed material	K (%)	^{40}Ar rad. (10^{-6} cc/g)	^{40}Ar atm. (%)	Apparent age ± 2 σ (Ma)
KR28	Kaersutite	Kaersutite	1.01	11.311	23.4	268 ± 5
FL28	Host dyke	Whole rock	0.82	4.078	46.2	124
KR29	Kaersutite	Kaersutite	0.94	10.451	25.4	266 ± 5
FL29	Host dyke	Whole rock	1.86	8.507	44.4	114 ± 9
KR31	Kaersutite	Kaersutite	0.88	9.796	20.9	266 ± 10
FL31	Host dyke	Whole rock	2.45	7.704	38.2	79 ± 8
KR40	Kaersutite	Kaersutite	0.92	10.431	14.7	271 ± 9
FL40	Host dyke	Whole rock	3.55	8.682	57	62 ± 5

LOUET, 1989), from the Upper Triassic (around 196 Ma; MONTIGNY et al., 1982) tholeiitic dolerites (ophites) (e.g. ROMEU, 1907; ALIBERT, 1985; Figs 5, 6; Tab. 1), as well as from the alkaline magmatism, mid-Cretaceous in age (110–85 Ma), of the North Pyrenean Zone and Spanish Basque Country (e.g. MONTIGNY et al., 1986; AZAMBRE et al., 1992). Actually, the only igneous rocks suitable to compare with these dykes are the (scarce) alkaline formations making up the fifth and last episode of the Stephanian-Permian volcanism (see the "Basque" and "Anayet" groups; Figs 1, 5; Tab. 1). The age ascribed to these alkaline volcanics on the basis of field data is Saxonian (BIXEL, ibid.), corresponding to the dyke emplacement age we have determined (ca. 268 Ma). In addition, this age fits the dates recently obtained for various late-Hercynian volcanics and dykes of the Mediterranean domain, either alkaline as in eastern Provence (278–264 Ma; ZHENG et al., 1991–1992) or calc-alkaline and peraluminous as in northern Sardinia (282–268 Ma; VACCARO et al., 1991). However, in the latter region, alkaline dykes could be significantly younger (ca. 230 Ma).

The present dominant trend of the dykes studied is about N105°E (Fig. 3). Nevertheless, assuming the Axial Zone of the Pyrenees was part of the Iberian Peninsula in late Palaeozoic times (review in BOILLOT et al., 1984; McCLELLAND and McCAIG, 1988–89) and thus may have suffered a mid-Cretaceous counterclockwise rotation by about 35°, their original orientation was possibly close to N140°E.

Surprisingly enough, the dominant trend of the dykes studied (WNW–ESE; Fig. 3) has no equivalent, in western Pyrenees, among the elongated Stephanian-Permian sedimentary or volcanic structures (NW–SE, NE–SW, ENE–WSW; BIXEL, 1984, 1988, 1989; LUCAS, 1985, 1989), despite their similarity in age and location. In the global framework of late-Hercynian wrench tectonics in South-Western Europe (e.g. ARTHAUD and MATTE, 1975; ZIEGLER, 1984), these structures have been related to strike-slip faulting, subparallel to the Pyrenean Range elongation (BIXEL and LUCAS, 1983, 1987; BIXEL, 1984, 1988; LUCAS, 1985). Besides, due to a reversal of the strike-slip movement direction (viz. dextral to sinistral), their trend completely changes, from NW–SE to NE–SW and ENE–WSW, on moving from Stephanian to mid Permian times (e.g. BIXEL, 1988). By comparison with the mode of emplacement recently proposed for Late Cretaceous en echelon granitoids of the Sierra Nevada (TIKOFF and TEYSSIER, 1992), it is suggested that, in such a Permian sinistral strike-slip system, roughly parallel to the Pyrenees elongation, the dykes studied could have been emplaced along second-order

