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Mantle-like Sr–Nd isotope composition of Fe–K subalkaline granites: the Peneda–Gerês Variscan massif (NW Iberian Peninsula)

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ABSTRACT

The Peneda–Gerês massif is one of the most representative NW Iberian late- to post-orogenic Variscan granitic plutons. It resulted essentially from the subsynchronous emplacement, at 290–296 Ma, of two granitic magmas of Fe–K subalkaline affinity, with primitive isotopic composition: Sr_i = 0.703–0.707 and $\varepsilon Nd_i = -1.5$ to -2.4. An origin by mantle input followed by mantle–crust interactions is proposed, implying the contribution of a less enriched mantle component than that involved in the genesis of synorogenic hybrid granitoids of Mg–K subalkaline affinity. A less voluminous aluminopotassic and isotopically more evolved magma (Sr_i = 0.708–0.709 and $\varepsilon Nd_i = -3.5$ to -3.9) with little or no mantle input was also generated, suggesting the involvement of lower crust materials. Therefore, this study suggests an input of juvenile magmas in late Variscan times, the mantle-like isotope signature of Fe–K granitic magmatism being clearly related to a geodynamic setting of extensional processes, large-scale uplift and thinning.

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Introduction

The central and western Iberian Peninsula constitutes an extensive segment of the west European Variscan Fold Belt, the Iberian Massif. The geological evolution of this segment has been previously described in detail (e.g. Bard *et al*., 1980; Iglésias *et al*., 1983; Ribeiro *et al*., 1983, 1990; Matte, 1986, 1991; Ribeiro and Pereira, 1986; Lagarde *et al*., 1992; Dias and Ribeiro, 1995; Rey *et al*., 1997). Tectonic characteristics of the European Variscides are those of a classical obduction–collision belt that originates from the convergence, obduction, subduction and collision of the North Laurentia and the Gondwana continents, with minor intermediate blocks. In the NW Iberian Massif, three main ductile deformation phases, D1, D2 and D3, are usually considered responsible for the structural development of this part of the Variscan belt (Noronha *et al*., 1979; Dias and Ribeiro, 1995). The D1 and D2 deformation phases correspond to the collisional stage of the Variscan orogeny, and the D3 deformation phase is related to post-thickening extensional tectonics.

The Iberian Massif is noteworthy with regard to the abundance and variety of granitoids, largely represented in the most internal zone, the Central Iberian Zone as defined by Julivert *et al*. (1974). These were emplaced mainly during the post-collisional stage of the Variscan orogeny and were classically subdivided into 'older granites' and 'younger granites' (Schermerhorn, 1956; Oen, 1958, 1970). The classification has been substantially refined and is now based on the emplacement age relative to the last Variscan ductile deformation phase D3 (Ferreira *et al*., 1987; Pinto *et al*., 1987; Dias *et al*., 1998): (1) pre-orogenic (580–480 Ma); (2) synorogenic, subdivided into pre-D3 (~380–345 Ma), syn-D3 (319–313 Ma), late-D3 (311–306 Ma), late- to post-D3 (~300 Ma); and (3) late- to post-orogenic (post-D3; 296–275 Ma).

Most granites described in this paper are K-rich calc-alkaline rocks to the point that some no longer meet the original criteria of Peacock (1931) for calc-alkaline rocks and are formally alkali-calcic or subalkaline (as used in the French literature). The nomenclature of Rossi and Chevremont (1987) will be used here to distinguish different K-rich granitic associations. Depending on the relative whole-rock proportions of K, Al, Mg and Fe, we use the terms: aluminopotassic, which stands for peraluminous S-type granites; Mg–K subalkaline, which stands for high-K calc-alkaline to alkali-calcic monzonitic series (with abundant sphene, hornblende and vaugnerites); and Fe–K subalkaline, which stands for high-K evolved alkali-calcic granites with high Fe/Mg ratio (type location: Ploumanac'h, Brittany, France).

