# Multiple crustal sources for post-tectonic I-type granites in the Hercynian Iberian Belt

C. Villaseca · F. Bellido · C. Pérez-Soba · K. Billström

**Abstract** A post-tectonic plutonic array of felsic I-type granites crops out in the western Hercynian Iberian Belt. Isotope (Sr, Nd, Pb) data favour the absence of an important input of juvenile magmas in late- to post- tectonic Hercynian felsic magmatism in western Iberia, but suggest a reworking of different crustal protoliths, including oceanic metabasic rocks accreted to mid-to-lower crustal levels during the early stages of the collision. I-type granites were derived from different meta-igneous protoliths ranging from metabasic to felsic compositions depending on their geographical position from the external (e.g. Galicia—N Portugal, GNP) to the innermost continental areas (Spanish Central System and Los Pedroches Batholiths). The GNP I-type plutons related to eo-Hercynian accretional terranes have lower initial $^{87}Sr/^{86}Sr$ ratios, lower negative εNd values, and higher $^{206}Pb/^{204}Pb$ ratios than other I-type granites of the Central Iberian zone. These more isotopically primitive Hercynian I-type granites are important in tracking pre-Hercynian accreted oceanic lithosphere terranes.

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## Introduction

The Iberian Massif is the largest Hercynian outcrop in Europe. It is characterized by an abundance of granite plutons in their innermost zones: the Galicia Tras os Montes and the Central Iberian zones (Fig. 1a). These Hercynian granites were emplaced mainly following the extensional D3 deformation phase dated at 320 Ma to 310 Ma (Dias et al. 1998).

A segmented plutonic array of post-tectonic Hercynian I-type granites crops out in western Iberia, mainly concentrated in two areas: Galicia-N Portugal (GNP) and the Spanish Central System (SCS) (Fig. 1). Additionally, small massifs crop out in the southwestern Central Iberian Zone (central Extremadura, CEX), close to the boundary with the Ossa-Morena Zone (Fig. 1). They form isolated circular plutons in the GNP, mostly cropping out within the Galicia-Tras os Montes accretional zone. In the SCS they intrude mostly in the northern part of the large peraluminous Hercynian batholith, forming an almost continuous granitic massif.

The GNP I-type granites are the latest Hercynian magmatic activity in that area, whereas SCS I-type granites are coeval with S-type granites and minor basic intrusions (Zeck et al. 2007). A later post-batholithic complex succession of basic-acidic calc-alkaline dyke swarms intruded the SCS (Villaseca et al. 2004).

The studied I-type granites have been previously classified either as calc-alkaline rocks or as K-rich subalkaline

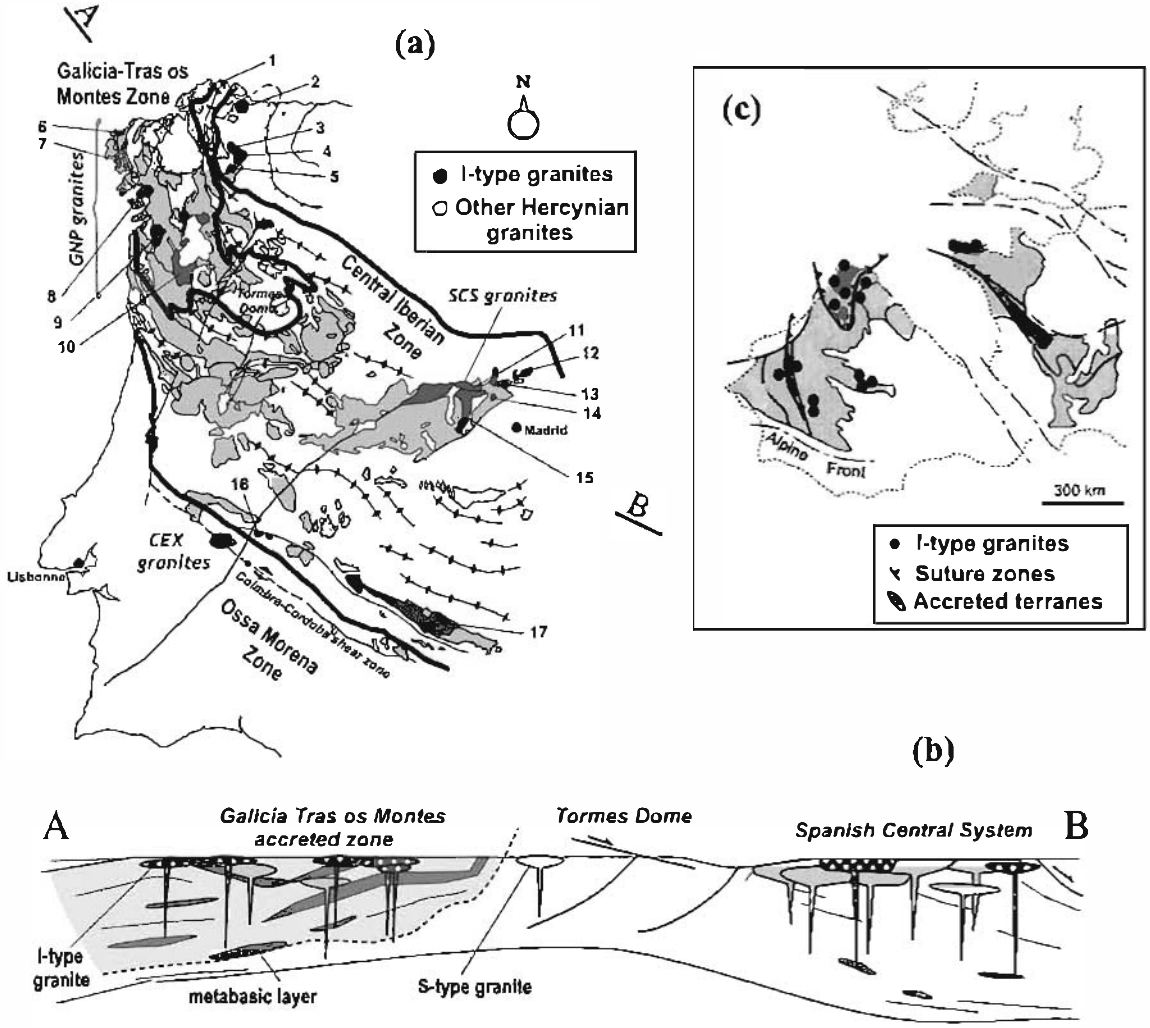


**Fig. 1** Geological setting of post-tectonic Hercynian I-type granites from the Western Iberian Belt. (a) Simplified geological map of granite outcrops in the Iberian Hercynian Zones. The location of cross section 1b is indicated. Numbers refer to some I-type plutons mentioned in text. GNP sector: 1 = Estaca de Bares, 2 = Tojiza, 3 = Lugo, 4 = Castroverde, 5 = Neira, 6 = Traba, 7 = El Pindo, 8 = Caldas de Reis, 9 = Porriño, 10 = Gêres. SCS sector: 11 = Villacastín, 12 = La Cabrera, 13 = La Pedriza, 14 = Atalaya Real, 15 = Navas del Marqués. Other plutons: 16 = Villar del Rey (CEX sector), 17 = Los Pedroches batholith (LPB). (b) Schematic cross section of Galicia-Tras os Montes and Central Iberian zones showing higher involvement of metabasic layers in NW accreted terranes. (c) Sketch of the western European Hercynian Massifs showing the location of accreted terranes and late- to post-tectonic I-type granite plutons

granites (e.g. Capdevila and Floor 1970; Capdevila et al. 1973; Mendes and Dias 2004; Cuesta and Gallastegui 2004). The markedly felsic composition and the peraluminous character of most of these granites make a direct comparison to the typical calc-alkaline series of subduction zones difficult. The more intracontinental setting of Iberian granitoids shows characteristics closer to the more universal alphabetic classification used in this work, although important differences with Lachlan Fold Belt I-type granites also exists (e.g. Villaseca et al. 1998). These differences with either calc-alkaline rocks of continental margins or I-type granite suites have also been observed in other Hercynian granite batholiths (e.g. Liew et al. 1989; Vellmer and Wedepohl 1994).

