ISSN: 0378-102X
www.ucm.es\JIG

Journal of Iberian Geology 30 (2004) 119-132

Journal of Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

The timing of the Cadomian and Variscan cycles in the Ossa-Morena Zone, SW Iberia: granitic magmatism from subduction to extension

Cronología de los ciclos Cadomiense y Varisco en la Zona de Ossa Morena, SO de Iberia: magmatismo granítico desde la subducción a la extensión

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Received: 01/02/03 / Accepted: 24/08/03

Abstract

The state of knowledge about the Ossa-Morena Zone is variable. There are petrologic, geochemical, isotopic and geochronological studies of many bodies, but few are exhaustive studies; and the interpretation of these data is complicated by the superposition of the Cadomian and Variscan deformations.

In this paper we present a summary of the published geochronological data and their interpretation. We also present a brief but systematic study of several granitic bodies of the Ossa-Morena Zone. Finally, we interpret the presented data in the context of the geological history of the region.

The age range of the studied plutons is ~ 532-502 Ma and ~ 348-332 Ma. Cambrian ages comprise: the Culebrín tonalite, 532 Ma, with calcalkaline chemistry, and characteristic of mantelic origin rocks formed in arc areas; the Calera de León granite, 524 Ma, with alkaline typology, and also with a mantelic origin; the Monesterio migmatites, 511 Ma, and the granodiorite, originated from deeper levels but intruded as the same time as the migmatites were forming; finally the Castillo granite, 502 Ma, with A-type affinity and mantelic origin too. Carboniferous ages are 332 Ma for Santa Olalla tonalite, and 348 Ma for Teuler granite, these bodies being of crustal derivation.

For some authors Cambrian bodies are still related to the Cadomian cycle; for others the existence of a Lower Cambrian detritic-carbonated platform is considered the end of the Cadomian cycle, therefore these granites are connected to the Lower Paleozoic extensional event, that is considered the beginning of the Variscan cycle.

Taking all this information, we propose the following: older granites as Culebrín and Calera are still related with the Cadomian cycle; both, magmatic and metamorphic events of Monesterio and Castillo are syn-kinematics with the deformation related to the Lower Paleozoic rifting. Younger ages would represent the late magmatism related to this extension.

Plutonic bodies of Carboniferous age were generated after the first deformation phase of the Variscan Orogeny.

Keywords: Ossa-Morena Zone, Cadomian Orogeny, Variscan Orogeny, magmatism

Resumen

El estado de conocimiento sobre la Zona de Ossa Morena es variable. Existen estudios petrológicos, geoquímicos, isotópicos y geocronológicos sobre muchos cuerpos pero pocos son estudios de detalle de alguno de los mismos. Además, la interpretación de estos datos es complicada por la superposición de las deformaciones ligadas a la orogenia Cadomiense y Varisca. En este artículo, se presenta un resumen de los datos geocronológicos publicados y su interpretación, así como un breve pero sistemático estudio de algunos cuerpos graníticos de la Zona de Ossa Morena; finalmente, se interpretan estos resultados dentro del contexto de la historia geológica de la región.

El rango de edades de los plutones estudiados es de ~ 532-502 Ma y ~ 348-332 Ma. Las edades cámbricas comprenden: la tonalita del Culebrín, 532 Ma, con quimismo calcoalcalino y origen mantélico, presenta características de rocas formadas en zonas de arco;

el granito de Calera de León, 524 Ma, con tipología alcalina y también con un origen mantélico; las migmatitas de Monesterio, 511 Ma, y la granodiorita de origen más profundo intruyendo al mismo tiempo que se forman las migmatitas; finalmente el granito del Castillo, 502 Ma, con tipología A y también de probable origen mantélico. Las edades carboníferas son 332 Ma para la tonalita de Santa Olalla y 348 Ma para el granito de Teuler, ambos con un origen cortical.

Para algunos autores los cuerpos cámbricos están aún relacionados con el ciclo Cadomiense; otros consideran que este ciclo acaba con la formación de la plataforma detrítico-carbonatada de edad Cámbrico inferior, y por tanto los granitos estarían conectados con el episodio extensional del Paleozoico inferior, considerado como el inicio del ciclo Varisco.

Teniendo en cuenta toda esta información se propone lo siguiente: los granitos más antiguos como Culebrín y Calera están aun relacionados con el ciclo Cadomiense; los procesos magmáticos y metamórficos de Monesterio y Castillo son sin-cinemáticos con la deformación asociada al rifting del Paleozoico inferior. Las edades más jóvenes representarían el magmatismo ligado a esta extensión.

Los cuerpos de edades carboníferas fueron generados tras la primera fase de deformación de la Orogenia Varisca.

Palabras Clave: Zona de Ossa Morena, Orogenia Cadomiense, Orogenia Varisca, magmatismo

1. Introduction

The Ossa-Morena Zone, SW Iberian Massif (Fig. 1), is characterized by an important tectonic, metamorphic and magmatic activity, the interpretation of which is complicated by the superposition of the Cadomian and Variscan deformations (Bard and Fabriès, 1970; Bard, 1971; Chacón *et al.*, 1974; Pons, 1982; Eguiluz *et al.*, 1983; Eguiluz, 1987; Galindo, 1989; Apalategui *et al.*, 1990; Schäfer, 1990; Ochsner, 1993; Azor, 1994; Martínez Poyatos, 1997; Apraiz, 1998; Ordóñez Casado, 1998; Eguiluz *et al.*, 1999; Expósito, 2000; Simancas *et al.*, this volume).

The Ossa-Morena Zone magmatism is characterized by the presence of small plutons with a wide compositional diversity, from peraluminous to calc-alkaline and peralkaline. Their ages range from Cadomian to Cambrian and Variscan.

By contrast, in the neighbouring Central Iberian Zone the magmatism is mainly characterized by batholiths of granodiorite, adamellite and leucogranite, which are usually peraluminous and show K_2O> Na_2O, in wt.%. They are allochthonous plutons emplaced in the middle crust and generally have a crustal protolith (Bea *et al.*, 1987, 1999). Furthermore, in the adjacent South Portuguese Zone the granites are calc-alkaline and were emplaced in a sub-volcanic context (Oliveira, 1990; Silva *et al.*, 1990, Quesada, 1991; De la Rosa *et al.*, 1999). The age of the magmatism in these two areas is mainly Variscan (Serrano Pinto *et al.*, 1987; Pereira *et al.*, 1992; Bea *et al.*, 1999; Valverde and Dunning, 2000; Oliveira, 1990; Silva *et al.*, 1990).

The state of knowledge about the Ossa-Morena Zone is variable. There are petrologic, geochemical, isotopic and geochronological studies on many bodies, but few of them present a detailed geological description of particular bodies. For this reason, it is necessary to make a detailed and systematic study of the magmatism summarising the existing data. This will allow us to make comparisons between the different granitic bodies and relate their genesis to the main geological events of this area.

In this work, I present a summary of the published geochronological data and their interpretation. I also present a brief but systematic study of several granitic bodies of the Ossa-Morena Zone, including new unpublished data. Finally, I interpret the presented data in the context of the geological history of the region.

In fact, in this volume, Simancas *et al.* also present their work "From the Cadomian Orogenesis to the Early Paleozoic Variscan Rifting in Southwest Iberia", where they analyse this regional timing problem from a structural point of view.