In Variscan times a rapid and drastic change occurred at about 300 Ma, between a compressive ductile tectonic regime (phase D3) associated with calc-alkaline, Mg–K subalkaline and aluminopotassic plutonism and a brittle deformation phase (phase D4), which controlled the emplacement of Fe–K subalkaline plutons (Dias *et al*., 1998). In the past decade there has been an increasing interest on this Fe–K subalkaline plutonism. However, Sr–Nd isotope data on this type of plutonism in the European Variscides are scarce. The nature of possible source reservoirs is still a matter of debate. According to Bonin *et al*. (1998), post-orogenic suites originate from enriched and not depleted mantle sources and their present compositions are a mixture of major mantle contribution and various crustal components. Debon and Lemmet (1999) consider that these rocks are hybrid, originating from subcontinental enriched mantle of lamproitic affinity and sialic crust. For Pupin and Persoz (1999) and Pupin (2000), the

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characteristics of the inherited zircons indicate a mixing–mingling process of two coeval magmas, one subsolvus alkaline and the other calc-alkaline. In this paper we present and discuss peculiar features and petrogenetic inferences on this type of plutonism, using the Peneda–Gerês granitic massif as a case study. This is one of the most representative and well-known late- to post-orogenic plutons in the Iberian Massif. The isotopic data are compared with available data on other Iberian late- to post-orogenic plutons.

Geological setting, petrography

The Peneda–Gerês massif outcrops in an area of *c.* 40 km (N–S direction) × 20 km (E–W direction), across the border between northern Portugal and Spain, in the Central Iberian Zone (Fig. 1). It is a discordant massif having intruded syn-D3 and late-D3 granites and Silurian metasedimentary rocks. U–Pb geochronological data indicate an emplacement age of 290–296 Ma (Dias *et al.*, 1998). It is composed of six main contemporaneous granitic