In this paper we present for the first time a Pb isotope study and an enlarged Sr-Nd isotopic data set of the post-tectonic Hercynian I-type granites of these three Iberian sectors: GNP, SCS and CEX. The petrogenesis of this type of plutonism is discussed including a comparison with other post-tectonic Hercynian granites of western Europe. Slightly older I-type granites from Los Pedroches Batholith (LPB), considered late-D3 (312 Ma, Donaire et al. 1999), and coeval S-type plutonism (in the SCS and LPB areas) are also included in the discussion on the characterization of these I-type granite batholiths and on granite sources during late-to-post Hercynian times. The origin of Hercynian I-type granites is still controversial on the roles of crustal and mantle contribution and the nature of granite sources (e.g. Mendes and Dias 2004; Villaseca et al. 2007).

## Geochronology and petrographical features

Post-tectonic Hercynian I-type plutons are described as post-D3 or post-collisional granites (e.g. Bellido et al. 1992; Dias et al. 1998). Available geochronological data yield ages younger than 310 Ma (Table 1). In the GNP area intrusion ages range from 301 Ma to 275 Ma.: 301 Ma (Castroverde), 297 Ma (Gêres), 295 Ma (Tojiza), 290 Ma (Lugo), 287 Ma (Porriño, Ma (Traba) (Cuesta 1991; Bellido et al. 1992; Dias et al. 1998; Fernández-Suárez et al. 2000). More scarce geochronological data are available for the SCS I-type granites, yielding a slightly older age range: 307 Ma (La Pedriza), 302 Ma (Navas del Marqués, La Cabrera), 299 Ma (La Granja), 284 Ma (Atalaya Real) (Villaseca et al. 1998, and references therein). I-type granites from Extremadura have not been dated yet.

The studied I-type granites are mainly felsic varieties ranging from monzogranite to leucogranite, with scarce granodiorite facies (Table 1). Coeval mafic rocks are absent in the GNP area, where Hercynian gabbros have been dated as pre- or syn-D3 (e.g. 323 Ma, Vivero gabbros, Fernández-Suárez et al. 2000). Scarce mafic microgranular enclaves appear in some plutonic facies. These enclaves are mostly granodiorite or monzogranite types, although some tonalitic enclaves have been also described (e.g. Cuesta 1991).

The more mafic monzogranitic facies often have accessory amphibole (hornblende or Fe-edenite) and more rarely relict clinopyroxene ($Wo_{47}$ $En_{25}$ $Fs_{27}$) hosted in plagioclase. Biotite is the main mafic unique mafic phase in most of the plutonic facies. Biotite is a good discriminant for I-type granites because it plots in subaluminous fields, when compared to biotite from more peraluminous Hercynian granitoids of the same area (Fig. 2). Biotites in the studied granites show also higher $Al_2O_3$ contents than biotites from anorogenic A-type suites (Fig. 2) (Nachit et al. 1985; Abdel-Rahman 1994). Another hallmark I-type feature of studied granites is the common presence of pink K-feldspar, giving a general reddish colour to the rock.

Common accessories are apatite, zircon, titanite, allanite, monazite, xenotime, ilmenite and some Fe-sulfides. Accessory almandine-spessartine garnet sometimes appears in leucogranite facies. More rare is the coeval presence of garnet with Fe-Mn-rich cordierite in some leucogranites (La Cabrera pluton, Villaseca and Barbero 1994). In the most felsic varieties of La Pedriza pluton, a highly fractionated rare-metal-rich leucogranite, a complex accessory paragen-

**Table 1** General features of studied post-tectonic Hercynian I-type granites of the Iberian Belt

| Pluton | Area ($Km^2$) | Enclaves | Rock types | Age (Ma) | Method | Reference |
|---|---|---|---|---|---|---|
| *Galicia - N Portugal (GNP)* | | | | | | |
| Estaca de Bares | 3 | MME | hbl-bt gdt | 286±53 ? | Rb-Sr (wr) | IGME unpublished |
| Tojiza | 200 | (MME), Bt-rich | bt mzgr, bt-ms lgr | 295±2 | U-Pb (zrn) | Fernández-Suárez et al. (2000) |
| Lugo | 130 | Bt-rich | bt mzgr | 290±5 | Rb-Sr (wr) | IGME unpublished |
| Castroverde | 165 | (MME) | (hbl)bt mzgr | 301±128 ? | Rb-Sr (wr) | IGME unpublished |
| Neira | 65 | MME | bt mzgr | 287±5 | Rb-Sr (wr) | Bellido et al. (1990) |
| Traba | 55 | Bt-rich | bt lgr | 275±3 | Rb-Sr (wr) | Bellido et al. (1992) |
| El Pindo | 65 | - | bt lgr | 276±4 | Rb-Sr (wr) | Bellido et al. (1992) |
| Caldas de Reis | 350 | MME | (hbl)bt gdt, bt mzgr | 287±10 | Rb-Sr (wr) | Cuesta (1991) |
| Porriño | 300 | MME | (hbl)bt mzgr | 287±9 | Rb-Sr (wr) | García Garzón (1987) |
| Gêres | 650 | MME | (hbl)bt mzgr | 297±7 | U-Pb (zrn) | Dias et al. (1998) |
| Vila Pouca de Aguiar | 150 | MME | bt mzgr | 299±3 | U-Pb (zrn) | Martins (1998) |
| *Spanish Central System (SCS)* | | | | | | |
| Villacastín | 150 | MME | hbl-bt gdt, bt mzgr | ? | | |
| La Cabrera | 160 | MME | hbl-bt gdt, bt mzgr, bt lgr | 302±3 | Pb-Pb (zrn) | Casquet et al. (2004) |
| Navas del Marqués | 500 | MME | hbl-bt gdt, bt (mzgr, lgr) | 302±4 | Rb-Sr (wr) | Casillas et al. (1991) |
| La Pedriza | 75 | Bt-rich | bt lgr | 307±3 | Rb-Sr (wr) | Pérez-Soba (1991) |
| La Granja | 85 | MME | hbl-bt gdt, bt mzgr | 299±55 | Rb-Sr (wr) | Villaseca et al. (1995) |
| Atalaya Real | 18 | MME | hbl-bt (gdt, mzgr, lgr) | 284±13 | Rb-Sr (wr) | Villaseca et al. (1995) |
| *Central Extremadura (CEX)* | | | | | | |
| Villar del Rey | 22 | MME | hbl-bt (gdt, mzgr) | ? | | |
| La Roca de la Sierra | 15 | (MME) | bt mzgr | ? | | |

MME: mafic microgranular enclave; gdt: granodiorite; mzgr: monzogranite; lgr: leucogranite; hbl: hornblende; bt: biotite; ms: muscovite; zrn: zircon; wr: whole-rock

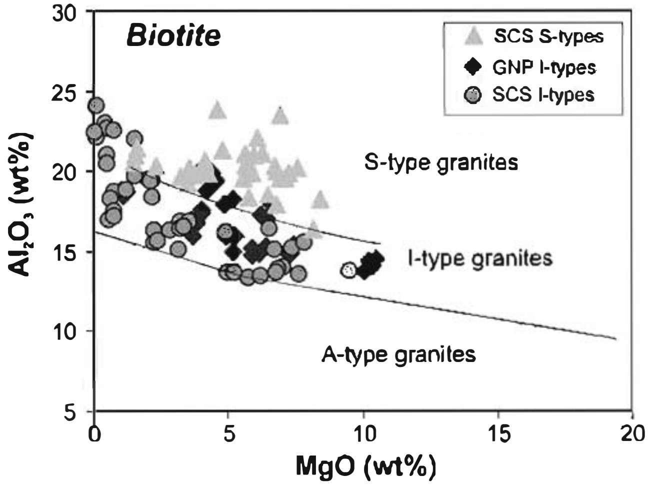


**Fig. 2** Biotite discrimination diagram of MgO-$Al_2O_3$ (wt%). Alkaline A-type granite field after Abdel-Rahman (1994). The boundary line between I-type and S-type granites is drawn on the basis of biotite composition from Hercynian Iberian granites from the literature (e.g. Villaseca and Barbero 1994) and unpublished data. Some Fe-rich green biotite analyses from the highly fractionated La Pedriza pluton (SCS) plot in the S-type granite field (Pérez-Soba 1991)

esis appears: magnetite, thorite, beryl, columbite and pyrochlore (González del Tánago et al. 2004).