2. Published geochronological data

Recent geochronological and isotopic studies in the Ossa-Morena Zone have contributed to the understanding

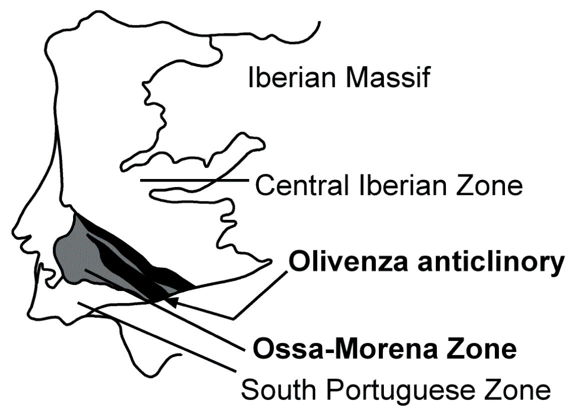

Fig. 1.- Variscan Chain divission in the Iberian Massif, after Julivert *et al*. (1974).

Fig. 1.- División en zonas de la Cadena Varisca en el Macizo Ibérico, según Julivert *et al*. (1974).

of the magmatic events proposed in previous petrological and geochemical studies on the granites of this area.

Table 1 compiles published geochronological data for 38 bodies: Precambrian to Carboniferous in age, representing ages of metamorphism and emplacement of the granitic massifs.

It is generally agreed that a magmatic event occurred in the Late Precambrian to Precambrian-Cambrian boundary. It is represented by acid-intermediate volcanic material and calc-alkaline plutonic rocks, and was related to an active continental margin associated with the Cadomian Orogeny (Sánchez Carretero *et al.*, 1990; Ochsner, 1993). The end of this cycle and the beginning of a new one, the Variscan cycle, is controversial. Some authors (Ochsner, 1993; Eguiluz *et al.,* 1995; Ordóñez Casado, 1998), put the beginning of the Variscan cycle at 490-480 Ma, although suggest a post-collisional-transition to rift-magmatism between 525-498 Ma with earlier syn- to post-collisional anatectic granitoids (533-523 Ma), related to the Cadomian Orogeny.

On the other hand, the existence of a Lower Cambrian detritic-carbonate platform is considered the end of the Cadomian cycle by other authors (Quesada, 1991; Giese and Bühn, 1993; Expósito, 2000; Simancas *et al.*, this volume). After a relatively stable period, continental rifting began, with associated igneous activity (Giese and Bühn, 1993), which continued sporadically until the Silurian so corresponding to the beginning and development of the Variscan cycle.

Plotting all the known geochronological data, 104 ages of 66 different rocks (Fig. 2), we see that the data distribution is bimodal with two maximum corresponding to metamorphic and magmatic activity between 540 and 450 Ma (Lower Cambrian-Middle Ordovician), and 360-300 Ma (Carboniferous ages).

At present, the main controversy in this region refers to bodies with Cambrian ages that formed between the Cadomian and Variscan cycles.

Previous workers (e.g., Ochsner, 1993; Ordóñez Casado, 1998) have considered the youngest granites to be related to the Cadomian cycle, not the Variscan one. So, in order to clarify this point we have selected a group of key plutons that represent the geochemical and geochronological diversity of the area.

We have chosen six granitic bodies from the Ossa-Morena Zone for petrological, geochemical, isotopic and geochronological study. These bodies are: the Calera granite, the Monesterio complex (migmatites, leucogranites and granodiorites), the Castillo granite, the Culebrín tonalite, the Santa Olalla del Cala tonalite and the Teuler granite. They are all located in the south part of the Olivenza Anticlinory (Fig. 3). Only the Monesterio complex crops out to the north of the Monesterio thrust; this structure which strikes N145°E divides the studied area along 120 Km, and has an age between Lower Devonian and Lower Carboniferous (Expósito, 2000). The Calera, Culebrín, Castillo granites and the Monesterio complex crop out in the Precambrian basement, whereas the Santa Olalla and Teuler intrude Uper Precambrian-Lower Cambrian rocks. The Precambrian basement, here, is represented by the Serie Negra, formed of metagreywackes, slates, schists and quartz-schists; by contrast, the Cambrian to Lower Carboniferous series are mainly slates and volcano-sedimentary rocks.

All of these bodies have been sampled for petrographic study of thin sections, minerals analyses by electron microprobe, petrographic study of accessory minerals assemblages by SEM (Scanning Electron microscopy), major and trace elements chemistry and Sr and Nd isotope analysis. Finally, zircons were concentrated and studied with a binocular microscope and cathodoluminiscence equipment; the most representative ones were selected and analysed via the Single Zircon Step-wise Evaporation Pb-Pb method (Kober, 1986, 1987) to determine the age of the granites.

3. Samples and methods

In the present study we collected 77 samples, 21 from the Monesterio complex (granodiorites, migmatites, gneisses and leucogranites), 9 from the Calera de Leon granite (main and leucocratic facies), 17 from the Culebrín tonalite (tonalites, enclaves and segregates), 11 from the Castillo granite, 13 from the Santa Olalla del Cala complex (tonalitic, dioritic and granitic facies) and 6 from the Teuler granite.

Major element determinations were performed by X-Ray fluorescence after fusion with lithium tetraborate. Typical precision was better than ±1.5% for an analytic concentration of 10 wt%, and Zr was determinated by X-Ray fluorescence on pressed pellets with a precision better than ±4% for 100 pm Zr.

Trace elements determinations were done by ICP-mass spectrometry after HNO_3 + HF digestion of 0.1000 g of sample powder in a Teflon-lined vessel at 180 ^{0}C and 200 psi for 30 min., evaporation to dryness, and subsequent dissolution in 100 ml of 4 vol %HNO_3. Instrument measurements were carried out in triplicate with a PE SCIEX ELAN-5000 spectrometer using rhodium as an internal standard. Precision was better than ±2% and ±5% for analytic concentrations of 50 and 5 pm respectively.

Samples for Sr and Nd isotope analyses were digested in the same way, using ultra-clean reagents, and analysed by thermal ionisation mass spectrometry in a Finnigan Mat

Table 1.- Previous geochronological data in the Ossa-Morena Zone
Tabla 1.- Datos geocronológicos previos de la Zona de Ossa Morena