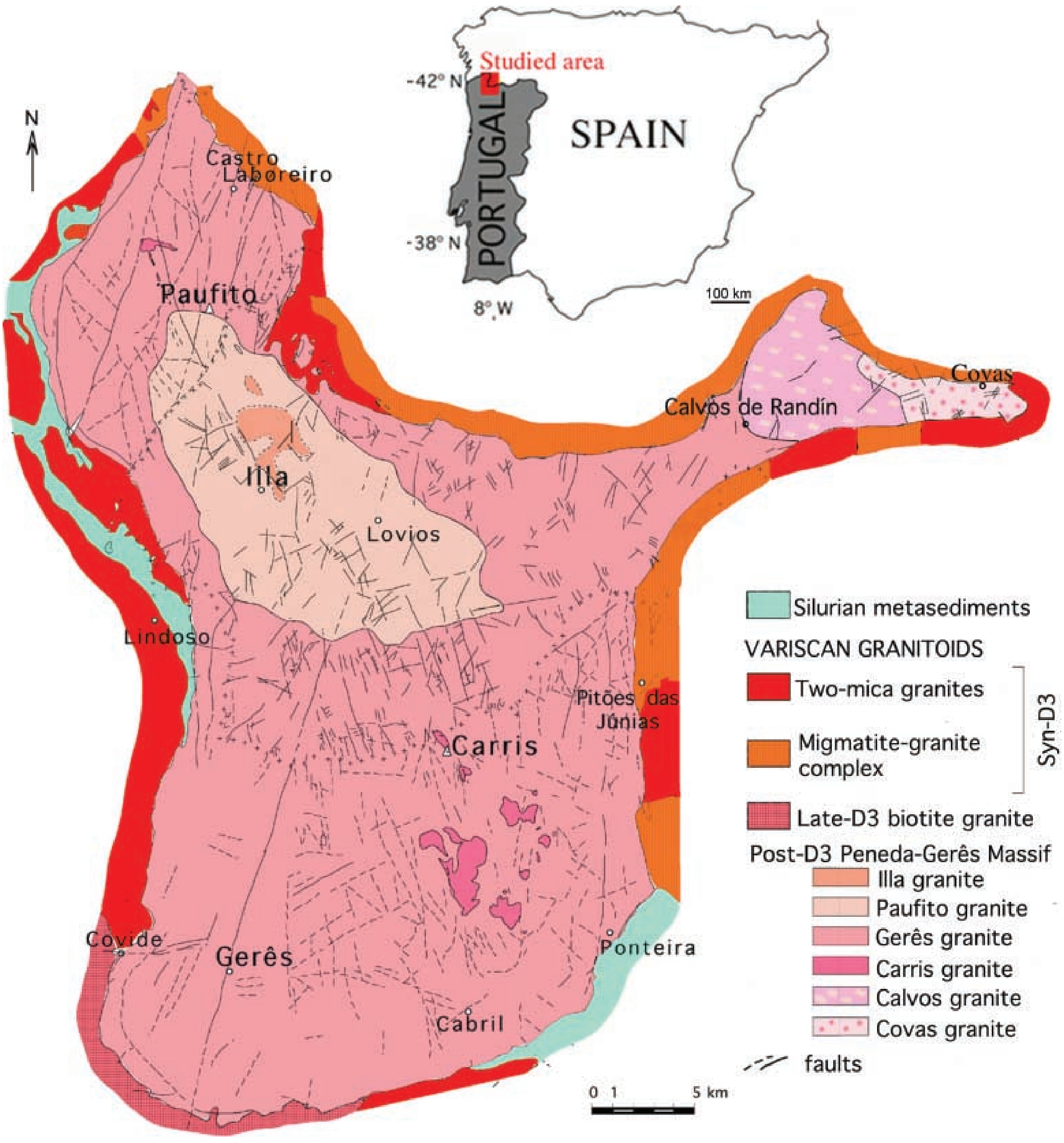

Fig. 1 Simplified geological sketch-map of the Peneda–Gerês granitic massif (NW Iberian Peninsula), based mainly on the work of Noronha, Martins and Moreira (in Moreira, 1984), Tomas and Mateo (1972a,b) and Mendes (2001).

units, three of which are roughly concentric (Fig. 1; Mendes, 2001). The most extensive and external unit is the Gerês granite. This is a porphyritic coarse- to medium-grained, slightly rose-coloured biotite monzogranite. Towards the interior of the massif, this granite adjoins the Paufito granite. The latter is a porphyritic medium-grained biotite monzogranite whose porphyritic character disappears and grain size decreases towards the innermost unit, the Illa granite, which is a two-mica fine-grained monzogranite. In the Gerês granite, irregular masses of fine-grained slightly porphyritic biotite monzogranite occur and are here referred to as the Carris granite. Outcropping in the north-eastern sector of this massif are two granitic units, the Calvos and Covas granites. These are biotite-dominant monzogranites. The Calvos granite has variable texture, being generally medium grained, whereas the Covas granite is weakly porphyritic, medium grained and hololeucocratic.

All six granites are, in general, leucogranites (maximum mafic mineral content 10.5%) and contain perthitic K-feldspar, plagioclase (albite–oligoclase, rarely andesine), quartz, biotite, ilmenite, zircon, apatite and monazite. Certain minor phases are exclusively present in some units, namely allanite, sphene and scarce hornblende in the Gerês granite, primary muscovite in the Illa granite, magnetite in the Carris granite and tourmaline in the Calvos and Covas granites.

Analytical techniques

Analytical data were obtained at the CRPG (Nancy, France). Major and trace element compositions of 54 samples from the six granite units were determined by ICP-AES and ICP-MS (data available upon request; Mendes, 2001). Sr and Nd isotopic data are given in Table 1. The isotope separation techniques have been previously reported (Michard *et al.*, 1985; Boher *et al.*, 1992). Rb, Sr, Sm and Nd concentrations were determined using the isotope dilution method and Sr and Nd isotopic ratios were measured using a Cameca TSN 206 (for Rb and Sm concentrations) and a Finnigan MAT 262 mass spectrometer. Chemistry blanks are of about 0.8 ng Sr for the acid dissolution and of about 2 ng Nd for the metaborate flux method. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were normalized to 0.1194 and 0.7219, respectively. Errors on the $^{87}Rb/^{86}Sr$ and $^{147}Sm/^{144}Nd$ ratios are estimated to be 1.5% and 0.5%, respectively (2σ).

Geochemistry

The six Peneda–Gerês granitic units are Si- and K-rich (SiO_2 = 71.2–76.5%, K_2O/Na_2O = 1.1–1.6, $K_2O + Na_2O$ = 7.5–8.5%) with a slightly metaluminous to peraluminous character [Al-(K + Na + 2Ca) domi-

Table 1 Sr and Nd isotope data of the Peneda–Gerês granitic massif, NW Iberian Peninsula