## Analytical methods

A total of 21 new granite samples were collected for this work, mostly from northwestern Iberia (Galicia). Major and trace element whole-rock composition is given in Table 2. The whole-rock major and trace element composition was analysed at Actlabs (Ontario, Canada). The samples were melted using $LiBO_2$ and dissolved with $HNO_3$. The solutions were analysed by inductively coupled plasma atomic emission spectrometry (ICP-AES) for major elements, whereas trace elements were determined by ICP mass spectrometry (ICP-MS). Uncertainties in major elements are between 1 and 3%, except for MnO (5 10%) and $P_2O_5$ (>10%). The precision of ICP-MS analyses at low concentration levels has been evaluated from repeated analyses of the international standards BR, DR-N, UB-N, AN-G and GH. The precision for Rb, Sr, Zr, Y, V, Hf and most of the REE are in the range 1% to 5%, whereas they range from 5% to 10% for the rest of trace elements. More information on the analytical procedures, precision and accuracy can be obtained from: www.actlabs.com

Sr-Nd isotopic analyses were performed at the CAI de Geocronología y Geoquímica Isotópica of the Complutense University of Madrid, using an automated VG Sector 54 multicollector thermal ionisation mass spectrometer with data acquired in multidynamic mode. Isotopic ratios of Sr and Nd were measured on a subset of whole-rock powders. The analytical procedures used in this laboratory have been described elsewhere (Reyes et al. 1997). Repeated analysis of NBS 987 gave $^{87}Sr/^{86}Sr=0.710249\pm30$ ($2\sigma$, n=15) and for the JM Nd standard the $^{143}Nd/^{144}Nd=0.511809\pm20$ ($2\sigma$, n=13). The $2\sigma$ uncertainty on $\varepsilon$(Nd) calculation is ±0.4.

K-feldspar separates from 8 granites were checked for purity under a binocular microscope and analyzed for their Pb isotopic composition at the Swedish Museum of Natural History, Stockholm. After successive leaching steps with acids (6 M HCl, 6 M HNO3 and 5% HF), to remove any possible radiogenic component, samples were dissolved in pressurised Krogh capsules using a mixture of concentrated HF and HNO3. Pb was purified using cation exchange columns and loaded on single Re filaments, and subsequently analyzed on a Finnigan MAT 261 TIMS instrument. Data for unknowns were corrected for mass fractionation using an empirical relationship derived by running the NBS 981 standard at different temperatures. The BCR-1 basalt standard was also run during the course of the study to secure the quality of the measurements, and the overall accuracy of Pb isotopic data is estimated to be ±0.10% (2 sigma).

Representative Sr-Nd isotopic composition and the whole Pb isotopic data of studied I-type granites are given in Table 3.

## Geochemical features

The studied I-type granites are silica-rich ($SiO_2$>65.5 wt%) and mostly peraluminous, although some subordinate metaluminous varieties in the less acid facies appear in some plutons (e.g. Atalaya Real, Gêres) (Villaseca et al. 1998; Mendes and Dias 2004). The alumina saturation index (ASI) of the studied granites has a general tendency to increase with $SiO_2$, which explains the occurrence of accessory amounts of garnet in the most felsic granites of the SCS. The ASI is mostly comprised between 1.0 and 1.1, mainly below the value proposed to separate I- and S-type granites (Chappell 1999), and clearly with lower mean ASI values than associated S-type granites in central Spain (Fig. 3). Moreover, these I-type granites have $K_2O/Na_2O$>1, plotting in high-K fields in the $SiO_2$-$K_2O$ diagram and close to or above the alkaline/subalkaline boundary of the TAS diagram (Fig. 4).

The post-tectonic Hercynian red granites of western Iberia have typical I-type features in having higher concentrations of Ca and Na than do associated S-type granites (Fig. 2 of Villaseca et al. 1998). Moreover, they show a marked increase in Th, Nb, Y, HREE contents at 74 to 76 wt% $SiO_2$, that is common in felsic I-type granite suites (Champion and Chappell 1992) (Fig. 4). However, there are no significant differences in other major or trace

**Table 2** Major (wt%) and trace element (ppm) composition of pos-tectonic Hercynian I-type granites of the Iberian Belt