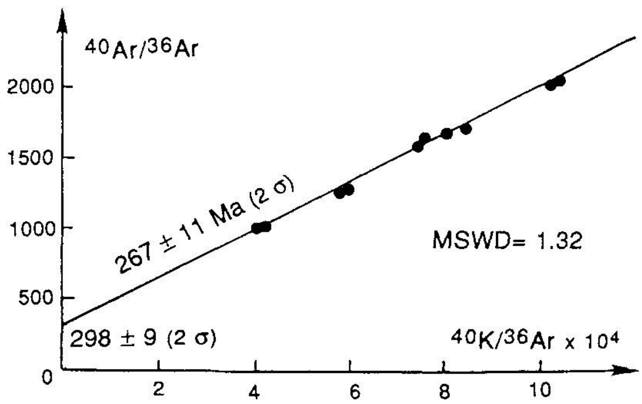

Fig. 7 $^{40}Ar/^{36}Ar$ vs $^{40}K/^{36}Ar$ diagram for the four analysed kaersutite phenocrysts (ten Ar determinations). See table 5 for other explanations.

Tab. 5 K-Ar isochrons for the four analysed kaersutite phenocrysts. For other explanations see, for instance, MONTIGNY (1985).

Isochron diagram	$^{40}Ar^*$ vs % ^{40}K	$^{40}Ar^*/^{36}Ar$ vs $^{40}K/^{36}Ar$
Correlation coefficient r	0.992	0.998
Initial intercept ± 2 σ	0.05 ± 2	298 ± 9
Apparent age (Ma) ± 2 σ	266 ± 54	267 ± 11
M.S.W.D.	0.98	1.32

fractures of the P type, while coeval sedimentary and volcanic formations developed along tension fractures T (Fig. 8). Additional field data are necessary to check up on this hypothetical mode of emplacement, while taking into account the possible Mesozoic rotation of the Axial Zone.

At the Pyrenean Range scale, most intrusion ages of the widespread Hercynian plutons (Fig. 1) range from 300 to 275 Ma (e.g. ENRIQUE and DEBON, 1987; review in COCHERIE et al., in press). In particular, Rb–Sr isotope ages of about 300 Ma, 300 ± 20 Ma and 282 ± 5 Ma have been determined for the Cauterets (DEBON, 1975), Néouvielle (ALIBERT et al., 1988) and St. Laurent-de-Cerdans (COCHERIE, 1985) plutons respectively. In addition, U–Pb zircon ages of 272–278 Ma have been obtained for the Pic du Midi d'Ossau volcanics (Fig. 1) which pre-date the dyke studied emplacement (see above). The brevity of time interval which separates the emplacement and the crystallization of most of this huge plutonism and volcanism from those of the dykes studied (ca. 268 Ma) is noteworthy. At the Range scale, the existence of a significant gap of time between the two types of magmatism is even doubtful, despite their completely different typologies: dominantly calc-alkaline (and aluminous) and of hybrid origin with a prominent sialic crust contribution for the former (e.g. CABANIS, in press; COCHERIE et al., in press; DEBON, in press), but dominantly alkaline, mafic and most likely of exclusively mantle origin for the dykes. Actually, such a drastic compositional change has already been pointed out within the Pyrenean Stephanian-Permian volcanism itself and considered as reflecting a major change in the geodynamic evolution of the belt, viz. from orogenic conditions to anorogenic ones, or, in other words, as marking the transition from the Hercynian cycle to the Atlantic-Alpine one (e.g. BIXEL, 1988, 1989; CABANIS and LE FUR-BALOUET, 1989; INNOCENT et al., 1993). The dykes studied provide us with an accurate reference mark in defining the timing of such a transition.

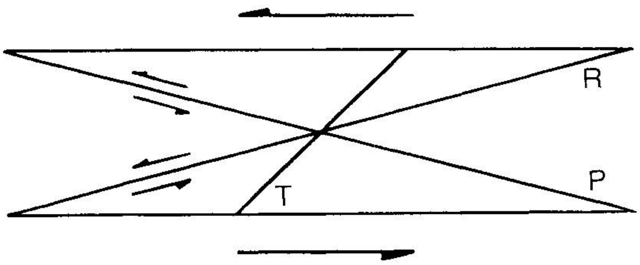

Fig. 8 Ideal fracture orientations in a sinistral strike-slip system. P and R are second order fractures and T is tension fracture. Notice that P and T fractures are oriented about 15° and 45° respectively off overall direction of shear. Modified from TIKOFF and TEYSSIER (1992).

