The lamprophyric sub-vertical dyke swarm from Aiguablava (Catalonian Coastal Ranges): petrology and composition

El enjambre sub-vertical de diques de lamprófido de Aiguablava (Cadenas Costero-Catalanas): petrología y composición

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RESUMEN

En este trabajo presentamos un estudio petrológico detallado de algunos de los diques de lamprófido sub-verticales de edad Pérmica del complejo intrusivo de Aiguablava (Cadenas Costero Catalanas). Aportamos nuevos datos composicionales, tanto en minerales (elementos mayores) como en roca total (elementos mayores y traza), de algunos de los diques más inalterados. Del estudio realizado se deduce que todos los magmas lamprofídicos estudiados tienen un origen común, si bien presentan un pequeño rango de fraccionamiento, en el que diferenciamos tres etapas relacionadas con tres pulsos magmáticos. Según nuestros datos, algunos de los diques considerados anteriormente como espesartitas de afinidad calco-alcalina podrían tener una afinidad transicional (de subalcalina a alcalina).

Palabras clave: *Lamprófido, afinidad transicional, Pérmico, Aiguablava, Cadenas Costero-Catalanas.*

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Introduction

The Aiguablava pluton is part of the Catalonian Coastal Ranges batholith (Fig. 1A). This batholith, composed of calc-alkaline biotite granites, granodiorites, and monzogranites (Enrique, 1990), was emplaced at the end of the Variscan cycle.

Two lamprophyric dyke families can be recognized crosscutting the Aiguablava pluton (Fig. 1B): the most frequent is a WNW-ESE sub-vertical system, mainly considered to be calc-alkaline and Permian in age (Losantos *et al.*, 2000). The second system is sub-horizontal and clearly alkaline in composition, and sometimes cut the former. The age of this second group is late-Cretaceous (Solé *et al.*, 2003).

Neither the late-Variscan nor the late-Cretaceous lamprophyres have ever been studied in detail from a petrological point of view. The first references deal with their location and petrography (San Miguel de la Cámara, 1936 and San Miguel Arribas, 1952). More recently, Gimeno (2002) described their structure and mineralogy.

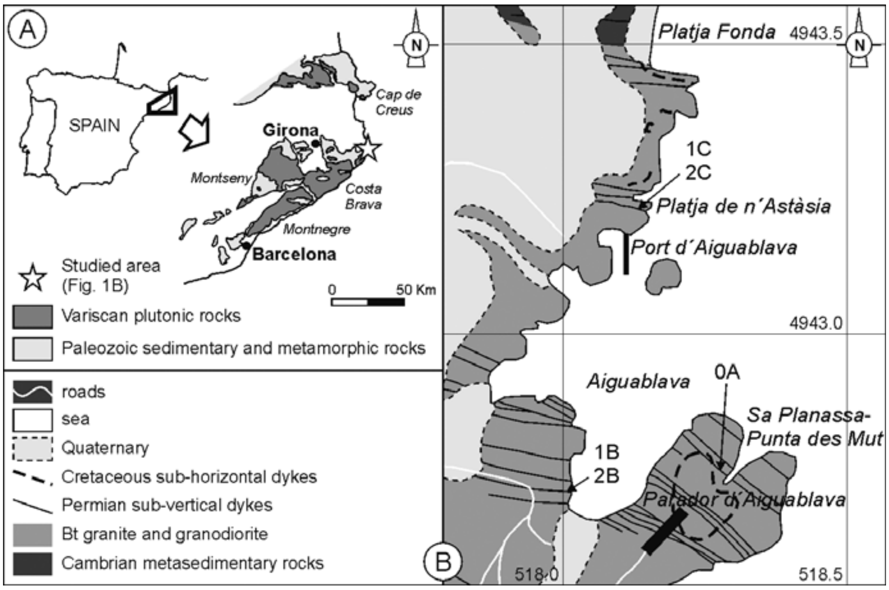

Fig. 1.- Location of the lamprophyric sub-vertical dyke swarm from Aiguablava. A) Modified from Enrique (1990); B) Modified from Losantos *et al.* (2000) and Enrique (2009). UTM grid and coordinates. Arrows indicate the location of the studied samples (0A, 1B, 2B, 1C, 2C).