Granitic bodies	Age (Ma)	Error (Ma)	Method	Rock	Age type	Num.	Ref.	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
San Guillermo	279	10	K/Ar	Granite?	E	150	1	-	-
Brovales	305	10	K/Ar	??	E	124	1	-	-
Los Molares	323	4	Rb/Sr	Migmatite	M	174	2	-	-
Alcovas (Portugal)	324	?	K/Ar	Plagiograníic Porphid	E	109	26	-	-
Burguillos	328	10	K/Ar	Granodiorite	E	129	1	-	-
Los Molares	328	4	Rb/Sr	Metanorite	M	176	2	-	-
Los Romeros	331	27	Rb/Sr	Migmatite	M	177	2	-	-
Burguillos	332	??	Rb/Sr	Leucogranite	E	127	3	-	-
Sta Olalla	332	3	Kober	Tonalite	E	151	4	-	-
Burguillos	335	??	Ar/Ar	Diorites, gabbros	E	128	5	-	-
Beja-Acebuches	337	1	Ar/Ar	Amphibolite	M	167	6	-	-
Beja	338	1	Ar/Ar	Undeformed gabbro	E	122	6	-	-
Valencia Ventoso	339	50	K/Ar	??	E	160	1	-	-
Beja	340	1	Ar/Ar	Undeformed gabbro	E	121	6	-	-
Brovales	340	4	Kober	Granite	E	125	4	-	-
Los Molares	340	23	Sm/Nd	Metanorite	M	175	2	-	-
Beja-Acebuches	341	1	Ar/Ar	Amphibolite	M	168	6	-	-
Valuengo R.B	342	4	Kober	Basic rock	E	161	4	-	-
Aroches	347	+51/-12	U/Pb	Tonalite	E	110	7	-	-
Teuler	348	4	Kober	Granite	E	159	4	-	-
Cortegana	351	58	Rb/Sr	Migmatite	M	169	2	-	-
S.Albarrana	351	1	Ar/Ar	Eschist	M	189	8	-	-
S.Albarrana	353	1	Ar/Ar	Eschist	M	192	8	-	-
Aguablanca	354	17	Rb/Sr	Principal Serie	E	106	9	-	-
Las Grullas	354	7	Rb/Sr	Ultramilonite	M	171	10	-	-
Las Grullas	359	7	Rb/Sr	Ultramilonite	M	173	10	-	-
S.Albarrana	359	1	Ar/Ar	Pegmatite	M	190	8	-	-
S.Albarrana	359	1	Ar/Ar	Eschist	M	193	8	-	-
Táliga	369	10	K/Ar	Biotitic granite	M	195	11	-	-
Las Grullas	380	10	Rb/Sr	Ultramilonite	M	170	10	-	-
Táliga	385	11	K/Ar	Biotitic granite	M	194	11	-	-
Las Grullas	392	9	Rb/Sr	Ultramilonite	M	172	10	-	-
S.Albarrana	392	1	Ar/Ar	Amphibolite	M	188	8	-	-
S.Albarrana	392	1	Ar/Ar	Paragneiss	M	191	8	-	-
Serie Negra	413	1	Ar/Ar	Eschist	M	186	8	-	-
Burguillos	423	30	K/Ar	Monzonite	E	126	1	-	-
Salvatierra	431	15	K/Ar	Granite	E	149	1	-	-
Almendral	450	12	K/Ar	Sienite	E		12	-	-
Alcovas (Portugal)	457	16	Rb/Sr	Orthogneisses	M?	162	26	-	-
Cala Prfido	458	4 (LI)	U/Pb	Porphiroid	E	130	13	-	-
Serie Negra	459	1	Ar/Ar	Granodiorite	M	187	8	-	-
Valuengo	460		Kober	Aplites	M?	198	4	-	-
Valuengo	463		Kober	Anatéctic granite	M?	197	4	-	-
Las Grullas	467	104	Rb/Sr	Ultramilonite	P	200	10	-	-
Valuengo	470	7	Kober	Microgranite	M?	196	4	-	-
Barcarrota	471	8	K/Ar	Peralkaline granite	E	116	11	-	-
Táliga.Hig.Vargas	474	8	K/Ar	Leucogranite	E	158	11	-	-
Barcarrota	475	10	K/Ar	Meladiorite	E	117	11	-	-
Monesterio	476	+13/-17 (LI)	U/Pb	Granodiorite	E	139	14	-	-
Almendral	481	10	K/Ar	Sienite	E		12	-	-
Barcarrota	482	10	Rb/Sr	??	E	114	15	-	-
Táliga	482	+ 37/-54 (LI)	U/Pb	Biotitic granite	E	157	14	-	-
Pallares	489	4	U/Pb	Granodiorite	E	146	16	-	-
Tablada	494	61	Rb/Sr	Granite	E	104	17	-	-
Pallares	495	+7/-8 (LI)	U/Pb	Granodiorite	E	142	13	-	-
Castillo	498	+10/-7 (UI)	U/Pb	Granite	E	132	14	-	-
Barcarrota	500	10	K/Ar	Cuarzomonzonite	E	115	11	-	-
Barcarrota	501	+ 4/-3 (UI)	U/Pb	Amphibolitic granite	E	112	14	-	-
Castillo	502	5	Kober	Alkaline granite	E	133	4	0.702	0.512015
Barcarrota	503	+ 5/-2 (UI)	U/Pb	Diorite	E	111	14	0.7032	-
Almonaster	505	37	U/Pb	Migmatite	M	166	18	-	-
Barcarrota	505	10	K/Ar	??	E	113	15	-	-
Barcarrota	506	12	K/Ar	Meladiorite	E	119	11	-	-

Table 1.- Previous geochronological data in the Ossa-Morena Zone (cont.)
Tabla 1.-Datos geocronológicos previos de la Zona de Ossa Morena (cont.)

Granitic bodies	Age (Ma)	Error (Ma)	Method	Rock	Age type	Num.	Ref.	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
Pallares	507	21	Sm/Nd	Granodiorite	E	145	13	-	-
Barcarrota	508	9	K/Ar	Meladiorite	E	120	11	-	-
Barcarrota	510	10	K/Ar	??	E	118	11	-	-
Monesterio	510	4	Kober	Granodiorite	E	140	19	0.706	0.5118
Monesterio	511	40	Kober	Leucosome	M	181	19	-	-
Tablada	511	8 (UI)	U/Pb	Bt-moscv granite	E	152	14	0.7068	-
Tablada	512	-1.4	U/Pb	Biotitic granite	E	153	14	-	-
Tablada	512	-1.6	U/Pb	Bt-moscv granite	E	154	14	-	-
Bodonal-Cala	514	9	SHRIMP	Porphiditic riolite	E	123	20	0.7025	0.5117
Salvatierra	516	+9/-3 (UI)	U/Pb	Granite	E	147	14	0.7075	-
Pallares	518	15	SHRIMP	Granodiorite	E	144	20	0.7076	0.5117
Monesterio	521	+131/-9 (UI)	U/Pb	Granodiorite	E	138	14	-	-
Malcocinado	522	8	SHRIMP	Tuff	P	202	20	-	-
Calera de León	524	4	Kober	Granite	E	131	21	0.7007	0.512008
Táliga	525	1 (UI)	U/Pb	Biotitic granite	E	155	14	0.707	-
Monesterio	527	+10/-7 (UI)	U/Pb	Granodiorite	E	136	14	-	-
Monesterio	528	100	Rb/Sr	Granodiorite	E	137	17	-	-
Táliga	530	32	Rb/Sr	Granite	E	105	15	-	-
Culebrín	532	4	Kober	Tonalite	E	134	4	0.704	0.51187
Valuengo	532	5	Kober	Orthogneiss	P	206	4	-	-
Monesterio	533	8	SHRIMP	Leucosome	M	180	20	-	-
Monteagudo	536	11	SHRIMP	Gabbro	P	203	20	-	0.51222
Táliga	541	42	Rb/Sr	Granite	E	156	15	-	-
Mosquil	544	+6/-5 (UI)	U/Pb	Tonalite	E	141	14	-	-
Calera de León	549	16	SHRIMP	Amphibolite	P	199	20	-	-
Serie Negra	550	7	Ar/Ar	Amphibolite	M	185	8	-	-
Serie Negra	551	3	Ar/Ar	Amphibolite	M	182	8	-	-
Ahillones	552	10	SHRIMP	Granite	E	108	20	-	-
Monesterio	552	16	Rb/Sr	Granodiorite	M	179	22	-	-
Monesterio	553	6	Ar/Ar	Amphibolitic enclave	M	178	8	-	-
Serie Negra	553	3	Ar/Ar	Amphibolite	M	183	8	-	-
Serie Negra	562	1	Ar/Ar	Eschist	M	184	8	-	-
Salvatierra	564	160	Rb/Sr	Granite	E	148	17	-	-
Serie Negra	564	30	SHRIMP	Metagreywackes	P	205	23	-	-
Pallares	573	74	Rb/Sr	Granodiorite	E	143	24	-	-
Ahillones	585	5 (UI)	U/Pb	Granite	E	107	13	-	-
Serie Negra	591	11	SHRIMP	Biotitic Gneiss	P	204	20	-	-
Lora del rio	600	13	SHRIMP	Granodiorite	P	201	20	-	-
Foz de Douro	604	?	Rb/Sr	Biotitic Orthogneiss	E	135	25	-	-
Almonaster	612	67	U/Pb	Migmatite	M	165	18	-	-
Almonaster	670	88	U/Pb	Migmatite	M	163	18	-	-