This drastic and abrupt compositional transition is not specific to the Pyrenees. Such an evolution in magmatic sequences is in fact not uncommon and has been pointed out in many collisional domains (BOULLIER et al., 1986). In particular, it has been described in different parts of the western European Variscan, especially in the Alpine-Mediterranean belt (review in BONIN, 1988). According to this author, mid-Permian times (270 Ma) are a critical period for this belt, marked by a sharp magmatic discontinuity evidenced in the emplacement of the first alkaline complexes, at the same places as previous calc-alkaline and peraluminous anatectic igneous formations. As in the Pyrenees, this change is accompanied by a reversal in the sense of movement of pre-existing late-Variscan faults ("harpoon effect" of BLACK et al., 1985) that may have triggered or enhanced partial melting in the mantle. The transition from orogenic to anorogenic regimes is also marked by a complete change in the nature of the magma source, viz. from a dominantly crustal or hybrid source to an exclusively undepleted mantle source (BONIN, ibid.).

An exemplary case of sharp transition from calc-alkaline to alkaline magmatism, displaying numerous features similar to those observed in the Pyrenees, has been described in the Pan-African belt of the Adrar des Iforas (e.g. BOULLIER et al., 1986; LIÉGEOIS and BLACK, 1987). The transition is clearly seen in spectacular dyke swarms and is accompanied by transcurrent movements along major shear zones. It has been related to reversals in the stress field during and after collision. The major reversal is thought to have been responsible for disruption of an oceanic subducted lithospheric slab allowing the rise to shallow depth, beneath the continental lithosphere, of asthenospheric mantle, believed to be the source of the alkaline magmatism. The switch from calc-alkaline to alkaline magmatism, which is attributed to a complete change of the magma source, occurred in a short interval of time (less than 10 Ma).

An asthenospheric source has also been proposed for the Saxonian alkaline volcanics of the western Pyrenees on the basis of isotopic data (BRIQUEU and INNOCENT, 1993; INNOCENT et al., 1993). As a result of the melting of this new source, mafic alkaline magmas are produced. Because the dykes studied compare with these volcanics (see above), their original magma is likely to have originated from the same asthenospheric source. The model proposed in the Adrar des Iforas to account for the rise of asthenospheric mantle at shallow depth seems not suitable for the Pyrenees as far as it involves the disruption of a subducted oceanic lithospheric slab. Actually, direct evidence of such a subducted slab is lacking here. An alternative model, based on recent works on the Variscan belt (e.g. MÉNARD and MOLNAR, 1988) and more specially on the Pyrenees (VISSERS, 1992; VISSERS et al., 1993), considers that "lithosphere thickening in the European Variscan led to the development of a gravitationally unstable lithospheric root, which consequently detached to be replaced by upwelling asthenospheric mantle" (VISSERS, ibid.). A progressive thinning and the final disappearance of the lithospheric mantle has also been proposed (BRIQUEU and INNOCENT, 1993; INNOCENT et al., 1993). Whatever it may be, an ascent of asthenospheric mantle, triggered by a reversal in the stress field, seems likely to account for the genesis of the Saxonian alkaline magmatism (volcanics and dykes) of the Pyrenees.