Fig. 1.- Localización de los diques sub-verticales de lamprófido de Aiguablava. A) Modificado de Enrique (1990); B) Modificado de Losantos* et al. *(2000) y Enrique (2009). Cuadrícula y coordenadas UTM. Las flechas indican la localización de las cinco muestras estudiadas (0A, 1B, 2B, 1C, 2C).

In the last three years, the first compositional data set of minerals (Ubide *et al*., 2008a and b) and new whole rock compositions (Enrique, 2009) have been published.

In this paper we focus on the Permian sub-vertical dyke system cropping out in Aiguablava coast (Fig. 1B). Traditionally, these lamprophyres have been classified as spessartites of calc-alkaline affinity. We present a detailed petrological study, providing new compositional results in minerals and whole rock.

Field relationships

The Permian dyke swarm from Aiguablava consists of sub-vertical lamprophyre dykes with a general strike of N100-110 (Fig. 1B). They are tabular in shape, centimetric to metric in thickness, present sharp contacts with the host and, frequently, they are branched to their extremes (Fig. 2A). Segmented geometries are very common, especially in the thinnest dikes (Fig. 2B). All the dikes are affected by a dense network of fractures, some of which are sub-parallel to them.

The rock in the central parts of the dikes is aphanitic, although it presents millimetre-sized non-oriented mafic minerals, and it develops aphyric chilled margins, which indicate that when the dikes emplaced, the host rock was considerably colder than the lamprophyric magma. Granitic xenoliths are sometimes observed inside the dykes.

Cross-cutting relationships among sub-vertical dykes with slightly different orientations are common (Fig. 2B). In such cases, the cutting dike (stage 2) develops a very thin chilled margin, indicating that the dyke which is cut (stage 1) was slightly colder. Chilled margins are also recognized within some dikes (Fig. 2C), indicating magma refilling processes.

Samples and methods

Most dykes belonging to the studied system are strongly altered, so petrographical observations and, afterwards, chemical analyses were carried out on the 5 least altered samples, obtained from Sa Planassa- Punta des Mut (sample 0A), Platja d´Aiguablava (samples 1B and 2B) and Platja de n'Astàsia (samples 1C and 2C) outcrops (Fig. 1B).

Sample 0A belongs to a dyke which is cut by one of the late-Cretaceous sub-horizontal lamprophyres. In Platja d´Aiguablava outcrop, sample 1B (stage 1) belongs to a dyke cut by another sub-vertical one, from which sample 2B (stage 2) was taken. In the same way, in Platja de n'Astàsia outcrop sample 1C (stage 1) was obtained from a dyke cut by another sub-vertical one, from which sample 2C (stage 2) was extracted.

Chemical analyses on minerals were developed using a JEOL JZA-8900 M electron microprobe at the Universidad Complutense de Madrid.

Major and trace element concentrations were determined at the Service d´Analyse des Roches et des Minéraux (SARM) in Nancy (France). The samples were analyzed by ICP-AES for major elements and ICP-MS for trace elements.