	Rb (p.p.m)	Sr (p.p.m)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ (2σ)	Sm (p.p.m)	Nd (p.p.m)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (2σ)	$^{87}Sr/^{86}Sr_i$*	εNd*	T_{DM}† (Ga)
Gerês											
G16	299.10	39.80	21.81	0.795652 (22)	4.83	21.25	0.1374	0.512446 (7)	0.70379	−1.51	1.05
G63	275.40	42.50	18.80	0.782503 (45)	6.30	28.02	0.1360	0.512440 (9)	0.70332	−1.57	1.05
G1	242.62	79.30	8.85	0.740919 (15)					0.70364		
G11	254.02	81.98	8.96	0.741175 (16)	6.53	29.65	0.1331	0.512437 (20)	0.70344	−1.52	1.05
Ap16‡	2.35	127.31	0.054	0.703572 (14)					0.70334		
Ap63‡	1.87	131.12	0.041	0.703802 (20)					0.70363		
Paufito											
M52	216.70	134.60	4.67	0.725682 (34)	5.72	28.92	0.1196	0.512371 (10)	0.70641	−2.36	1.11
M64	253.50	84.20	8.74	0.742146 (33)	6.28	26.83	0.1416	0.512412 (7)	0.70608	−2.37	1.11
M21	243.24	109.37	6.43	0.732924 (15)	6.66	32.04	0.1256	0.512381 (11)	0.70639	−2.39	1.11
Illa											
MM55	267.60	59.70	13.01	0.760574 (29)	3.24	17.14	0.1142	0.512359 (21)	0.70689	−2.39	1.11
MM58	238.70	96.70	7.16	0.735676 (31)	5.72	27.33	0.1265	0.512385 (11)	0.70613	−2.34	1.11
MM51	267.37	77.07	10.03	0.747992 (19)	4.18	17.14	0.1447	0.512419 (15)	0.70660	−2.35	1.11
Carris											
F9	237.80	94.00	7.34	0.735112 (70)	6.69	29.59	0.1326	0.512420 (10)	0.70482	−1.88	1.07
F45	283.40	87.10	9.44	0.744185 (28)	6.64	30.52	0.1316	0.512416 (9)	0.70523	− 1.92	1.08
F501	352.72	99.89	10.21	0.747395 (59)	7.02	34.34	0.1236	0.512399 (13)	0.70526	− 1.96	1.08
F503	259.16	78.72	9.52	0.744323 (15)					0.70504		
Covas											
5.3.4	436.54	11.31	112.40	1.176822 (18)	21.80	5.85	0.1622	0.512492 (19)	0.70339	−1.55	1.05
5.3.5	364.67	13.98	77.81	1.030782 (22)	18.39	5.61	0. 1846	0.512535 (17)	0.70304	−1.56	1.05
Calvos											
6.2.2	306.66	51.06	17.49	0.781287 (40)	17.95	4.10	0.1382	0.512346 (18)	0.70762	−3.49	1.20
10.3.4	277.91	80.99	9.97	0.751224 (36)	31.18	6.57	0.1274	0.512303 (22)	0.70923	−3.92	1.23

*$^{87}Sr/^{86}Sr_i$ and ε Nd were calculated at the emplacement ages (296 Ma for the Gerês, Covas and Calvos granites; 290 Ma for the other granites), using $^{143}Nd/^{144}Nd$ = 0.512638 and $^{147}Sm/^{144}Nd$ = 0. 1966 as present CHUR parameters (Goldstein *et al.*, 1984).
†Calculated according to Liew and Hofmann (1988), using $^{143}Nd/^{144}Nd$ = 0.513114 and $^{147}Sm/^{144}Nd$ = 0.222 as present DM parameters (Michard *et al.*, 1985).
‡Ap = apatite samples.

nantly between −4 and 40] and flattened REE patterns [(La/Yb)N between 2 and 12]. Some compositional characteristics are illustrated in Fig. 2. These reveal different chemical compositions for five of the six granites, as the Carris granite presents an identical composition to the Paufito granite. An evolutionary continuity is observed between the two innermost units of this massif, the Paufito and Illa granites, the latter representing the more evolved compositional end. The Covas granite has a very evolved composition, which is in accordance with its hololeucocratic nature. The Gerês, Paufito, Illa and Calvos granites present significant internal chemical–mineralogical evolutions (Fig. 2).