Age type: E- Emplacement, M- Metamorphism, P- Protolith.

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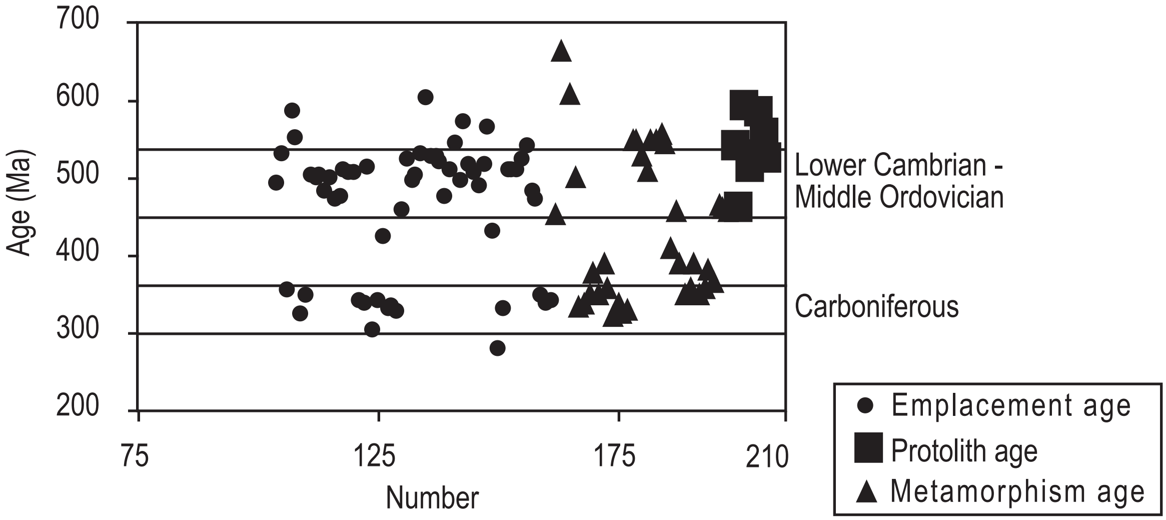

Fig. 2.- Table 1 geochronological data plot diagram.
Fig. 2.- Proyección de los datos geocronológicos de la Tabla 1.

262 spectrometer after chromatographic separation with ion exchange resins. Normalization values were $^{88}Sr/^{86}Sr$= 8.375209 and $^{146}Nd/^{144}Nd$=0.7219. Blanks were 0.6 and 0.09 ng for Sr and Nd respectively. The external precision (2 σ), estimated by analysing 10 replicates of the standard WS-E (Govindaraju *et al.*, 1994) was better than 0.003% for $^{87}Sr/^{86}Sr$ and 0.0015% for $^{143}Nd/^{144}Nd$. The $^{87}Rb/^{86}Sr$ and $^{147}Sm/^{144}Nd$ were directly determined by ICP-MS, following the method developed by Montero and Bea (1998), with a precision better than 1.2% and 0.9% (2 σ) respectively.

Major element minerals analyses were obtained by wavelength dispersive analyses with Camebax SX-50 electron microprobe, using synthetic standards. Work conditions were: Accelerating voltage 20 kV, beam current 30 nA and coefficients of variation were ±2.5% and ±5% for 1 wt% and 0.25 wt% analytical concentrations respectively.

Petrographic study of accessory mineral assemblages were made by Scanning Electron microscopy although the selected zircon crystals were also studied under binocular microscope and cathodoluminiscence equipment, and then analysed by the Kober's method to obtain the granite ages.

For the single-zircon, stepwise-evaporation $^{207}Pb/^{206}Pb$ method, or Kober's technique (Kober, 1986, 1987) Thermal Ionisation Mass Spectrometer was used. First, we study the external and internal morphology of crystals to select the most representative ones. The external morphology was studied using the Pupin method (Pupin *et al.*, 1978; Pupin, 1980), based on the number of prism and pyramids of the crystals, which are related to the magma chemistry. Looking at the internal morphology under cathodoluminiscence allowed us to recognize inherited cores, magmatic or metamorphic growths, and zoning irregularities. Following the morphological study, the zircons grains were mounted on a canoe-shaped Re filaments and heated until the Pb beam intensity was sufficient. Then the evaporated Pb was collected on the ionisation filament and afterwards analysed in consecutive steps. The procedure continued in series of temperature increments until the Pb was exhausted from the zircon. The number of steps depends on the size and Pb content of each zircon.

4. Petrographic, geochemical, isotopic and geochronological characterisation of selected granitic bodies

4.1. Monesterio Complex

This complex is composed of migmatites, gneisses, leucogranites and granodiorites. I present here the principal characteristics of the migmatites and granodiorites that allow us to determine their origin and relationships.

Granodiorite

The granodiorite is a mesocratic medium-grained porphyritic rock with a local gneissic fabric; it includes several hypermicaceous enclaves and metamorphic xenoliths. The main mineralogy consists of quartz, oligoclase-andesine (core An_{12-35}, rim An_{12-30}), K-feldspar and biotite. Accessory phases are apatite, ilmenite, zircon, allanite, titanite, monazite and rare xenotime. Generally, the chemical composition is moderately peraluminous and calc-alkaline with high CaO and K_2O contents (SiO_2 = 66-71 wt%, CaO = 2-3 wt%, $Na_2O + K_2O$ = 6.5-7.5 wt%, $Na_2O \geq K_2O$ and Al_2O_3 / ($CaO+Na_2O+K_2O$) = 0.93-1.17). In a multi-element diagram normalized to the average continental crust

(GERM-Geochemical Earth Reference Model Database), the trace element composition is characterized by positive anomalies in U and Li and negative anomalies in Nb, Sr and Eu (Fig. 4). The initial $^{87}Sr/^{86}Sr$ values vary between 0.7058 and 0.7075, and εNdt between -4.43 and -3.08.