| Massif | *Traba* | *Traba* | *CV* | *CV* | *E. Bares* | *E. Bares* | *Porriño* | *Porriño* | *Tojiza* | *Tojiza* | *Neira* | *Neira* | *El Pindo* | *El Pindo* | *Lugo* | *Lugo* | *V. Rey* | *V. Rey* | *V. Rey* | *Atalaya R.* | *La Pedriza* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | *4143 GNP* | *4145 GNP* | *4212 GNP* | *4216 GNP* | *4155 GNP* | *4157 GNP* | *GDPO-1 GNP* | *GDPO-3 GNP* | *4275 GNP* | *4277 GNP* | *4201 GNP* | *4203 GNP* | *4251 GNP* | *4253 GNP* | *4079 GNP* | *4217 GNP* | *VR-1 CEX* | *VR-2 CEX* | *VR-3 CEX* | *95921 SCS* | *87225 SCS* |
| **$SiO_2$** | 73.18 | 75.84 | 68.23 | 68.69 | 66.89 | 67.08 | 69.52 | 71.57 | 73.43 | 73.20 | 72.09 | 68.19 | 74.58 | 74.52 | 71.13 | 71.91 | 67.35 | 69.02 | 69.15 | 67.87 | 74.21 |
| **$TiO_2$** | 0.16 | 0.15 | 0.47 | 0.47 | 0.55 | 0.54 | 0.39 | 0.39 | 0.13 | 0.16 | 0.33 | 0.57 | 0.15 | 0.04 | 0.28 | 0.33 | 0.50 | 0.52 | 0.56 | 0.39 | 0.15 |
| **$Al_2O_3$** | 14.05 | 12.71 | 15.17 | 14.98 | 15.29 | 15.18 | 15.54 | 14.55 | 14.12 | 13.89 | 13.69 | 14.97 | 13.27 | 13.87 | 14.37 | 14.10 | 16.55 | 14.89 | 14.52 | 15.46 | 13.19 |
| **$Fe_2O_3$** | 1.79 | 1.64 | 4.06 | 4.03 | 4.64 | 4.36 | 2.95 | 2.97 | 1.98 | 1.94 | 3.21 | 4.56 | 2.03 | 0.94 | 2.78 | 3.03 | 3.12 | 3.35 | 3.52 | 3.67 | 1.72 |
| **MnO** | 0.04 | 0.04 | 0.07 | 0.08 | 0.07 | 0.07 | 0.04 | 0.04 | 0.03 | 0.02 | 0.05 | 0.07 | 0.04 | 0.02 | 0.03 | 0.05 | 0.04 | 0.04 | 0.05 | 0.03 | 0.04 |
| **MgO** | 0.22 | 0.25 | 0.91 | 0.97 | 1.60 | 1.62 | 0.81 | 0.71 | 0.22 | 0.20 | 0.47 | 0.80 | 0.18 | 0.09 | 0.24 | 0.46 | 0.90 | 0.96 | 1.04 | 0.75 | 0.19 |
| **CaO** | 0.86 | 0.81 | 2.73 | 2.90 | 2.88 | 3.14 | 1.54 | 1.21 | 1.10 | 1.37 | 1.28 | 2.15 | 0.94 | 0.38 | 1.46 | 1.17 | 2.40 | 2.30 | 2.35 | 3.11 | 1.05 |
| **$Na_2O$** | 4.00 | 3.52 | 3.30 | 3.24 | 3.20 | 3.15 | 3.34 | 3.02 | 3.52 | 2.93 | 3.57 | 3.83 | 3.78 | 4.26 | 3.59 | 3.30 | 4.45 | 4.08 | 4.04 | 3.23 | 3.47 |
| **$K_2O$** | 5.05 | 4.15 | 4.42 | 3.94 | 3.99 | 4.07 | 5.10 | 4.73 | 4.76 | 5.74 | 4.60 | 4.24 | 4.73 | 5.53 | 5.61 | 4.88 | 4.19 | 4.42 | 4.24 | 4.39 | 4.65 |
| **$P_2O_5$** | 0.02 | 0.04 | 0.13 | 0.13 | 0.15 | 0.15 | 0.27 | 0.26 | 0.05 | 0.03 | 0.11 | 0.19 | 0.03 | 0.01 | 0.07 | 0.13 | 0.14 | 0.14 | 0.15 | 0.14 | 0.05 |
| **LOI** | 0.63 | 0.65 | 0.51 | 0.57 | 0.74 | 0.65 | 0.50 | 0.55 | 0.66 | 0.52 | 0.60 | 0.45 | 0.42 | 0.40 | 0.45 | 0.64 | 0.38 | 0.28 | 0.39 | 1.03 | 0.40 |
| **Total** | 99.82 | 99.79 | 99.60 | 99.59 | 99.54 | 99.57 | 99.70 | 99.71 | 99.80 | 99.81 | 99.68 | 99.55 | 100.10 | 99.94 | 99.72 | 99.99 | 99.69 | 99.66 | 99.66 | 99.75 | 99.11 |
| **Sc** | 4 | 4 | 10 | 11 | 13 | 11 | 5 | 3 | 5 | 5 | 7 | 10 | 4 | 2 | 5 | 6 | 8 | 7 | 5 | 7 | 6 |
| **V** | 9 | 10 | 41 | 52 | 65 | 61 | 27 | 23 | 8 | 10 | 15 | 36 | 5 | 2 | 8 | 19 | 35 | 32 | 36 | 32 | 8 |
| **Cr** | 154 | 150 | 123 | 127 | 161 | 136 | 174 | 176 | 142 | 124 | 147 | 129 | 90 | 101 | 143 | 90 | 77 | 92 | 80 | 95 | 49 |
| **Ga** | 24 | 23 | 18 | 19 | 18 | 17 | 20 | 19 | 21 | 16 | 20 | 21 | 22 | 22 | 21 | 24 | 22 | 21 | 21 | 22 | 19 |
| **Ba** | 189 | 165 | 520 | 481 | 578 | 536 | 702 | 443 | 278 | 540 | 420 | 577 | 325 | 133 | 560 | 495 | 597 | 534 | 453 | 752 | 334 |
| **Rb** | 315 | 305 | 183 | 191 | 175 | 169 | 231 | 260 | 312 | 144 | 160 | 136 | 292 | 318 | 173 | 213 | 163 | 171 | 175 | 186 | 247 |
| **Sr** | 43 | 39 | 189 | 187 | 229 | 215 | 262 | 84 | 59 | 105 | 116 | 147 | 53 | 21 | 101 | 102 | 247 | 213 | 200 | 149 | 43 |
| **Cs** | 26.7 | 17.8 | 9.8 | 20.2 | 9.5 | 15.1 | 15.2 | 27.4 | 19.4 | 7.1 | 6.6 | 10.9 | 12.0 | 12.4 | 9.0 | 8.3 | 10.6 | 9.5 | 6.6 | 7.0 | 7.2 |
| **Y** | 80.9 | 70.0 | 42.7 | 39.8 | 23.7 | 25.2 | 20.3 | 17.7 | 33.9 | 19.8 | 28.7 | 28.8 | 59.5 | 35.3 | 35.7 | 44.9 | 27.5 | 21.2 | 31.9 | 33.1 | 48.9 |
| **Zr** | 137 | 126 | 178 | 163 | 139 | 141 | 165 | 149 | 86 | 105 | 219 | 272 | 192 | 101 | 224 | 253 | 144 | 183 | 196 | 201 | 119 |
| **Hf** | 3.9 | 5.2 | 6.3 | 4.6 | 5.3 | 3.1 | 4.4 | 3.3 | 2.3 | 1.8 | 4.1 | 4.8 | 5.9 | 3.2 | 5.0 | 6.9 | 4.1 | 4.7 | 6.2 | 5.0 | 4.3 |
| **Nb** | 24.1 | 25.5 | 11.2 | 10.8 | 10.4 | 9.8 | 12.0 | 12.7 | 19.4 | 10.3 | 16.3 | 15.0 | 19.3 | 18.8 | 17.4 | 21.5 | 18.1 | 18.7 | 20.9 | 10.7 | 11.9 |
| **Ta** | 3.80 | 4.39 | 2.50 | 1.30 | 3.10 | bdl | 0.40 | 0.70 | 0.80 | bdl | 1.70 | bdl | 3.09 | 1.90 | 1.90 | 2.30 | 2.80 | 1.40 | 2.40 | bdl | 3.57 |
| **Pb** | 43.6 | 36.0 | 22.5 | 24.0 | 21.2 | 24.0 | 59.7 | 49.1 | 25.5 | 30.2 | 28.1 | 22.9 | 38.0 | 31.1 | 25.9 | 28.0 | 24.1 | 25.4 | 26.1 | 32.0 | 37.0 |
| **Th** | 25.8 | 26.4 | 14.0 | 15.0 | 16.0 | 14.9 | 25.7 | 20.3 | 14.7 | 17.8 | 14.1 | 13.0 | 24.8 | 15.2 | 15.7 | 18.5 | 13.7 | 22.6 | 30.7 | 19.3 | 21.9 |
| **U** | 19.60 | 24.80 | 4.60 | 7.50 | 7.50 | 6.10 | 8.10 | 7.50 | 4.50 | 2.70 | 3.90 | 3.70 | 16.50 | 12.60 | 3.30 | 4.32 | 2.80 | 8.70 | 8.70 | 3.10 | 5.29 |
| **La** | 37.40 | 24.50 | 45.20 | 34.30 | 31.10 | 37.60 | 47.20 | 47.40 | 26.70 | 44.40 | 40.80 | 44.50 | 26.70 | 10.50 | 41.60 | 49.10 | 33.90 | 26.10 | 55.70 | 59.15 | 29.70 |
| **Ce** | 80.60 | 51.20 | 92.20 | 68.70 | 61.20 | 68.40 | 108.70 | 89.50 | 58.60 | 96.10 | 90.50 | 85.00 | 57.10 | 23.80 | 85.40 | 101.00 | 63.80 | 50.70 | 101.00 | 123.60 | 62.90 |
| **Pr** | 9.60 | 6.43 | 10.20 | 7.80 | 7.10 | 7.80 | 10.20 | 10.20 | 6.40 | 10.60 | 9.70 | 10.20 | 6.46 | 3.40 | 9.90 | 11.10 | 6.60 | 5.80 | 11.00 | 13.92 | 7.31 |
| **Nd** | 36.80 | 28.70 | 37.90 | 29.70 | 25.70 | 27.50 | 34.10 | 36.30 | 23.50 | 36.70 | 35.30 | 38.20 | 25.90 | 14.10 | 35.90 | 43.10 | 25.70 | 22.10 | 40.30 | 53.54 | 27.00 |
| **Sm** | 9.70 | 7.78 | 8.30 | 7.00 | 5.50 | 5.30 | 5.90 | 6.20 | 6.00 | 7.60 | 7.30 | 7.70 | 6.48 | 4.40 | 7.50 | 8.84 | 5.30 | 4.60 | 7.60 | 10.45 | 6.98 |
| **Eu** | 0.75 | 0.46 | 1.80 | 1.30 | 1.30 | 1.20 | 0.89 | 1.00 | 0.52 | 0.94 | 1.20 | 1.30 | 0.63 | 0.34 | 1.10 | 1.12 | 1.40 | 1.00 | 1.40 | 1.19 | 0.44 |
| **Gd** | 10.20 | 8.94 | 7.40 | 6.60 | 4.80 | 4.80 | 4.40 | 4.30 | 5.70 | 5.90 | 6.20 | 6.60 | 7.15 | 4.80 | 6.30 | 8.47 | 4.70 | 4.00 | 6.50 | 7.57 | 7.28 |
| **Tb** | 2.00 | 1.74 | 1.20 | 1.10 | 0.73 | 0.76 | 0.53 | 0.57 | 1.10 | 0.81 | 1.00 | 1.00 | 1.37 | 1.00 | 0.94 | 1.39 | 0.69 | 0.60 | 0.91 | 1.07 | 1.40 |
| **Dy** | 12.20 | 10.80 | 6.80 | 6.40 | 4.10 | 4.10 | 2.60 | 2.70 | 6.00 | 3.90 | 5.10 | 5.30 | 8.64 | 6.50 | 5.10 | 7.85 | 3.70 | 3.40 | 4.80 | 6.11 | 8.48 |