Sr and Nd isotopic data are reported in Table 1 and are illustrated in Fig. 3 together with the isotopic composition of other NW Iberian plutonic rocks. For the Gerês granite a whole-rock Rb–Sr isochron yields an age of 296 ± 6 Ma and a $(^{87}Sr/^{86}Sr)_i$ ratio of 0.7035 ± 0.0010 (MSWD = 0.08; four samples). For the Paufito and Illa granites a whole-rock Rb–Sr isochron yields an age of 292 ± 6 Ma and a $(^{87}Sr/^{86}Sr)_i$ ratio of 0.70619 ± 0.00058 (MSWD = 0.26; six samples). The Rb–Sr and U–Pb geochronological data are in agreement. The U–Pb isotopes yielded ages of 296 ± 2 Ma (monazite) and 297 ± 7 Ma (zircon) for the Gerês granite, whereas an age of 290 ± 2.5 Ma (zircon) was obtained for the Paufito granite (Dias *et al*., 1998). The low $(^{87}Sr/^{86}Sr)_i$ ratio of the Gerês granite was confirmed by Rb–Sr isotope data from two pure apatite concentrates (Table 1). In terms of Sr and Nd composition, the six granitic units form four compositional groups (Table 1; Fig. 3). The Gerês and Covas granites present the same isotope composition, with $(^{87}Sr/^{86}Sr)_{296}$ between 0.7030 and 0.7038, and εNd_{296} between −1.51 and −1.57. The Paufito and Illa granites also present the same composition: $(^{87}Sr/^{86}Sr)_{290}$ from 0.7061 to 0.7069 and εNd_{290} between −2.34 and −2.39. The Carris granite has an intermediate composition between these two groups: $(^{87}Sr/^{86}Sr)_{290}$ between 0.7048 and 0.7053, εNd_{290} between −1.88 and −1.96. The Calvos granite yields the most evolved isotope composition: $(^{87}Sr/^{86}Sr)_{296}$ between 0.7076 and 0.7092, εNd_{296} between −3.49 and −3.92. The model ages T_{DM} vary between 1.2 Ga for the Calvos granite and 1.1 Ga for the other granites. Additionally, a 1.2-Ga inherited component has been found in U–Pb zircon analysis of the Carris granite (Dias *et al*., 1998).