Zircon crystals correspond to Pupin morphotypes of calc-alkaline granites. Under cathodoluminiscence the crystals have magmatic zoning, apatite inclusions and sometimes anhedral cores. Eight evaporation steps carried out on four magmatic zircons gave an average Pb-Pb age of 510 ± 4 Ma, which is interpreted as the age of crystallization (Montero *et al.*, 1999). Inherited old cores, with a minimum age of 1696 Ma, were also detected (Fig. 5).

Migmatites

The migmatites consist of metapelitic metatexites. Biotite and sillimanite are the major components of the melanosome, while quartz, K-feldspar, plagioclase (An_{2-15}), muscovite and cordierite apear in the lens-shaped veins of leucosome. Accessory phases are limited to a few grains of ilmenite, apatite, monazite and zircon. The chemical composition is peraluminous with lower contents of CaO, Na_2O, Zr, Ti, Sc and HREE than the granodiorites.

A Rb/Sr isochron obtained from concentrates of plagioclase, K-feldspar, and muscovite and four whole-rock samples of migmatitic leucosomes, gave an age of 511 ± 40 Ma with $^{87}Sr/^{86}Sri = 0.70914 \pm 0.00048$ (Montero *et al.*, 1999) (Fig. 5).

It is worth mentioning that, although the ages of the granodiorite and migmatites are the same, there are significant differences in their initial $^{87}Sr/^{86}Sr$ ratio and geochemical compositions that indicate that they are not co-genetic. The data suggest that the granodioritic melts, originated from a feldspar-rich deeper source, with a low $^{87}Sr/^{86}Sr$ ratio than the metapelites, were intruded into a ductile migmatitic core. This interpretation is consistent

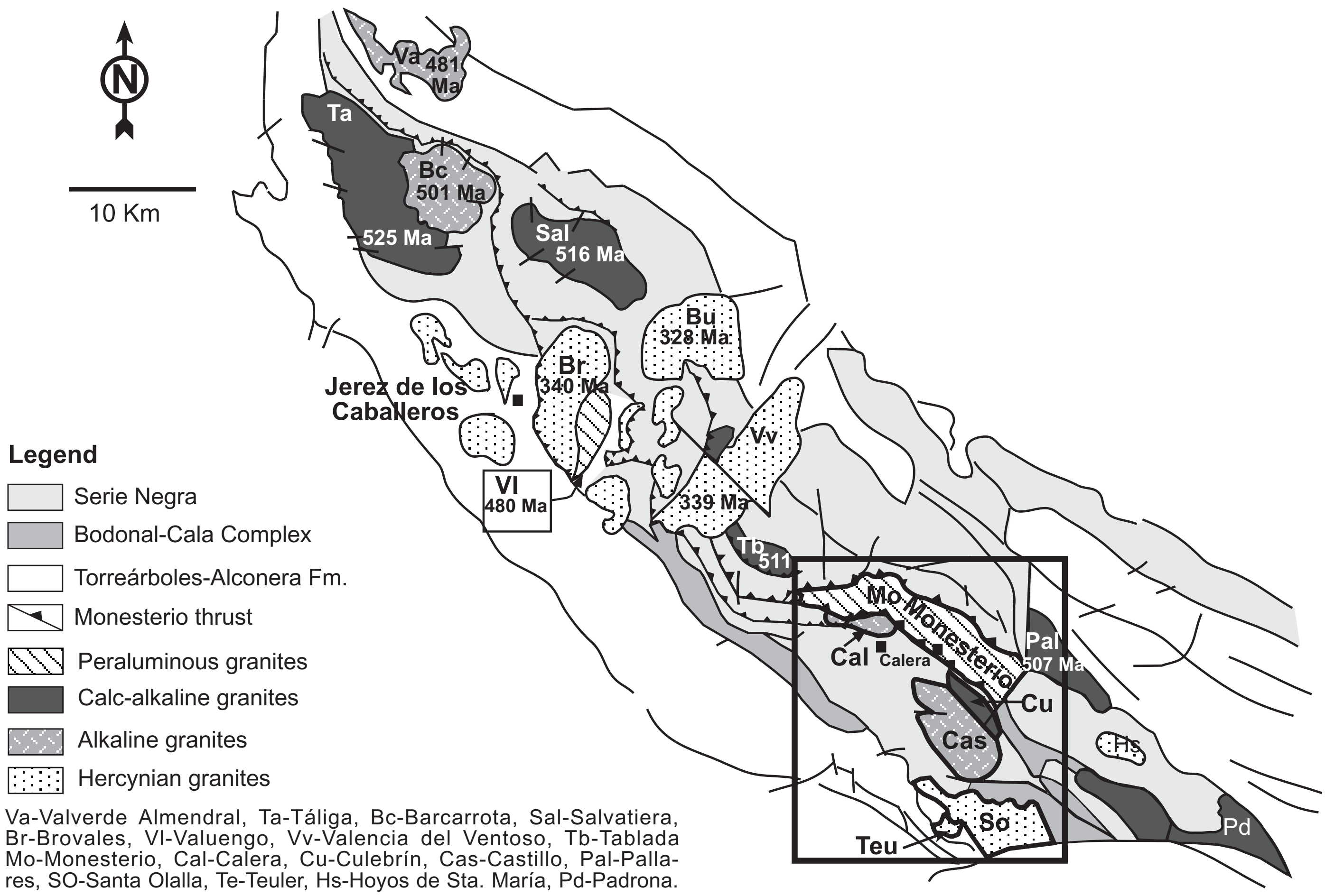

Fig. 3.- Olivenza anticlinory plutonic scheme (Figure from Ochner, 1993, modified by Expósito, 2000). Selected area correspond to this paper studied zone. Numbers are the granites ages.

Fig. 3.- Esquema plutónico del anticlinorio de Olivenza (Figura tomada de Ochsner, 1993, modificaciones de Expósito, 2000). El recuadro corresponde al área de estudio. Los números son las edades de los granitoides.

with their field relationships.

4.2. Calera de León granite

This is a sub-volcanic intrusive body cut by aplitic dykes; its contacts and western part are highly deformed by the Hercynian Monesterio thrust.

Previous studies (Eguiluz, 1987) distinguish two facies in this pink coloured granite: a main facies and a leucocratic one, which outcrop as small dykes into the main facies. The former consists of quartz, K-feldspar, Ab-rich plagioclase ($An_{0.8-11}$) and biotite, with few accessory minerals as apatite, zircon, epidote, titanite, allanite, monazite, xenotime and fluorite. It has hypermicaceous enclaves. The granite is alkaline in composition with low contents in FeO, MgO and CaO (SiO_2 = 74-80 wt%, CaO = 0.25-0.7 wt%, $Na_2O + K_2O$ = 7.91-10.73 wt%, $K_2O > Na_2O$, Al_2O_3 / ($CaO+Na_2O+K_2O$) = 0.78-1.10, FeOt / (FeOt+MgO) = 0.55-1). The main granitic facies has higher values in Zr, U, Th and HREE (Fig. 4), compared with the average continental crust (GERM-Geochemical Earth Reference Model Data base).