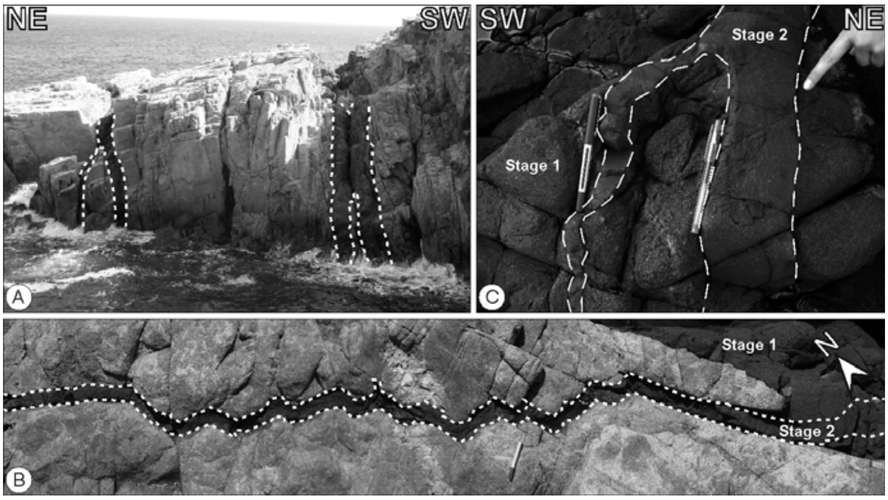

Fig. 2.- Field photographs of the lamprophyric sub-vertical dyke swarm from Aiguablava. A) Sa Planassa- Punta des Mut outcrop. B) and C) Platja de n'Astàsia outcrop.

Fig. 2.- Fotografías de campo de los diques de lamprófido sub-verticales de Aiguablava. A) Afloramiento de Sa Planassa- Punta des Mut; B) y C) Afloramiento de Platja de n'Astàsia.

Petrography

The mineral assemblage of the studied lamprophyres is given in table I. Modal proportions are very similar among stage 1 dykes or stage 2 dykes, so average proportions are given in each case. These lamprophyres show porphyritic holocrystalline and occasional hypocrystalline microstructures, where the glass is recrystallized; the phenocrysts correspond to partly altered clinopyroxene, plagioclase (variably transformed to sericite) and olivine, completely pseudomorphosed by chlorite-smectite assemblages. Noteworthy, in some of the stage 2 dykes (samples 2B and 2C) olivine-clinopyroxene-plagioclase microenclaves have been identified. Plagioclase and quartz xenocrysts are sometimes present.

Mineral chemistry

Clinopyroxene is Ti-rich augite-diopside (TiO_2 up to 4.5 wt. %). The obtained compositions define a differentiation trend (Fs8-Fs22) from sample 0A to samples 2B and 2C (Fig. 3). However, Cpx in the microenclaves described for stage 2 samples yield primitive compositions in agreement with those found in sample 0A (Fig. 3).

The Ti-increasing trend, together with the fact that most compositions plot in the alkaline field defined by Leterrier *et al.*

Mineral	0A	1B + 1C	2B + 2C
(Ol)	2	--	4
Cpx	12	15	25
Amp	--	2	<1
Pl	75	65	40
Op	5-6	7-8	7-8
Bt	2	0-1	--
Ap	<1	<1	--
Chl	1	7-8	--
Cal	2	2	<1
Glass	--	--	25
x-Qtz	2	1	--

Table I.- Modal composition (% in vol.) of the studied lamprophyres. (Ol): olivine pseudomorphs; Op: opaque minerals; x-Qtz: quartz xenocrysts).

Tabla I.- Proporciones modales (% en vol.) de los lamprófidos estudiados. (Ol): pseudomorfos de olivino; Op: minerales opacos; x-Qtz: xenocristales de cuarzo.

(1982), supports an alkaline affinity for this mineral in the studied lamprophyres (Fig. 3).

Plagioclase composition varies from An80 to An30, where the most primitive crystals belong to sample 0A (An80–An46). The most evolved compositions (lowest An values) show the highest Or contents, yielding a trend typical of alkaline plagioclase.

Amphibole occurs only as a late phase in the groundmass of the samples. According to Leake *et al.* (1997), the compositions correspond to edenite, Mg-hornblende and actinolite in sample 1B, Mg-hastingsite in sample 1C and Mg-hastingsite and tschermakite in sample 2B. The actinolite compositions (sample 1B) correspond to pale-green amphibole developed at clinopyroxene rims, probably related to the pneumatolytic action of residual water-enriched magmatic fluids on primary pyroxene crystals.

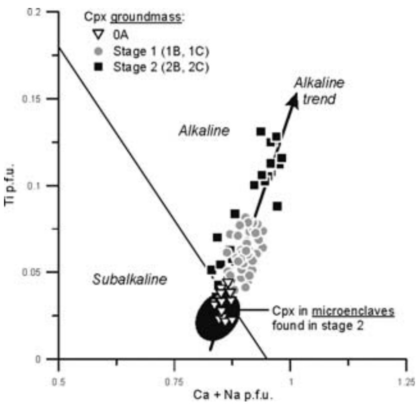

Fig. 3.- Ti p.f.u. vs. Ca+Na p.f.u. diagram for Cpx compositions (Leterrier *et al.*, 1982).