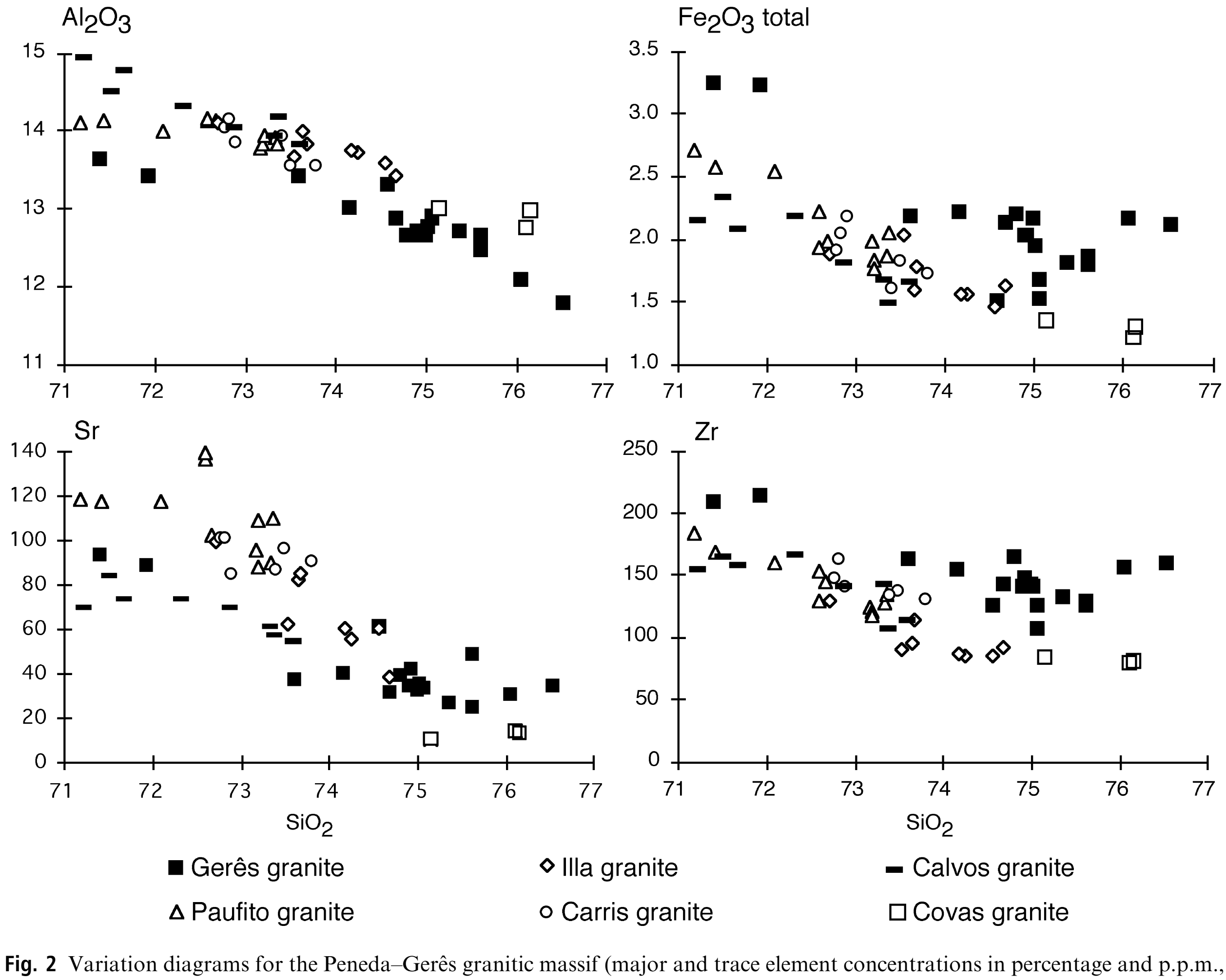

Fig. 2 Variation diagrams for the Peneda–Gerês granitic massif (major and trace element concentrations in percentage and p.p.m., respectively).