Central to the discussion about the Pyrenean tectonics in mid-Permian times is the following observation of ROMEU (1907) on the distribution of the dykes studied along the Axial Zone: "...il y a une très grande variété dans la répartition de ces filons dans les diverses parties de la chaîne. Ils sont presque complètement absents dans les massifs granitiques des Pyrénées-Orientales, de l'Aude et de l'Ariège et dans leur ceinture sédimentaire; ils abondent au contraire dans les Hautes-Pyrénées et dans l'est des Basses-Pyrénées. C'est un fait que nous nous bornons à constater sans en pouvoir donner une explication plausible". So, these dykes are almost completely lacking in central and eastern parts of the Axial Zone and very abundant on the west. This contrasting distribution suggests that mid-Permian tectonic conditions prevailing in the western part of the Pyrenean Range were different from those prevailing in its central and eastern parts. For example, it could indicate that the western part was under transtension while, at the same time, the central and eastern parts were under transpression. The coexistence of extension on the west and compression on the east of the Pyrenees has been reported in Upper Cretaceous times (e.g. PUIGDEFÀBREGAS and SOUQUET, 1986) and two major ways of accounting for it have been proposed: (1) According to CHOUKROUNE and MATTAUER (1978), the existence of transitions from extensional to compressive conditions is a quite common feature along large transcurrent faulting zone, and as such would have been the case along the wide (more than 200 km) "North Pyrenean Transform Zone" related to the opening of the Bay of Biscay. (2) Following DUCASSE et al. (1986), the Upper Cretaceous synchronism between rifting on the west and strong N–S compression on the east of the Pyrenees would result from the anti-clockwise rotation of the Iberian plate in a global motion of the scissors-opening type, the pole of which being assumed approximately located in the middle part of the Axial Zone. Though rather different, the model recently defined by SIBUET and COLLETTE (1991) for the formation of the Bay of Biscay also invokes a motion of the scissors-opening type and predicts simultaneous compression in Central and Eastern Pyrenees. Whatever it may be, the mid-Permian dyke distribution along the Range could suggest that, as soon as the Saxonian times, tectonic conditions somewhat similar to those prevailing during the Cretaceous and including, in particular, the rotation of Iberia, controlled the Pyrenean evolution. Therefore, the earliest beginnings of the Iberian plate motion away from Europe and of the rotational events responsible for the opening of the Bay of Biscay would be older than usually assumed, i.e. Saxonian instead of Triassic or Upper Jurassic (MATTAUER and SÉGURET, 1971; BOILLOT et al., 1984).

Concluding remarks

A comprehensive inventory and structural study of the Saxonian dykes all along the Pyrenean (and Catalonian Coastal) Range should be important in determining the mid-Permian tectonic constraints and thus in defining what was, at this time, the type of movement, if any, between Iberian and European plates.

Due to the scarcity of good markers, it is often very difficult if not impossible to clearly distinguish between late-Hercynian and Alpine tectonics in the Pyrenees. The Saxonian dykes of the Axial Zone should be helpful for such a distinction. In addition, these dykes could be useful markers in reconstructing the north Atlantic domain in mid-Permian times.

Whole rock K–Ar dates obtained for the dykes studied (Tab. 4) are much younger than their emplacement age (ca. 268 Ma). It is noteworthy that they scatter between 62 and 124 Ma that is close to the time interval (110–85 Ma) where the intriguing mid-Cretaceous magmatic and metamorphic event recorded in the North Pyrenean Zone and Spanish Basque Country occurred (e.g. MONTIGNY et al., 1986; AZAMBRE et al., 1992). It may be asked whether, in addition to alteration-devitrification processes, this event could have played a role in the resetting of the whole rock K–Ar system of the Saxonian dykes, viz. could have also affected the Pyrenean Axial Zone. A $^{40}Ar/^{39}Ar$ study on kaersutite phenocrysts could be fruitful in checking such a possibility.

The dykes studied mark the transition from orogenic to anorogenic conditions in the late-Palaeozoic Pyrenees. Their detailed mineralogical, chemical and isotopic study should be crucial in deciphering the effects of this transition on the magmatic and geodynamic evolution of the Pyrenean range.

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References

ALIBERT, C. (1985): A Sr–Nd isotope and REE study of late Triassic dolerites from the Pyrenees (France) and the Messejana Dyke (Spain and Portugal). Earth Planet. Sci. Lett. 73, 81–90.

ALIBERT, C., DEBON, F. and TERNET, Y. (1988): Le pluton à structure concentrique du Néouvielle (Hautes-Pyrénées): typologie chimique, âge et genèse. C.R. Acad. Sci. Paris 306, II, 49–54.

ARTHAUD, F. and MATTE, P. (1975): Les décrochements tardi-hercyniens du sud-ouest de l'Europe. Géométrie et essai de reconstitution des conditions de la déformation. Tectonophysics 25, 139–171.

AUTRAN, A., COCHERIE, A., ENRIQUE, P., LIESA, M. and MORALÉS, V. (in press): Pluton de Saint Laurent-de-Cerdans et pluton associé de Batère. In: Plutonisme hercynien des Pyrénées, DEBON, F. and ENRIQUE, P. coords. Synthèse géologique et géophysique des Pyrénées, BRGM and ITGE eds.

AZAMBRE, B., ROSSY, M. and ALBARÈDE, F. (1992): Petrology of the alkaline magmatism from the Cretaceous North-Pyrenean Rift Zone (France and Spain). Europ. J. Mineral., 4, 813–834.