**Table 2** (continued)

| Massif | Traba | Traba | CV | CV | E. Bares | E. Bares | Porriño | Porriño | Tojiza | Tojiza | Neira | Neira | El Pindo | El Pindo | Lugo | Lugo | V. Rey | V. Rey | V. Rey | Atalaya R. | La Pedriza |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | 4143 | 4145 | 4212 | 4216 | 4155 | 4157 | GDPO-1 | GDPO-3 | 4275 | 4277 | 4201 | 4203 | 4251 | 4253 | 4079 | 4217 | VR-1 | VR-2 | VR-3 | 95921 | 87225 |
| | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | GNP | CEX | CEX | CEX | SCS | SCS |
| **Ho** | 2.60 | 2.07 | 1.40 | 1.30 | 0.80 | 0.80 | 0.50 | 0.50 | 1.10 | 0.70 | 1.00 | 1.00 | 1.73 | 1.40 | 1.00 | 1.41 | 0.70 | 0.65 | 0.90 | 1.20 | 1.71 |
| **Er** | 7.80 | 6.29 | 4.00 | 3.90 | 2.20 | 2.50 | 1.70 | 1.80 | 2.70 | 1.80 | 2.80 | 2.80 | 5.40 | 4.00 | 3.70 | 4.11 | 2.10 | 1.90 | 2.50 | 3.15 | 5.25 |
| **Tm** | 1.20 | 1.04 | 0.59 | 0.59 | 0.34 | 0.35 | 0.24 | 0.24 | 0.35 | 0.25 | 0.39 | 0.38 | 0.87 | 0.64 | 0.49 | 0.63 | 0.28 | 0.27 | 0.35 | 0.46 | 0.81 |
| **Yb** | 8.00 | 6.74 | 3.80 | 3.90 | 2.20 | 2.50 | 1.60 | 1.60 | 2.20 | 1.50 | 2.40 | 2.40 | 5.59 | 4.10 | 2.90 | 4.06 | 1.80 | 1.90 | 2.40 | 2.99 | 5.10 |
| **Lu** | 1.20 | 0.97 | 0.59 | 0.61 | 0.34 | 0.38 | 0.24 | 0.22 | 0.30 | 0.23 | 0.35 | 0.37 | 0.79 | 0.62 | 0.46 | 0.59 | 0.26 | 0.28 | 0.35 | 0.41 | 0.74 |

Pluton abbreviation as follows: CV = Castroverde; E. Bares = Estaca de Bares; V. Rey = Villar del Rey; Atalaya R. = Atalaya Real

element contents when compared to coeval Hercynian S-type granites of the SCS.

Slight compositional differences are observed between the I-type granites from Galicia-N Portugal and those from central Spain. GNP granites show slightly higher concentrations of Na, K, Sr, Eu, Zr, LREE, U and Nb than SCS granites (Fig. 4). The CEX granites plot in the same compositional field as GNP granites. I-type granites from Los Pedroches Batholith (LPB) are less felsic, richer in MgO contents and show a markedly higher Sr (and slightly lower Zr, Y, HREE) contents than any of the studied I-type granites, but plot in intermediate compositional fields between GNP and SCS when considering other components (Fig. 4). The great difference in Sr contents between I-type batholiths suggest that the source of the Los Pedroches granites was distinct from the other studied granites.

The chondrite-normalized REE patterns (Fig. 5) vary from moderately fractionated in monzogranites {$(La/Yb)_N$ ratios of 19–20} towards relatively flat in the more felsic leucogranites {$(La/Yb)_N$ ratios of 1–2}. Correlatively, the magnitude of the negative Eu anomaly evolves from small (Eu/Eu*=0.84–0.58) towards more pronounced (Eu/Eu*= 0.23–0.15) in the leucogranite varieties. This trend is common in all studied I-type granite suites, with the most fractionated granite (La Pedriza pluton in the SCS) showing the highest negative Eu anomaly (Eu/Eu*=0.01) and the flattest REE pattern ($La/Yb_N$=0.4–0.9) (Fig. 5).

More significant differences appear when considering isotopic data (Table 3). Most of the GNP granites show low initial $^{87}Sr/^{86}Sr$ ratios (0.7024 to 0.7086) when compared to SCS granites (0.7036 to 0.7152). The GNP granites tend to have low negative εNd values (mostly from −0.1 to −5.2) whereas the SCS I-type granites have more negative εNd values, in the narrower range of −4.2 to −6.6 (Fig. 6). The Porriño

lowest εNd values of the Galician I-type granites, plotting even below the SCS compositional field (Fig. 6). The CEX I-type granites plot in the centre of the GNP Sr-Nd isotope compositional field, reinforcing their chemical similarity. On the other hand, the LPB I-type granites plot in the lower Nd isotopic range values of the GNP compositional field (Fig. 6).

Lead isotopic composition of some GNP granites shows more radiogenic $^{206}Pb/^{204}Pb$ ratios (Fig. 7). Most of the studied I-type granites plot within the same compositional field and have similar Pb composition to other western european Hercynian granites of different types (Michard-Vitrac et al. 1981; Bernard-Griffiths et al. 1985; Downes et al. 1997). In fact, Pb isotopic data of S-type granites from the SCS and LPB have the same values than coeval I-type granites, as was also stated with Sr-Nd-O isotopes in previous works (Villaseca et al. 1998; Donaire et al. 1999;