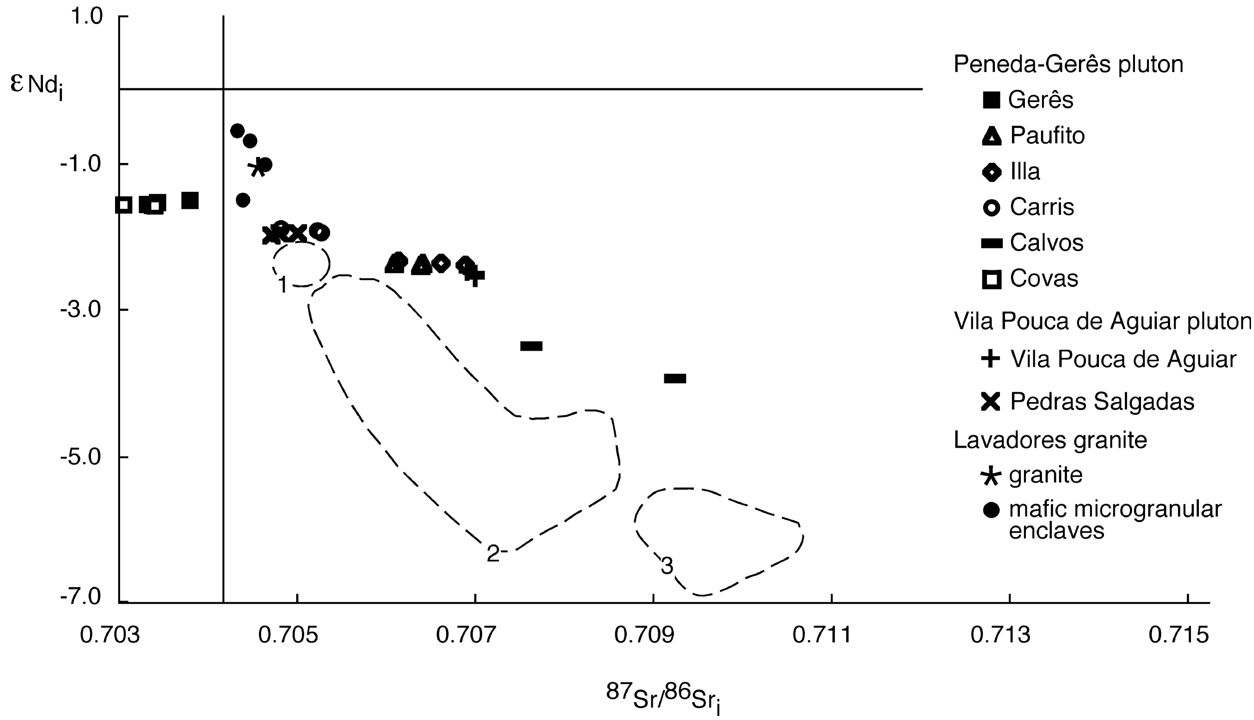

Fig. 3 εNd_i vs. $(^{87}Sr/^{86}Sr)_i$ for Hercynian plutons of NW Iberia (parameters calculated for the emplacement ages). The late- to post-orogenic plutons (290–299 Ma) are represented by symbols. Data for the Lavadores granite and enclaves are from Silva (1995) and for the Vila Pouca de Aguiar pluton from Martins (1998). The synorogenic magmatic rocks (305–320 Ma) are represented by fields (Dias *et al*., 2002): (1) late-D3 basic rocks (gabbro–norites); (2) intermediate and acid rocks of hybrid origin (monzodiorites, quartz-diorites, quartz-monzodiorites, granodiorites and monzogranites); (3) monzogranites of crustal origin.

Petrogenesis

The granites of the Peneda–Gerês massif belong to the ferriferous association of Debon and Le Fort (1988). They display a subalkaline affinity in the X vs. Or*–MM* multicationic diagram of La Roche *et al.* (1980), with the exception of the Calvos granite, which presents an alumino-potassic affinity. Furthermore, other typological indicators (zircon morphology, biotite composition) point to an Fe–K subalkaline nature for the Gerês, Paufito and Illa granites (Mendes and Dias, 1996).

Geochemical and isotopic data suggest that the granitic units of the Peneda–Gerês massif resulted from the synchronous emplacement of three intrusive magmas (Gerês–Covas, Calvos and Paufito–Illa–Carris) that evolved independently. In fact, the geochemical data suggest that the Paufito and Illa granites are co-magmatic. Based mainly on the Sr and Nd isotope data, a co-magmatic origin can also be postulated for the Gerês and Covas granites. The distinct isotope signatures of these two sets of units and of the Calvos granite suggest that they were derived from different magmas. With regard to the Carris granite, its isotope and mineralogical (biotite) composition is intermediate between the surrounding Gerês granite and the nearby Paufito granitic unit, although its whole-rock geochemistry is similar to the Paufito granite. Note that the Carris granite occurs as various hectometric bodies in the Gerês granite. Furthermore, there is field evidence of mingling processes at the contact between the two granites. The isotope signature of the Carris granite may possibly not correspond to a primary character, which may have been modified by diffusive transfer between the original magma (probably the same as that of the Paufito granite) and the more evolved surrounding magma (that of the Gerês granite).

The internal composition variations presented by the Gerês–Covas granites, Calvos granite and Paufito–Illa granites are most probably the result of fractional crystallization processes in which minerals such as plagioclase, quartz, biotite, K-feldspar and zircon played a major role (Mendes, 2001).

Two models are briefly examined for the genesis of the Peneda–Gerês pluton: (i) the purely crustal origin model and (ii) the model of mantle input. Compositions of the least evolved samples are similar to those of melts produced experimentally from metagreywackes or felsic meta-igneous protoliths, but different from melts of pelitic and mafic meta-igneous sources (for a review see Patiño Douce, 1999, and references therein). Middle and lower crust protoliths with an appropriate Sr–Nd isotopic composition were checked from the available data on the pre-Variscan basement of the Iberian massif (Beetsma, 1995; Villaseca *et al.*, 1998, 1999; Villaseca and Herreros, 2000). These data do not match the more primitive isotopic composition of the Peneda–Gerês granites, except for the peraluminous Calvos granite. Felsic peraluminous granulites from the lower crust that occur as meta-igneous xenoliths in the Spanish Central