BÉDARD, J.H. (1988): Comparative amphibole chemistry of the Monteregian and White Mountain alkaline suites, and the origin of amphibole megacrysts in alkali basalts and lamprophyres. Mineral. Mag. 52, 91–103.

BIXEL, F. (1984): Le volcanisme stéphano-permien des Pyrénées. Thèse Sci., Univ. Paul Sabatier, Toulouse, 637 p.

BIXEL, F. (1988): Le volcanisme stéphano-permien des Pyrénées Atlantiques. Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine 12/2, 661–706.

BIXEL, F. (1989): Le volcanisme des Pyrénées. In: Synthèse géologique des bassins permiens français, CHÂTEAUNEUF, J.J. and FARJANEL, G. coords. Mém. BRGM 128, C3.7, 258–265.

BIXEL, F. and LUCAS, C. (1983): Magmatisme, tectonique et sédimentation dans les fossés stéphano-permiens des Pyrénées occidentales. Rev. Géogr. phys. Géol. dyn. 24, 329–342.

BIXEL, F. and LUCAS, C. (1987): Approche géodynamique du Permien et du Trias des Pyrénées dans le cadre du sud-ouest européen. Cuad. Geol. Iberica 11, 57-81.

BLACK, R., LAMEYRE, J. and BONIN, B. (1985): The structural setting of alkaline complexes. J. Afr. Earth Sci. 3, 5–16.

BOILLOT, G., MONTADERT, L., LEMOINE, M. and BIJU-DUVAL, B. (1984): Les marges continentales actuelles et fossiles autour de la France. Masson Paris, 342 p.

BONIN, B. (1988): From orogenic to anorogenic environments: evidence from associated magmatic episodes. Schweiz. Mineral. Petrogr. Mitt. 68, 301–311.

BOULLIER, A.M., LIÉGEOIS, J.P., BLACK, R., FABRE, J., SAUVAGE, M. and BERTRAND, J.M. (1986): Late Pan-African tectonics marking the transition from subduction-related calc-alkaline magmatism to within-plate alkaline granitoids (Adrar de Iforas, Mali). Tectonophysics 132, 233–246.

BRESSON, A. (1903): Etudes sur les formations anciennes des Hautes et Basses Pyrénées (Haute Chaîne). Bull. Serv. Carte géol. Fr. XIV/93, 45–323.

BRESSON, A. and CAREZ, L. (1905): Carte géologique de la France à 1/80000, feuille Luz, 1re édit., Serv. Carte géol. Fr., Paris.

BRIQUEU, L. and INNOCENT, C. (1993): Datation U/Pb sur zircon et géochimie isotopique Sr et Nd du volcanisme permien des Pyrénées occidentales (Ossau et Anayet). C.R. Acad. Sci. Paris 316, II, 623–628.

CABANIS, B., coord. (in press): Volcanisme stéphano-permien. In: Synthèse géologique et géophysique des Pyrénées, BRGM and ITGE eds.

CABANIS, B. and LE FUR-BALOUET, S. (1989): Les magmatismes stéphano-permiens des Pyrénées marqueurs de l'évolution géodynamique de la Chaîne: apport de la géochimie des éléments en traces. Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine 13/1, 105–130.

CHOUKROUNE, P. and MATTAUER, M. (1978): Tectonique des plaques et Pyrénées: sur le fonctionnement de la faille transformante nord-pyrénéenne; comparaison avec les modèles actuels. Bull. Soc. géol. Fr. (7), 20/5, 689–700.

Cocherie, A. (1985): Interaction manteau-croûte: son rôle dans la genèse d'associations plutoniques calco-alcalines, contraintes géochimiques (éléments en traces et isotopes du strontium et de l'oxygène). Doc. BRGM 90, 246 p.

Cocherie, A., Wickham, S.M. and Autran, A. (in press): Géochimie des isotopes stables et radioactifs – Géochronologie. In: Plutonisme hercynien des Pyrénées, Debon, F. and Enrique, P. coords. Synthèse géologique et géophysique des Pyrénées, BRGM and ITGE eds.

Cullers, R.L. and Graf, J.L. (1984): Rare earth elements in igneous rocks of the continental crust: predominantly basic and ultrabasic rocks. In: Rare earth element geochemistry, Henderson, P. ed. Developments in Geochemistry 2, Elsevier Amsterdam, 237–274.