Fig. 3.- Composiciones de Cpx en el diagrama Ti p.f.u. vs. Ca+Na p.f.u. (Leterrier **et al.*, 1982).***

Most of the analysed opaque minerals are ilmenite, although some pyrite crystals were also found.

Finally, biotite was analysed in sample 0A, where it represents up to 2% in vol. of the rock. The Fe2+/(Fe2++Mg) ratio p.f.u. (per formula unit) varies from 0.39 to 0.48. Although it is classified as biotite, its composition is close to phlogopite.

Whole rock chemistry

The composition of the five studied lamprophyres (Table II) is highly coincident, being 0A the most primitive. This composition is very similar to the two analyses previously published by Enrique (2009) on Permian lamprophyres from Aiguablava.

Concerning the affinity of the rocks, their low Nb/Y and Zr/TiO2 ratios and their relatively high total-alkalis contents, together with their mineralogy, support an intermediate (transitional) affinity.

Regarding the trace element composition, the analysed samples are also highly coincident (Fig. 4). In detail, the five normalized REE patterns arrange in order of increasing REE (especially HREE) abundance as follows: 0A, stage 1 dykes (1B and 1C)

	0A	1B	1C	2B	2C
SiO_2	49,79	49,38	49,56	50,93	49,08
TiO_2	1,01	1,24	1,29	1,31	1,29
Al_2O_3	15,55	15,93	16,23	16,16	16,10
Fe_2O_3	8,32	9,16	9,06	8,49	9,15
MnO	0,13	0,16	0,18	0,15	0,16
MgO	8,47	7,74	8,29	7,32	8,02
CaO	7,17	7,57	6,49	6,10	6,82
Na_2O	2,01	3,26	3,16	4,69	3,19
K_2O	1,99	1,38	1,65	1,08	1,77
P_2O_5	0,26	0,30	0,33	0,31	0,33
L.O.I.	5,89	4,26	4,39	4,06	4,42
Total	100,57	100,37	100,64	100,60	100,34
mg#	*0,70*	*0,66*	*0,68*	*0,66*	*0,67*
La	27,32	21,02	23,49	24,60	24,09
Ce	57,24	46,91	51,08	55,03	52,11
Pr	6,95	5,97	6,46	7,02	6,55
Nd	27,60	25,02	26,73	29,16	26,94
Sm	5,65	5,55	5,69	6,38	5,77
Eu	1,45	1,52	1,55	1,39	1,55
Gd	4,96	5,19	5,19	5,87	5,34
Tb	0,77	0,82	0,81	0,92	0,83
Dy	4,48	4,94	4,83	5,46	4,85
Ho	0,88	0,98	0,95	1,10	0,97
Er	2,47	2,74	2,65	3,05	2,69
Tm	0,36	0,41	0,39	0,46	0,39
Yb	2,37	2,69	2,55	2,99	2,61
Lu	0,37	0,41	0,40	0,45	0,41
Nb/Y	0,37	0,32	0,37	0,29	0,37
Zr/TiO_2	168,6	138,0	134,0	150,0	135,3

Table II.- Whole rock composition (major elements in wt.% and trace elements in ppm) of the studied lamprophyres. L.O.I.: loss on ignition; mg#: molar ratio Mg/(Mg+Fe2+).

Tabla II.- Composición en roca total (elementos mayores en % en peso y elementos traza en ppm) de los lamprófidos estudiados. L.O.I.: pérdida al fuego; mg#: relación molar Mg/(Mg+Fe2+).

and stage 2 dykes (2B and 2C). The most evolved sample, with the highest HREE contents and the strongest Eu negative anomaly is 2B.

Discussion

The five studied lamprophyre samples present little compositional variations, suggesting a common origin. However, the small compositional differences among them define a clear differentiation trend. Sample 0A displays the most primitive composition. Its Cpx and Pl crystals are the least evolved; furthermore, it presents the highest mg# and lowest TiO2, Na2O, P2O5 and REE (especially HREE) values. On the contrary, samples 2B and 2C (stage 2 dykes) show opposite characteristics, even developing a Eu negative anomaly (Fig. 4), probably due to plagioclase fractionation.