The leucocratic facies comprises quartz, Ab-rich plagioclase ($An_{0.2-1}$), scarce biotite and is also poor in accessory minerals, containing apatite, zircon, titanite, monazite, xenotime and thorite. This facies has an anomalous composition with high SiO_2, Na_2O and MgO contents but is low in K_2O (SiO_2 = 77-78 wt%, MgO = 0.66-1.72 wt%, $Na_2O + K_2O$ = 5.42-6.43 wt%, $K_2O < Na_2O$, Al_2O_3 / ($CaO+Na_2O+K_2O$) = 1.19-1.46). It is also depleted in Rb, Cs, Tl, Ba, Sr, Pb, U, Th and REE, particularly in the LREE.

The Calera de León granite has initial $^{87}Sr/^{86}Sr$ of 0.70075, a very low value that combined with a high $^{143}Nd/^{144}Nd$ ratio and εNdt values between 0.84 and 0.98 indicate a primitive isotopic signature.

Zircons correspond to Pupin morphotypes of alkaline compositions. They show igneous oscillatory zoning, small inherited cores and inclusions. Thirteen evaporation steps were made on five zircons, four from the main facies and one from the leucocratic facies giving an average Pb-Pb age of 524 ± 4 Ma. No inherited cores were analyzed (Fig. 5).

4.3. Culebrín tonalite

The Culebrín tonalite is a mesocratic medium-grained rock. The main minerals are quartz, plagioclase (core An_{18-55}, rim An_{25-49}), amphibole (Mg-hornblende) and biotite. Accessory minerals include epidote, zircon, apatite, titanite, oxides, sulphurs, magnetite, ilmenite, thorite, Th-group minerals, LREE-rich minerals (La and Ce, probably from monazite), lead and Ba sulphate. The chemical composition is metaluminous or moderately peraluminous and calc-alkaline, with $Na_2O > K_2O$ and high contents of CaO (SiO_2 = 59.01-66.1 wt%, MgO = 1.79-3.18 wt%, CaO = 3.37-6.20 wt%, $Na_2O + K_2O$ = 4.62-5.46 wt%, Al_2O_3 / ($CaO+Na_2O+K_2O$) = 0.97-1.24). The trace element composition is characterized by incompatible elements enrichment. The multi-element diagram normalized to the average continental crust (GERM-Geochemical Earth Reference Model Database) is similar to I-type arc-related granites, having negative anomalies in Nb (and Ta and Ti, Salman, 2002) and positive anomalies in Sr, Li and Ga (and Pb, Salman, 2002) (Fig. 4).

An essential characteristic of this tonalite is the common presence of basic enclaves, mainly in the central southern part of the pluton. They apear as swarms of different sizes, not wider than 50 cm, with ellipsoidal, angular or sinuous shapes. They are compositionally variable. The most abundant enclaves are mafic, fine-grained rocks, with plagioclase (core An_{37-48}, rim An_{42-46}), biotite, amphibole (Mg-hornblende) and some quartz; they usually have sub-rounded shapes, with sharp boundaries, although sometimes, at the microscopic scale, they are more diffuse. These enclaves have a comparable chemical composition to the tonalite and were interpreted as autholites or cogenetic enclaves (Salman, 2002).

The isotopic study of the Culebrín tonalite gives an initial $^{87}Sr/^{86}Sr$ ratio between 0.7039 and 0.7046. εNd values oscillate between -1.701 and -1.28, suggesting a mantelic origin.

Zircons are typical of calcalkaline granitoids according to Pupin morphotypes; under cathodoluminiscence all the crystals present magmatic zoning, usually symmetric but in some case eccentric and asymmetric. Inherited cores have not been observed. We obtained an average Pb-Pb age of 532 ± 4 Ma from thirteen evaporation steps made on three crystals (Fig. 5).

The tonalite is cross cut by late diabase dykes (Fig. 3). These dykes strike N140E/70E, are 20 cm to 1.5 m wide and in some cases show chilled margins.

The Culebrín tonalite produces a small metamorphic aureole, mainly at its northern border. The wall rock has sericitic nodules, probably representing andalucite pseudomorphs. This wall rock is cut by several quartz or quartz-feldspar veins, probably derived from the intrusion.

4.4. Castillo granite

This body is a pink coloured zoned pluton with a slightly deformed main facies and highly deformed minor facies (Eguiluz, 1987, 1989; Eguiluz *et al.*, 1999); several dykes of this granite intrude the Culebrín tonalite. This granite

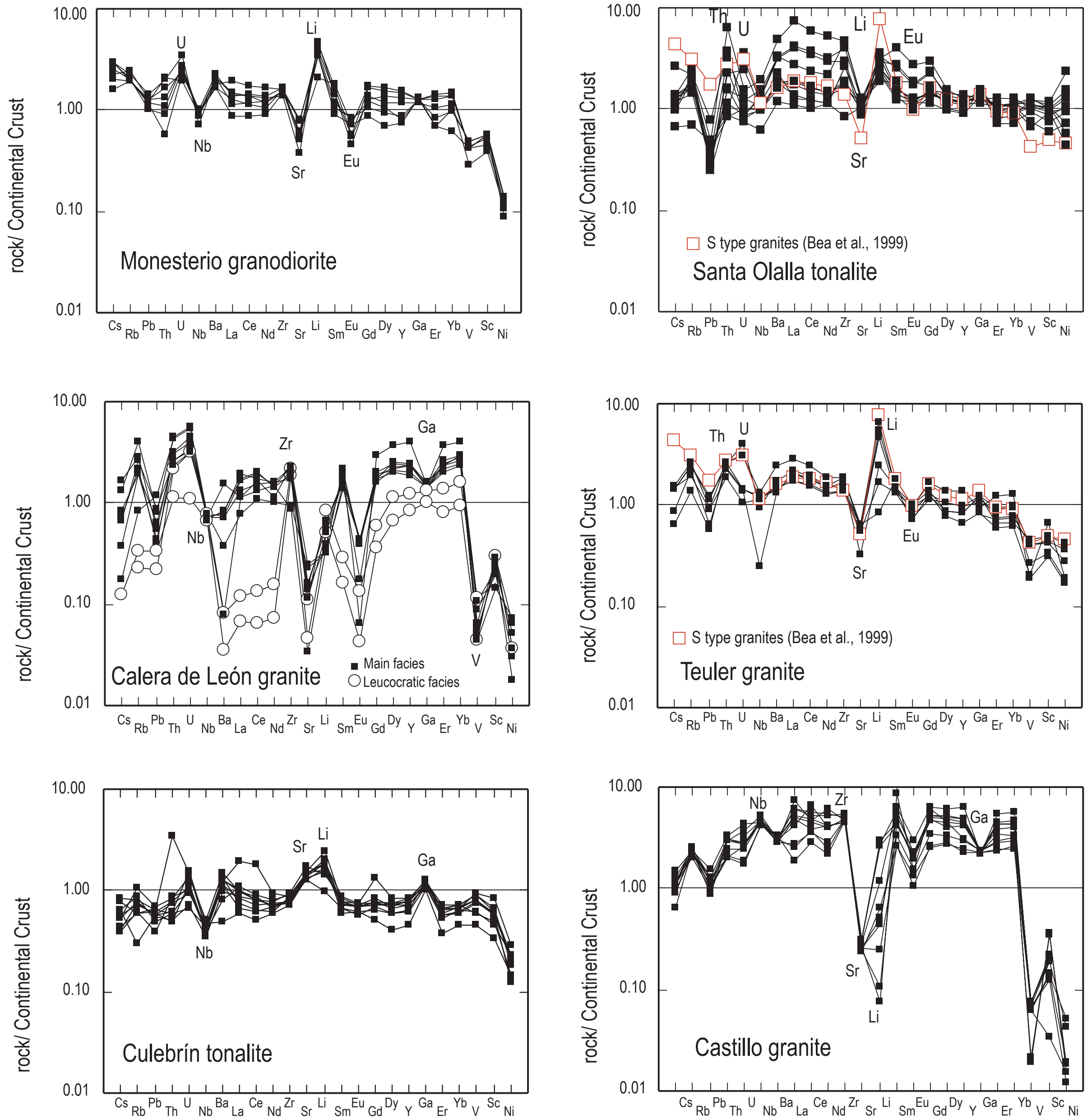

Fig. 4.- Trace elements compositions of selected granitoids normalized to the average composition of the continental crust (GERM-Geochemical Earth Reference Model Data base)