System [$(^{87}Sr/^{86}Sr)_{300}$ and εNd_{300} dominantly in the range 0.706–0.713 and −2.6 to −8.2, respectively] are potential sources for the Calvos granite. For this granite the following features also support a major crustal contribution: moderately to highly peraluminous composition; aluminopotassic affinity; occurrence of Al- and Fe-rich biotites; absence of mafic microgranular enclaves and occurrence of surmicaceous enclaves. The T_{DM} model ages at 1.2 Ga indicate that, just as in other zones of the European Variscan chain, a portion of continental crust was present at least since the mid Proterozoic. For the other granites, with a slightly metaluminous to peraluminous character, evidence such as the occurrence of mafic microgranular enclaves, mantle-like isotope compositions and absence of crustal protoliths with an appropriate isotopic composition can be explained by the contribution of mafic mantle-derived magma(s). Sr–Nd isotope data do not exclude interaction processes between mafic mantle-derived magmas and the continental crust, mainly for the Paufito–Illa–Carris granites (Fig. 3). These processes of contamination with crustal materials may account for the occurrence of a heterogeneous zircon core population with calc-alkaline and aluminous characteristics in the Paufito–Illa granites (Mendes, 2001). Therefore, we propose that the Fe–K subalkaline granites of the Peneda–Gerês pluton are the products of mantle input followed by mantle–crust interaction. It must be noted that, at least for the Gerês and Covas granites, the mantle component would have a more depleted isotopic signature than the enriched mantle-derived melts involved in the genesis of synorogenic hybrid granitoids in NW Portugal (Fig. 3; Dias and Leterrier, 1994; Dias *et al*., 2002).

The majority of the late- to post-orogenic Variscan granites in NW Iberia are dominantly of Fe–K subalkaline affinity, with isotope composition in the range $(^{87}Sr/^{86}Sr)_i = 0.703$–0.707 and $\varepsilon Nd_i = -1.0$ to −2.5 (e.g. Fernandez, 1991; Silva, 1995; Martins, 1998; Fig. 3), corresponding dominantly to mantle-like isotope compositions. The isotopic composition of these granites is less evolved than that of the synorogenic granites in the region [$(^{87}Sr/^{86}Sr)_i > 0.7064$ and $\varepsilon Nd_i < -4.4$, Dias *et al.* (2002); see Fig. 3], which belong to aluminopotassic, calc-alkaline and Mg–K subalkaline associations. Various interacting factors related to the nature of the protoliths, as well as the physical and chemical conditions of melting, may account for this compositional contrast. Changes in the melting conditions were probably linked with the late-Variscan geodynamic setting of extensional processes, large-scale uplift and thinning. In the Iberian Massif a continuous emplacement of granitic magmas occurred between 320 Ma and 290 Ma, but with a drastic change in the tectonic conditions at about 300 Ma, from a compressive ductile tectonic regime to a brittle phase of deformation. This brittle tectonic regime controlled the emplacement of Fe–K subalkaline magmas.

Conclusions

The Peneda–Gerês granitic massif, one of the most representative late- to post-orogenic plutons in the Iberian Massif, is the result of the emplacement of three coeval (290–296 Ma) and independent magma batches. Fe–K subalkaline magmas with primitive Sr–Nd isotopic compositions are predominant. For these magmas an origin by mantle input followed by mantle–crust interactions is suggested, implying the contribution of a less enriched mantle component than that involved in the genesis of synorogenic hybrid granitoids of Mg–K subalkaline affinity. A less voluminous aluminopotassic and isotopically more evolved magma with little or no mantle input was generated, suggesting the involvement of lower crust materials (metagreywackes and/or felsic meta-igneous rocks).

A comparison among late- to post-orogenic Fe–K subalkaline granites of NW Iberia reveals that this type of plutonism presents a similar isotopic signature, globally weakly evolved, in the range $(^{87}Sr/^{86}Sr)_i = 0.7030$–0.7069 and $\varepsilon Nd_i = -1.0$ to −2.5. This rather primitive composition is in contrast with that of the synorogenic granitic plutonism in the region [$(^{87}Sr/^{86}Sr)_i > 0.7064$ and $\varepsilon Nd_i < -4.4$], involving aluminopotassic, calc-alkaline and Mg–K subalkaline associations. This compositional contrast is clearly associated with a drastic change in tectonics, from a compressive tectonic regime to extensional processes, large-scale uplift and thinning, which occurred in late Variscan times.

This study strongly suggests an input of juvenile magmas in late- to post-orogenic Variscan context. Based on these results and previous studies (Dias *et al*., 2002) we emphasize the occurrence of a major and continuous crustal growth event in late Variscan times (290–320 Ma) leading to the genesis of composite calc-alkaline and subalkaline plutons, largely represented in the Iberian Massif.

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