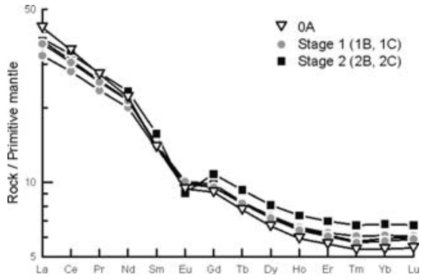

Fig. 4.- Primitive mantle (McDonough & Sun, 1995) normalized REE patterns.

Fig. 4.- Pautas de REE normalizadas al manto primitivo (McDonough & Sun, 1995).

Therefore, the differentiation steps might be: 0A (stage 0) – 1B and 1C (stage 1) – 2B and 2C (stage 2). Accordingly, stage 0 dykes may be slightly older than stage 1 dykes; stage 2 dykes should be the youngest. This assumption agrees with field observations that stage 2 dykes cut stage 1 dykes (Fig. 2B and 2C).

An interesting observation is that Cpx crystals in stage 2 dykes (the most evolved) show two contrasting compositions (Fig. 3). On the one hand, groundmass Cpx crystals are the most evolved. But on the other hand, Cpx crystals from the microenclaves show similar compositional characteristics as Cpx crystals from sample 0A (stage 0, the least evolved). These observations lead to the conclusion that microenclaves in stage 2 dykes could represent fragments of stage 0 rocks or crystal clusters that, afterwards, are carried by stage 2 magmas to the emplacement level.

Traditionally, the Aiguablava subvertical Permian lamprophyres have been considered calc-alkaline spessartites, related to the latest emplacement stages of the pluton (e.g. Enrique, 1990). However, this detailed petrological study provides new data for their classification. First, taking into account the petrography and mineral chemistry of the samples, the studied lamprophyres are closer to the camptonite group than to spessartite (Le Maitre, 2002): the primary mineral assemblage in our samples contains Ti-augite, olivine, biotite and more plagioclase than K-feldspar, although amphibole is present in very low proportions, or even absent. In second place, although the whole rock compositions point to a subalkaline affinity (e.g. relatively low Nb/Y and Zr/TiO2 ratios), other criteria indicate an alkaline affinity, namely: the presence of olivine and Ti-rich clinopyroxene, the alkaline trend defined by Cpx and Pl compositions, the fact that biotite compositions are close to phlogopite and the relatively high total-alkalis content of the whole rock compositions. This content increases from stage 0 to stage 2, so that an increasing alkaline character has been recognized parallel to the fractionation process.

According to all the presented data, the studied Permian dykes in Aiguablava have a subalkaline to alkaline transitional affinity and are not strictly calc-alkaline spessartites, as traditionally considered. A similar case has been proposed previously for Permian lamprophyres in the Central Pyrenees (Galé, 2005). This kind of rocks, with compositional features intermediate between calc-alkaline and alkaline rocks may represent the products of a transitional tectono-magmatic regime, between the Variscan compression (ending with the formation of calc-alkaline plutons in the Pyrenees and Catalonian Coastal Ranges) and the beginning of the Alpine extension (which made the crust thinner, enabling the ascent of mantle-derived magmas with little crust contamination) (Lago *et al.*, 2004).

Conclusions

The petrological and geochemical study of the Permian lamprophyric subvertical dyke swarm from Aiguablava (Catalonian Coastal Ranges) has led to the following conclusions:

1. All these lamprophyres share a common magma source.
2. During the emplacement of the dykes, the lamprophyric magma suffered a short but continued differentiation process.
3. Three differentiation stages, related to three emplacement pulses, can be defined: stage 0, 1 and 2, in order of decreasing age and increasing alkalinity. Stage 2 magmas carry stage 0 microenclaves.
4. The studied lamprophyres are not strictly calc-alkaline, as traditionally considered, but transitional to alkaline.

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