Fig. 4.- Composición de elementos traza de los cuerpos seleccionados, normalizados a la composición media de la Corteza continental (GERM-Geochemical Earth Reference Model Data base)

contains quartz, K-feldspar, Ab-rich plagioclase ($An_{0.9-9}$), biotite and amphibole (hastingsitic-ferro hornblende), and many accessory minerals such as apatite, zircon, allanite, carbonates, monazite, fluorite, ilmenite, oxides, and sulphides that apear as isolated crystals or as heterogeneous aggregates. The chemical composition is mainly alkaline, with low contents in Al_2O_3 and CaO and high K_2O/Na_2O and FeOt/FeOt+MgO ratios (SiO_2 = 70.5-72.16 wt%, CaO = 0.84-1.52 wt%, $Na_2O + K_2O$ = 4.62-5.46 wt%, Al_2O_3 / ($CaO+Na_2O+K_2O$) = 0.95-1.09, FeOt / (FeOt+MgO) = 0.91-1). The trace element compositions are characterized by high contents in Zn, Ga, Y, Nb, Ta, Zr, Hf and REE. When normalized to the average continental crust (GERM-Geochemical Earth Reference Model Data base), compatible elements are depleted with negative anomalies in Li and Sr and positive anomalies in Nb and Zr, giving similar spectra to A-type granites (Fig. 4). The initial $^{87}Sr/^{86}Sr$ is 0.702 and εNd values are also homogeneous, varying between 0.38-0.44. These isotopic data indicate a deep origin for this granite.

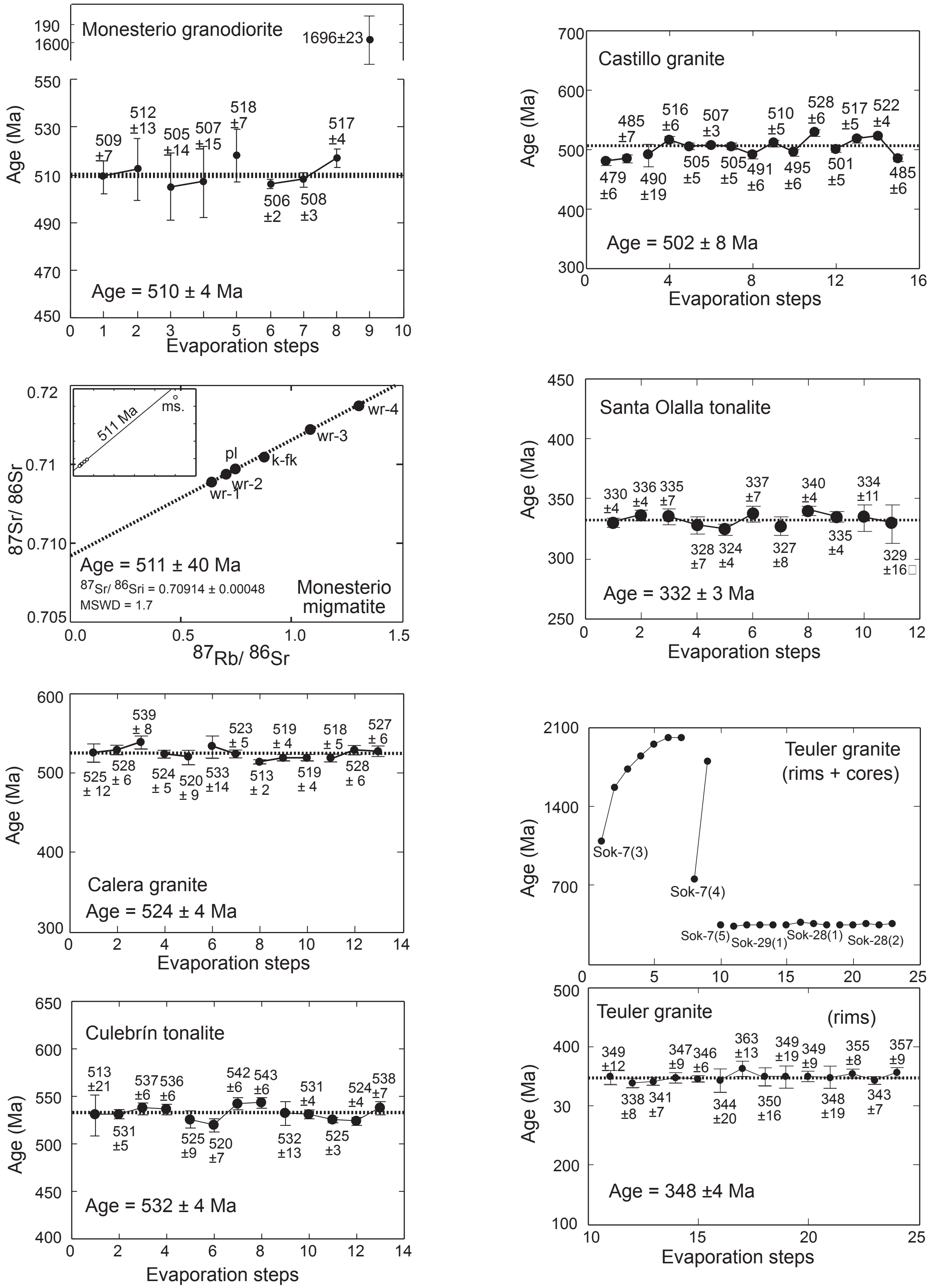

Fig. 5.- Age diagrams for the selected granitic bodies. Rb-Sr isochron for the Monesterio migmatite and Pb-Pb diagramas for the rest, obtained with the Single zircon step-wise evaporation Pb-Pb method.

Fig. 5.- Diagramas de la edad de los cuerpos seleccionados. Isocrona Rb-Sr para la migmatita de Monesterio y diagramas Pb-Pb para el resto, obtenidos con el método Pb-Pb de evaporación secuencial en cristal único de circón.

Zircons correspond to Pupin morphotypes of alkaline granites with igneous oscillatory zoning truncated by some irregularities. Fifteen evaporation steps were made on three zircons. All the steps yielded an average Pb-Pb age of 502 ± 8 Ma (Fig. 5). No inherited cores were found.