Dalrymple, G.B., Gromme, C.S. and White, R.W. (1975): Potassium-argon age and paleomagnetism of diabase dikes in Liberia: initiation of Central Atlantic rifting. Geol. Soc. Am. Bull. 86, 399–411.

Debon, F. (1972): Carte géologique à 1/50 000 des massifs granitiques de Cauterets et Panticosa (Pyrénées occidentales) et notice explicative. BRGM and CNRS eds., 37 p.

Debon, F. (1975): Les massifs granitoïdes à structure concentrique de Cauterets-Panticosa (Pyrénées occidentales) et leurs enclaves. Une étude pétrographique et géochimique. Mém. Sci. de la Terre, Nancy 33, 420 p.

Debon, F. (1980): Genesis of the three concentrically-zoned granitoid plutons of Cauterets-Panticosa (French and Spanish Western Pyrenees). Geol. Rundsch. 69, 107–130.

Debon, F. (in press): Problèmes génétiques. In: Plutonisme hercynien des Pyrénées, Debon, F. and Enrique, P. coords. Synthèse géologique et géophysique des Pyrénées, BRGM and ITGE eds.

Ducasse, L., Muller, J. and Velasque, P.C. (1986): La chaîne pyrénéo-cantabrique: subduction hercynienne, rotation crétacée de l'Ibérie et subductions alpines différentielles. C. R. Acad. Sci. Paris 303, II, 419–424.

Enrique, P. and Debon, F. (1987): Le pluton permien calcoalcalin de Montnègre (Chaînes Côtières Catalanes, Espagne): étude isotopique Rb–Sr et comparaison avec les granites hercyniens des Pyrénées, Sardaigne et Corse. C.R. Acad. Sci. Paris 305, II, 1157–1162.

Evensen, N.M., Hamilton, P.J. and O'Nions, R.K. (1978): Rare-earth abundances in chondritic meteorites. Geochim. Cosmochim. Acta 42, 1199–1212.

François, J.M. (1983): Etude géologique et métallogénique de la région du Pic du Midi de Bigorre (Hautes-Pyrénées). Thèse 3e Cycle, INPL Nancy, 235 p.

Haq, B.U. and Van Eysinga, F.W.B. (1987): Geological time table. Elsevier Amsterdam.

Harrison, T.M. and McDougall, I. (1980): Investigations of an intrusive contact, northwest Nelson, New Zealand – Diffusion of radiogenic and excess ^{40}Ar in hornblende revealed by $^{40}Ar/^{39}Ar$ age spectrum analysis. Geochim. Cosmochim. Acta 44, 2005–2020.

Hart, S.R. (1964): The petrology and isotopic mineral age relations in a contact zone in Front Range Colorado. J. Geol. 72, 493–525.

Innocent, C. (1989): Géochimie Sr–Nd et géochronologie Rb–Sr et U–Pb du volcanisme stéphano-permien du bassin arago-béarnais. Implications géodynamiques. D.E.A., Univ. Montpellier II, 92 p.

Innocent, C., Briqueu, L. and Cabanis, B. (1993): Permian volcanism in the Pyrenees: another type of calc-alkaline magmatism? Doc. BRGM 219, 98–99.

Lamouroux, C. (1976): Les mylonites dans le massif du Néouvielle (textures, déformations intracristallines). Déformations pyrénéennes dans un complexe plutonique hercynien. Thèse 3e Cycle, Univ. Paul Sabatier, Toulouse, 148 p.

La Roche, H. de, Leterrier, J., Grandclaude, P. and Marchal, M. (1980): A classification of volcanic and plutonic rocks using R1R2 diagram and major element analyses. Its relationships with current nomenclature. Chem. Geol. 29, 183–210.

Leake, B.E. (1978): Nomenclature of amphiboles. Amer. Miner. 63, 1023–1052.

Liégeois, J.P. and Black, R. (1987): Alkaline magmatism subsequent to collision in the Pan-African belt of the Adrar des Iforas (Mali). In: Alkaline igneous rocks, Fitton, J.G. and Upton, B.G.J. (eds) Geol. Soc. Spec. Publ. 30, 381–401.