**Table 3** Sr, Nd and Pb isotope data of post-tectonic Hercynian I-type granites of the Iberian Belt

| Massif | *El Pindo* | *Tojiza* | *Traba* | *Lugo* | *Neira* | *Castroverde* | *Porriño* | *Villar Rey* | *Villar Rey* | *Villacastín* | *Atalaya Real* | *Navas Marqués* | *La Pedriza* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | 4253 *GNP* | 4275 *GNP* | 4145 *GNP* | 4217 *GNP* | 4201 *GNP* | 4212 *GNP* | GDTPO-3 *GNP* | VR-1 *CEX* | VR-3 *CEX* | 92460[a] *SCS* | 95921 *SCS* | G-48 *SCS* | 87225 *SCS* |
| ***t (Ma)*** | 276 | 295 | 275 | 290 | 287 | 301 | 287 | 300 (?) | 300 (?) | 300 (?) | 285 | 302 | 307 |
| **Rb (ppm)** | 318 | 312 | 305 | 213 | 160 | 183 | 260 | 163 | 175 | 131 | 186 | 180 | 247 |
| **Sr (ppm)** | 21 | 59 | 39 | 102 | 116 | 189 | 84 | 247 | 200 | 143 | 149 | 103 | 43 |
| **($^{87}$Rb/$^{86}$Sr)** | 44.56 | 5.29 | 22.82 | 6.06 | 4.00 | 2.81 | 9.00 | 1.91 | 2.54 | 2.66 | 3.62 | 5.07 | 16.74 |
| **($^{87}$Sr/$^{86}$Sr)m** | 0.877408±05 | 0.772303±07 | 0.793433±06 | 0.729426±05 | 0.723398±05 | 0.720593±08 | 0.751497±09 | 0.713576±06 | 0.716423±05 | 0.721622±06 | 0.725932±03 | 0.732899±06 | 0.776700±06 |
| **($^{87}$Sr/$^{86}$Sr)t** | 0.70244 | 0.70764 | 0.70412 | 0.70402 | 0.70707 | 0.70858 | 0.71475 | 0.70541 | 0.70560 | 0.70883 | 0.71127 | 0.71108 | 0.70357 |
| **Sm (ppm)** | 4.40 | 6.06 | 7.78 | 8.84 | 7.30 | 8.30 | 6.2 | 5.3 | 7.60 | 7.46 | 10.45 | 4.93 | 6.98 |
| **Nd (ppm)** | 14.10 | 23.50 | 28.70 | 43.10 | 35.30 | 37.90 | 36.30 | 25.70 | 40.30 | 34.44 | 53.54 | 20.41 | 27.00 |
| **($^{147}$Sm/$^{144}$Nd)** | 0.1887 | 0.1465 | 0.1639 | 0.1240 | 0.1250 | 0.1324 | 0.1032 | 0.1247 | 0.1140 | 0.1309 | 0.1180 | 0.1460 | 0.1563 |
| **($^{143}$Nd/$^{144}$Nd)m** | 0.512603±04 | 0.512356±03 | 0.512561±04 | 0.5123990±03 | 0.512498±03 | 0.512255±05 | 0.512118±03 | 0.512402±03 | 0.512380±03 | 0.512214±03 | 0.512196±07 | 0.512308±03 | 0.512276±03 |
| **($^{143}$Nd/$^{144}$Nd)t** | 0.512263 | 0.512055 | 0.512266 | 0.512163 | 0.512263 | 0.511994 | 0.51 | 0.512157 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 |
| **E(Nd)t** | −0.39 | −3.97 | −0.35 | −1.98 | −0.10 | −5.01 | −6.73 | −1.85 | −1.87 | −5.76 | −5.76 | −4.49 | −5.47 |
| ***TDM (Ga)*** | – | 1.74 | 1.45 | 1.11 | 0.97 | 1.46 | 1.28 | 1.11 | 1.04 | 1.50 | 1.34 | 1.61 | 1.94 |
| | *Kfs.* | | *Kfs.* | *Kfs.* | | | *Kfs.* | *Kfs.* | | *Kfs.* | *Kfs.* | | *Kfs.* |
| **($^{206}$Pb/$^{204}$Pb)t** | 18.900 | | 18.604 | 18.351 | | | 18.321 | 18.277 | | 18.560 | 18.252 | | 18.303 |
| **($^{207}$Pb/$^{204}$Pb)t** | 15.650 | | 15.671 | 15.650 | | | 15.623 | 15.644 | | 15.688 | 15.641 | | 15.702 |
| **($^{208}$Pb/$^{204}$Pb)t** | 38.305 | | 38.376 | 38.395 | | | 38.266 | 38.407 | | 38.611 | 38.339 | | 38.535 |

[a] Sr and Nd isotope data from Villaseca et al. (1998)

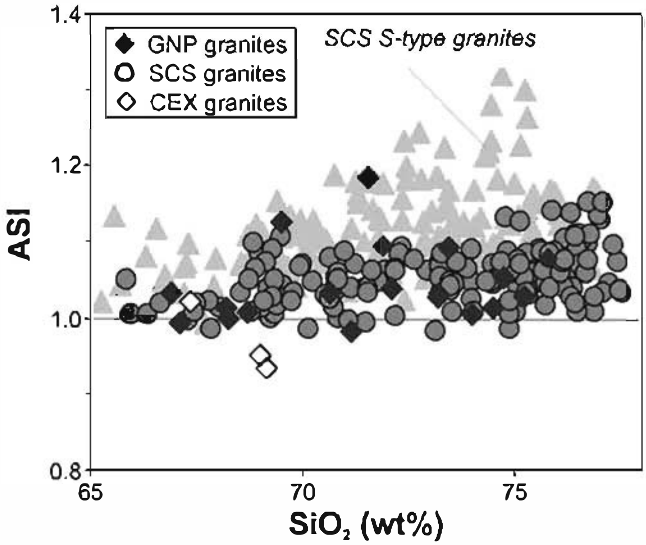


**Fig. 3** Diagram of $SiO_2$—alumina saturation index (ASI; mol ratio) of the studied Hercynian I-type granites. Compositional field for SCS S-type granites from Villaseca et al. (1998) is included for comparison

Villaseca and Herreros 2000; García de Madinabeitia 2002) (Fig. 7).

## Discussion

### Nature of granite sources

Major differences in Sr-Nd isotopic composition suggest the involvement of different protoliths for NW Iberia (and central Extremadura) compared to the I-type granites from central Spain. Hercynian basic rocks are very scarce in all the Central Iberian zone, although some minor gabbro outcrops are also present, representing much less than 1 vol% of the plutonic belt (e.g. Bea et al. 1999). Furthermore, coeval basic intrusions are absent in the GNP and LPB areas. Basic-acid magma mixing has been invoked for the origin of I-type granites in the innermost areas of this Central Iberian zone (e.g. Moreno-Ventas et al. 1995; Mendes and Dias 2004). Available Sr-Nd data for the outcropping Hercynian basic rocks of the Central Iberian zone are also plotted in Fig. 6. The gabbroic rocks plot in a narrow field close to Bulk Earth values or slightly displaced to higher Sr radiogenic values ($^{87}Sr/^{86}Sr$=0.7045 0.7065, and εNd values from +0.6 to −2.6). Although some I-type granites from Galicia plot within this mafic compositional field, their greater variation in $^{87}Sr/^{86}Sr$ ratios is notable. This kind of array suggests the involvement of other components such as protoliths with low $^{87}Sr/^{86}Sr$ ratios and relatively negative εNd values, which are rare in associated mantle-derived basic rocks. The SCS granites do not overlap the Sr-Nd isotopic field of basic rocks and show a wide range of $^{87}Sr/^{86}Sr$ ratios (Fig. 6).