4.5. Santa Olalla del Cala tonalite

These rocks form the main facies of the Plutonic Complex of Santa Olalla del Cala (Casquet, 1980, 1982; Eguiluz, 1987; Eguiluz *et al.*, 1989; Bateman *et al.*, 1992; Casquet *et al.*, 1998). The tonalite is a mesocratic, medium-grained rock with quartz, K-feldspar, plagioclase (An_{22-58}), biotite and amphibole (Mg-hornblende) as main minerals and apatite, zircon, epidote, allanite, monazite, ilmenite, sulphides and oxides as accessory phases. Chemically it is metaluminous-peraluminous and calc-alkaline, with high CaO content and $Na_2O \approx K_2O$ (SiO_2 = 53.9-61.5 wt%, CaO = 3.89-6.99 wt%, $Na_2O + K_2O$ = 3.64-6.75 wt%, Al_2O_3 / ($CaO+Na_2O+K_2O$) = 0.91-1.12, FeOt / (FeOt+MgO) = 0.35-0.68). In a normalized multi-element diagram, the spectra is similar to S-type granites (Fig. 4). The initial $^{87}Sr/^{86}Sr$ of 0.7095 and the εNd average value of -7.30 also indicate that the tonalite had a crustal origin.

It is possible to include the zircons from these rocks in several Pupin morphologies that correspond to calc-alkaline compositions. The crystals show oscillatory magmatic zoning, although some of them present corrosion and dissolution features. Eleven evaporation steps were made on five zircons yielding an average Pb-Pb age of 332 ± 3 Ma (Fig. 5). No inherited cores were found.

4.6. Teuler granite

This small body is related to the Santa Olalla del Cala Complex. It comprises a fine-grained granite with quartz, K-feldspar, plagioclase (core An_{14-49}, rim An_{8-45}) and biotite, and apatite, zircon, titanite, allanite, monazite, xenotime, ilmenite and oxides as accessory phases. It has microgranular enclaves with similar composition to the host granite. Chemically it is peraluminous and calc-alkaline, with $Na_2O \approx K_2O$ (SiO_2 = 67.32-71.44 wt%, CaO = 1.82-2.51 wt%, $Na_2O + K_2O$ = 7.06-7.71 wt%, Al_2O_3 / ($CaO+Na_2O+K_2O$) = 1.09-1.15, FeOt/(FeOt+MgO) = 0.5-0.66). Trace element compositions are very similar to the Santa Olalla del Cala tonalite, although with lower values of Sr, Eu, HREE, V, Sc and Ni (Fig. 4). The calculated initial $^{87}Sr/^{86}Sr$ is 0.7093 and the εNd mean value is -7.69, again similar values as the Santa Olalla del Cala tonalite, probably indicating a crustal origin.

Fourteen evaporation steps were carried out on four magmatic zircons, giving an average Pb-Pb age of 348 ± 4 Ma. Inherited old cores, with a minimum age of 1794 Ma, were found in two other zircons from the same granite (Fig. 5).

5. Discussion

On the basis of the presented data two age groups can be identified, ~ 532-502 Ma (Cambrian ages) and ~ 348-332 Ma (Carboniferous ages). This temporal bimodality is typical of the Ossa-Morena Zone although there are various interpretations of its cause.

The aforementioned magmatic event which occurred in the late Precambrian to Precambrian-Cambrian boundary represented by acid-intermediate volcanic material and the calc-alkaline plutonic rocks has been related to an active continental margin associated with the Cadomian Orogeny (Sánchez Carretero *et al.*, 1990; Ochsner, 1993). Some previous workers place the end of this cycle and the beginning of a new one, the Variscan, at 490-480 Ma (Ochsner, 1993; Eguiluz *et al*, 1995, and Ordóñez Casado, 1998), although they suggest the existence of syn- to post-collisional anatectic granitoids at 533-523 Ma and then a post-collisional-transition to rift-magmatism between 525-498 Ma, all related with the Cadomian Orogeny. However, the existence of a Lower Cambrian detritic-carbonated platform is considered the end of the Cadomian cycle by others (Quesada, 1991; Giese and Bühn, 1993; Expósito, 2000; Simancas *et al.*, this volume).

The key question is then: did the Cadomian cycle end at 490 Ma (Ochsner, 1993; Euiluz *et al*, 1995, and Ordóñez Casado, 1998) or at ~ 530 Ma (Expósito, 2000; Simancas *et al.*, this volume).

The age range of the studied plutons is 532-502 Ma, crossing the period of doubt between the end of the Cadomian and the beginning of the Variscan cycles. They comprise: the Culebrín tonalite, 532 Ma, with calcalkaline chemistry, characteristic of rocks formed in arc areas, and Sr-Sr ratio mainly suggesting a mantelic origin; the Calera de León granite, 524 Ma, with alkaline typology and isotopic characteristics of mantelic origin; the Monesterio migmatites with 511 Ma, and the granodiorite massif, derived from deeper crustal levels but intruded as the same time as the migmatites were forming; finally the Castillo granite, 502 Ma, with A typology, and isotopic values characteristics of a mantelic origin too.

Therefore making reference to their tectonic affinity, Culebrín represents a magma originated in a subduction zone, and Calera would correspond to the high pressure differentiated in the same context, because of its geochemistry.

We found isotopic values similar to those (Culebrín and Calera) in coetaneous granites of the Ossa-Morena Zone and this let us to think in the presence of a subcontinental depleted mantle (Table 1: Pallares granodiorite, Barcarrota igneous complex, Bodonal-Cala riolite- Cueto *et al.*, 1983; Galindo *et al.*, 1990; Ordóñez Casado, 1998).

Accordingly, the Castillo pluton could represent the real magmatism, together with the Monesterio migmatite and granodiorite, associated with the rifting process that would mark the beginning of the Variscan cycle.

If we add this fact to the development of the Lower Cambrian stable platform it would represent the probable end of the Cadomian cycle and the beginning of the Lower Paleozoic extensional event. Therefore the migmatitic complex is related to this rifting event, where the mantle and lower crust material rise and generate melt. A shear zone is developed in the area of Monesterio, being able to canalise the aqueous fluids that help the migmatization process (extensional shear zone defined by Expósito, 2000; Simancas *et al.*, this volume).

The common presence, in this area, of intrusive granites with an age close to those studied here (Culebrín, Calera, Monesterio and Castillo) (Table 1) suggest the existence of a significant melting event that involved protoliths of very different geochemical and isotopic signatures and the development of a low-pressure metamorphism, from 540 to 500 Ma, at the beginning of the Variscan cycle.

Concluding, we propose the following: older granites as Culebrín and probably Calera are still related to the Cadomian cycle, while magmatic and metamorphic events of Monesterio and Castillo are syn-kinematic with the deformation related to the Lower Cambrian rifting at the beginning of the Variscan cycle. Younger ages (500-460 Ma) would represent the late magmatism related to the beginning of this rifting. Thus, in the Ossa-Morena Zone, the Cadomian cycle ended at ~ 530 Ma and the Variscan cycle began with the Lower Paleozoic extensional event at ~ 520 Ma.

With regard to the Carboniferous ages of Santa Olalla (332 Ma) and Teuler (348 Ma), it must be stressed that these granites have crustal compositional characteristics, and like many bodies in the area, were generated after the first deformation phase of the Variscan Orogeny.

Acknowledgements

I am very grateful to Jane Scarrow and Antonio Azor for their revision of this paper. This research has been financed by the Spanish CICYT grant PB-1995-1266 and PB-1998-1345 and by the Granada University Postdoctoral grants.

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