Lucas, C. (1985): Essai sur la géodynamique de dépôts continentaux du Permien et du Trias: le grès rouge du versant nord des Pyrénées. Thèse Sci., Univ. Paul Sabatier, Toulouse, 266 p.

Lucas, C. (1989): Le Permien des Pyrénées. In: Synthèse géologique des bassins permiens français, Châteauneuf, J.J. and Farjanel, G. coords. Mém. BRGM 128, B17, 139–150.

Mattauer, M. and Séguret, M. (1971): Les relations entre la chaîne des Pyrénées et le golfe de Gascogne. In: Histoire structurale du golfe de Gascogne, Technip. ed., Paris, t.1, IV/4, 1–24.

McClelland, E.A. and McCaig, A.M. (1988–89): Palaeomagnetic estimates of total rotation in basement thrust sheets, Axial Zone, Southern Pyrenees. Cuad. Geol. Iberica 12, 181–193.

Ménard, G. and Molnar, P. (1988): Collapse of a Hercynian Tibetan Plateau into a late Palaeozoic European Basin and Range province. Nature 334, 235–237.

Montigny, R. (1985): Méthode classique potassium-argon. In: Méthodes de datation par les phénomènes nucléaires naturels – Applications, Roth, E. and Poty, B. Directs. Collection CEA, Série Sci., Masson Paris, 311–340.

Montigny, R., Azambre, B., Rossy, M. and Thuizat, R. (1982): Etude K/Ar du magmatisme basique lié au Trias supérieur des Pyrénées. Conséquences méthodologiques et paléogéographiques. Bull. Minéral. 105, 673–680.

Montigny, R., Azambre, B., Rossy, M. and Thuizat, R. (1986): K–Ar study of Cretaceous magmatism and metamorphism in the Pyrenees: age and length of rotation of the Iberian peninsula. Tectonophysics 129, 257–273.

Onstott, T.C. and Peacock, M.W. (1987): Argon retentivity of hornblendes: A field experiment in a slowly cooled metamorphic terrane. Geochim. Cosmochim. Acta 51, 2891–2903.

Puigdefabregàs, C. and Souquet, P. (1986): Tecto-sedimentary cycles and depositional sequences of the Mesozoic and Tertiary from the Pyrenees. Tectonophysics 129, 173–203.

Roddick, J.C. and Farrar, E. (1971): High initial argon ratios in hornblendes. Earth Planet. Sci. Lett. 12, 208–214.

Romeu, A. de (1907): Les roches filoniennes paléozoïques non granitiques des Pyrénées. Bull. Soc. Fr. Minéral. 30, 110–216.

SHAND, S.J. (1927): Eruptive rocks. Their genesis, composition, classification and their relation to ore-deposits. Murby, London.

SIBUET, J.C. and COLLETTE, B.J. (1991): Triple junctions of Bay of Biscay and North Atlantic: new constraints on the kinematic evolution. Geology 19, 522–525.

TIKOFF, B. and TEYSSIER, C. (1992): Crustal-scale, en echelon "P-shear" tensional bridges: A possible solution to the batholithic room problem. Geology 20, 927–930.

VACCARO, C., ATZORI, P., DEL MORO, A., ODDONE, M., TRAVERSA, G. and VILLA, I.M. (1991): Geochronology and Sr isotope geochemistry of late-Hercynian dykes from Sardinia. Schweiz. Mineral. Petrogr. Mitt. 71, 175–186.

VISSERS, R.L.M. (1992): Variscan extension in the Pyrenees. Tectonics 11, 1369–1384.

VISSERS, R.L.M., DE JONG, A.C. and WORTEL, M.J.R. (1993): Late Variscan extension in the Pyrenees: geological constraints and a thermal model study. Doc. BRGM 219, 207.

ZHENG, J.S., MERMET, J.F., TOUTIN-MORIN, N., HANES, J., GONDOLO, A., MORIN, R. and FÉRAUD, G. (1991–1992): Datation ^{40}Ar–^{39}Ar du magmatisme et de filons minéralisés permiens en Provence orientale (France). Geodinam. Acta 5, 203–215.

ZIEGLER, P.A. (1984): Caledonian and Hercynian crustal consolidation of Western and Central Europe – A working hypothesis. Geol. Mijnbouw 63, 93–108.

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