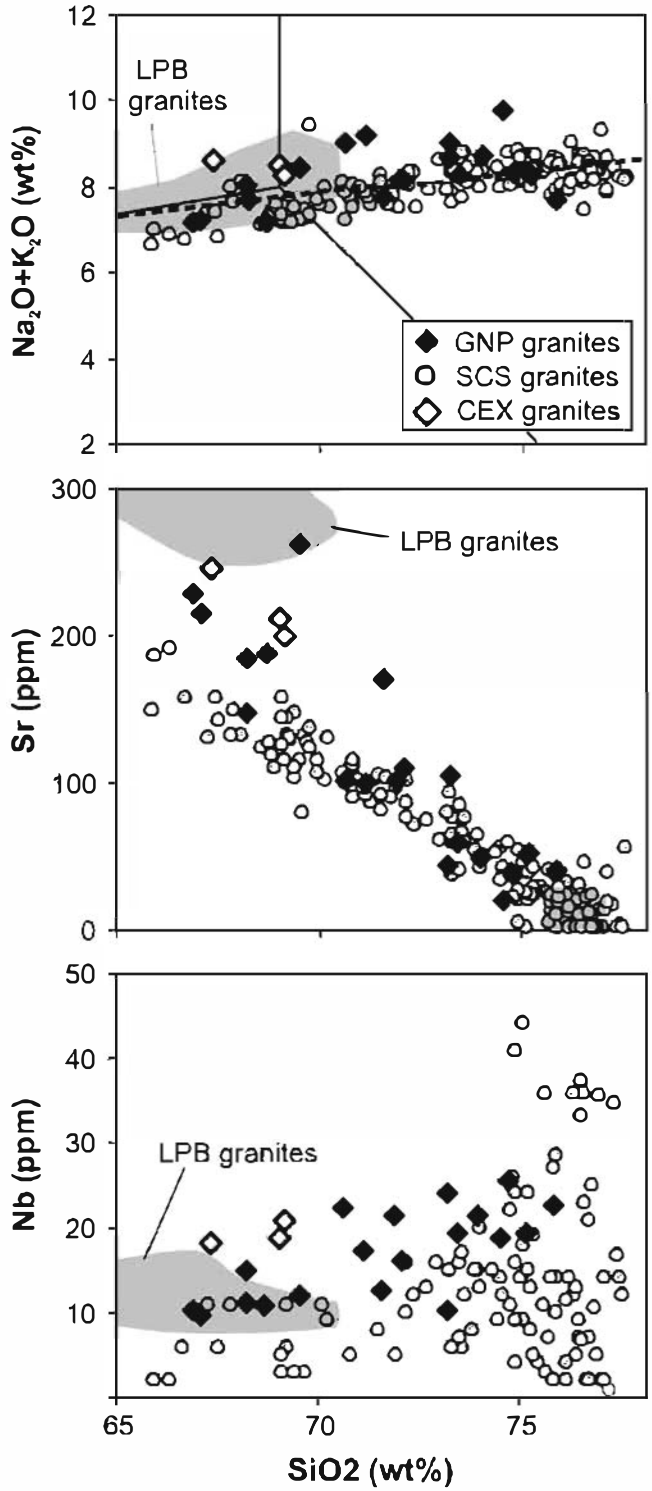


**Fig. 4** Chemical diagrams for post-tectonic Hercynian I-type granites. Compositional field of LPB I-type granites from Donaire et al. (1999) and Jiménez San Pedro (2003). TAS fields and Kuno's alkaline/subalkaline boundary taken from Rollinson (1993)

Direct involvement of basic rocks is unlikely because of the markedly felsic composition of Iberian I-type granites and the lack of spatial and temporal relationships with gabbroic magmas. However, the low radiogenic Sr values

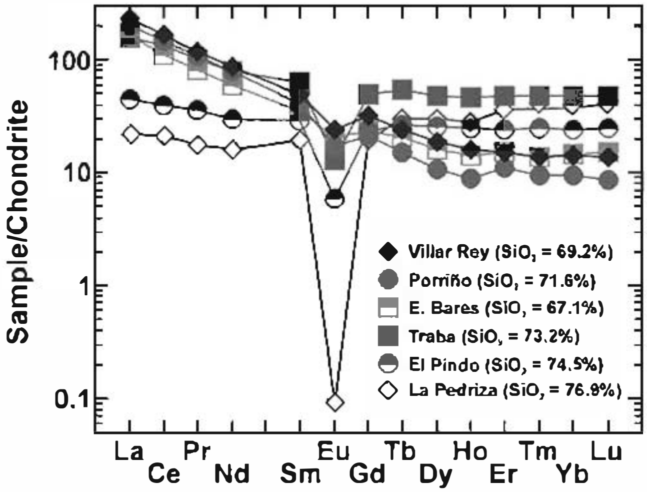


**Fig. 5** Chondrite-normalised REE patterns of representative post-tectonic I-type granites of the Hercynian Iberian Belt. Data for La Pedriza granite taken from Pérez-Soba and Villaseca (2009). Normalising values after Sun and McDonough (1989)

combined with less negative εNd values suggest reworked basic sources. Indeed, the large variation of $^{87}Sr/^{86}Sr$ ratios could be a consequence of the high Rb/Sr ratios usually found in crustal rocks. Granulite xenoliths from the SCS lower crust are isotopically much more similar to the Hercynian granites than the outcropping metamorphic rocks (Villaseca et al. 1999). Deep-seated mafic granulite xenoliths (charnockites *s.l.*) have lower $^{87}Sr/^{86}Sr$ ratios and higher εNd values compared to other metamorphic rocks found in the Central Iberian zone, and plot in the middle of the GNP I-type compositional field (Fig. 6). The compositional similarity in Pb isotopic ratios between SCS charnockites and GNP granites is also remarkable, and suggests granite generation from metabasic sources (Fig. 7).

Rutile is a common accessory phase in lower crustal granulite xenoliths from central Spain (Villaseca et al. 1999). This phase is ubiquitous and modally abundant in felsic granulite xenoliths whereas it occasionally appears in charnockites. Granite melts equilibrated with mafic metaluminous residual granulites (charnockite xenoliths) would have higher Nb contents compared to melts equilibrated with residual rutile-bearing felsic granulites. As the SCS I-type granites show lesser Nb contents than the GNP granites (Fig. 4), a more mafic granulitic residuum is suggested for the GNP granites. On the other hand, the SCS felsic granulite xenoliths have been interpreted as the lower crustal residuum of the outcropping batholith, both on the basis of major, trace and isotope (Sr, Nd, O, Pb) compositions (Villaseca et al. 1999; Villaseca and Herreros 2000; Villaseca et al. 2007), and geochronological data (Fernández-Suárez et al. 2006).

In Fig. 8 studied I-type granites plot between two fields: the GNP (excepting Porriño massif) and CEX granites have less evolved εNd values and younger model ages (0.89 to

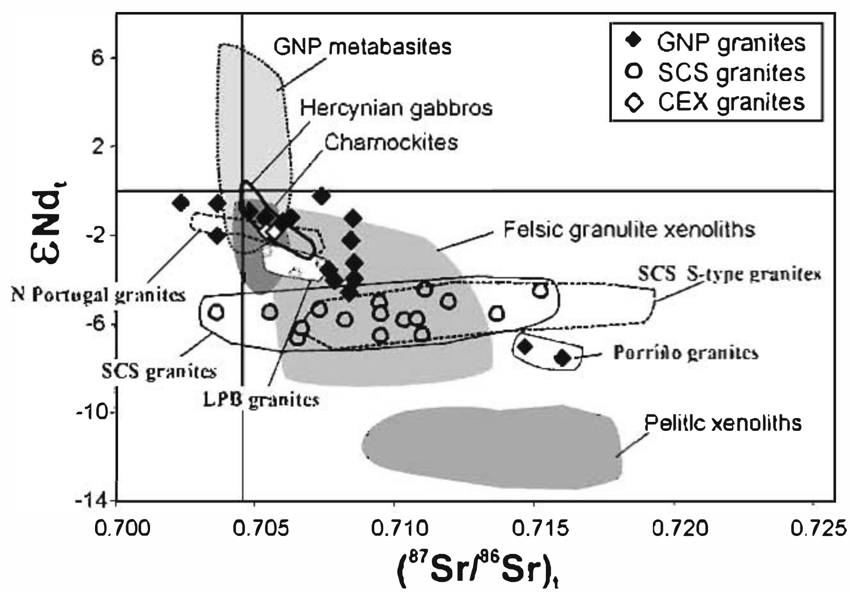


**Fig. 6** $\varepsilon Nd_t$ vs $(^{87}Sr/^{86}Sr)_t$ for the studied Hercynian I-type granites (calculated for emplacement ages, Table 1). N-Portugal data are taken from Mendes and Dias (2004). Hercynian gabbro field is based on Bea et al. (1999) and unpublished data. Isotopic data from the LPB I-type granites were taken from Donaire et al. (1999). Compositional range of mafic-ultramafic complexes from the GNP area is taken from Cabo Ortegal (Santos et al. 2002). Metamorphic data are calculated at 300 Ma. Xenoliths are lower crustal granulites carried up by the SCS upper Permian alkaline lamprophyres, classified by Villaseca et al. (1999) in: i) felsic granulites, ii) pelites, and iii) charnockites (data from Villaseca et al. 1999, 2007). Outcropping metamorphic rocks are not included in this diagram as they plot outside of the granite compositional field, mostly towards higher $^{87}Sr/^{86}Sr$ ratios (see Fig. 7 of Villaseca et al. 1998). S-type granites of the SCS and LPB (these ones are not included in the plot for clarity) show similar initial Sr-Nd isotopic ratios than coeval I-types

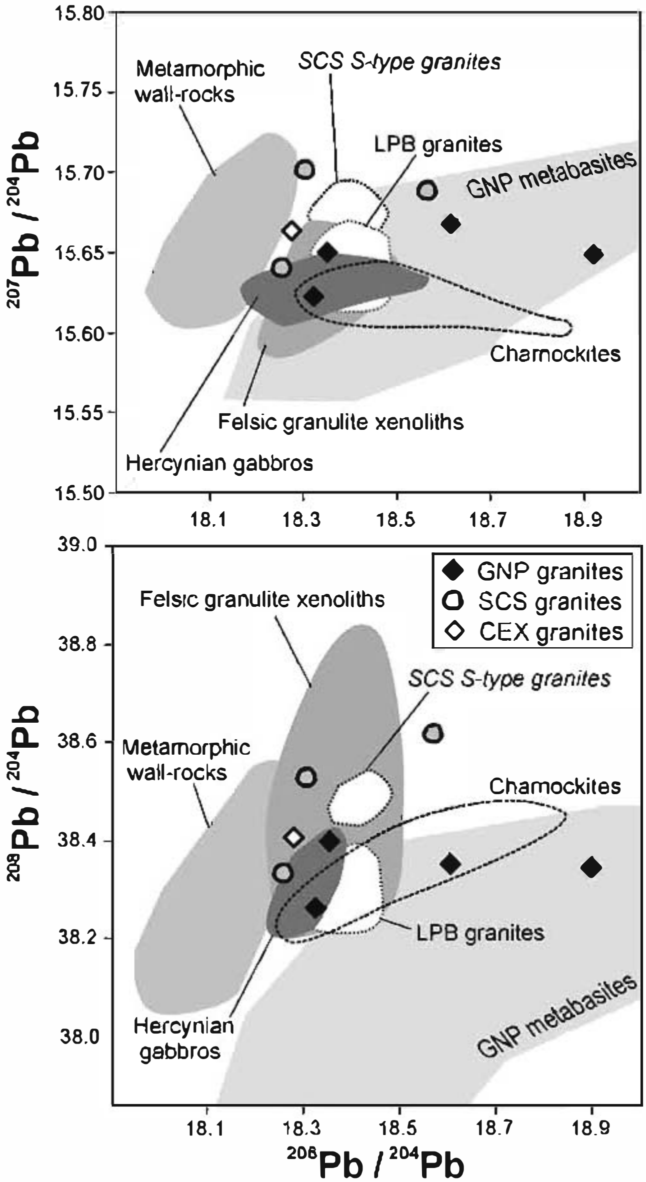


**Fig. 7** $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ of K-feldspars from the Iberian post-tectonic Hercynian I-type granites. K-feldspars from Los Pedroches I- and S-type granites show the same Pb isotopic compositional field (García de Madinabeitia 2002). Compositional range of mafic-ultramafic complexes in the GNP area comprises Pb isotopic ratios of garnets in mafic granulites from Cabo Ortegal (Santos et al. 2002, and references therein) and from an age corrected metaperidotite from Morais (Beetsma 1995). Also shown are fields of SCS felsic and charnockite xenoliths (Villaseca et al. 2007) calculated at 300 Ma. Compositional fields of K-feldspars from SCS metamorphic wall-rocks, S-type granites and Hercynian gabbros are unpublished data

1.5 Ga), whereas the SCS granites have more negative εNd values and older model ages (1.1 to 2.0 Ga). The SCS lower crustal granulite xenolith suite comprises most of the granite isotopic compositional field although charnockite types fit better with the field of CEX and most of the GNP granites. However, the Porriño granites plot within the compositional field of felsic meta-igneous granulites. Metasedimentary granulitic xenoliths plot below the granite field due to its strongly negative εNd values, reinforcing the meta-igneous origin of Central Iberian I-type granites. This suggests that most of the GNP and CEX granites were generated from more juvenile and metabasic sources compared to the SCS (and Porriño) granites which contain large proportions of felsic recycled pre-Ordovician crust.

The slightly more radiogenic Nd ratios of the LPB granites compared to the GNP granites suggest a minor involvement of basic metaigneous sources, which is consistent with the proposed derivation from mainly intermediate metaigneous protoliths (see also Donaire et al. 1999). Is interesting to remark that the coeval S-type granites of the SCS and LPB areas have been described as derived from similar isotopic sources than associated I-type granites (Villaseca et al. 1998; Donaire et al. 1999).

### The role of mid-crustal components

Some granite units plot outside the lower crustal compositional field towards more radiogenic values (e.g. Atalaya Real in the SCS and Porriños in the GNP; Fig. 6). This may imply shallower crustal sources or the involvement of metasedimentary rocks. Although the isotopic data preclude a direct origin from pelitic sources, the possibility of assimilation during magma transport or emplacement, and even some mixed sources at partial melting levels, should also be considered. Assimilation processes for the origin of the Iberian granites have been proposed, mostly for cordierite-bearing S-type varieties (e.g. Ugidos and Recio 1993; García-Moreno et al. 2007). Two different scenarios have been discussed: i) assimilation at marginal facies during emplacement (Ugidos and Recio 1993), or ii) assimilation occurring at low crustal levels, involving induced partial melting after underplated basic magmatism (Castro et al. 1999; García-Moreno et al. 2007).

Petrographical evidence for contamination by host-rocks or metasediments from deeper crustal levels is missing in the studied I-type granites. The lack of xenoliths or xenocrysts and the presence of the most peraluminous and fractionated facies in the inner parts of the plutonic units preclude assimilation during transport or magma emplacement. Nevertheless, some mixed crustal sources could be involved in the origin of some of the studied granites. The markedly negative εNd values of metasedimentary rocks from the northern part of the CIZ (Beetsma 1995; Villaseca et al. 1998, 1999) should be reflected in isotopic ratios of I-type granites if they were lithotypes involved in their origin. In Fig. 9 we have included two mixing models between an averaged felsic meta-igneous granulite and two averaged mid crustal

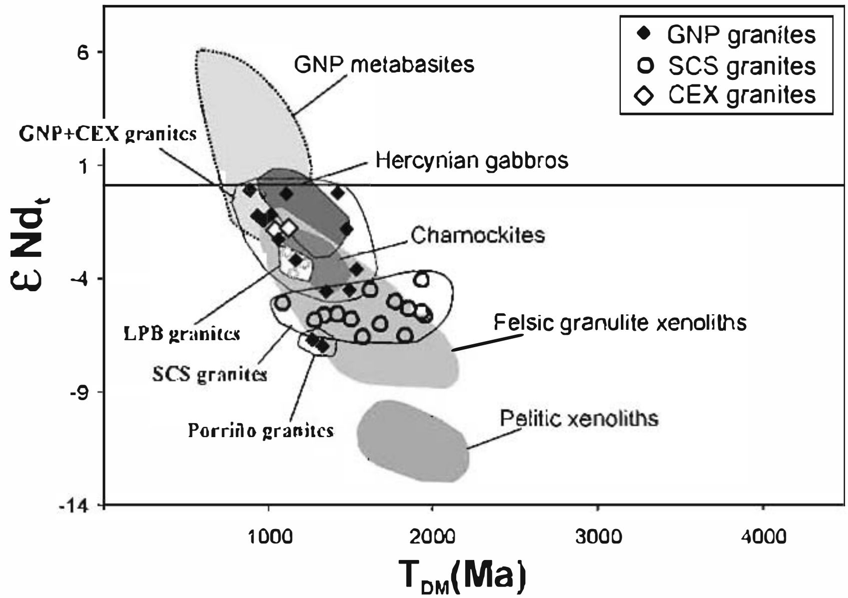


**Fig. 8** $\varepsilon Nd_t$ vs $T_{DM}$ of studied post-tectonic Hercynian I-type granites. To avoid the effect of REE fractionation on $T_{DM}$ values, a limited range of Sm/Nd fractionation has been taken (< 0.17) (Jahn et al. 2000). Others fields as in Fig. 6

components: i) metasedimentary and ii) felsic orthogneissic rocks. The Atalaya Real pluton is an isotopically heterogeneous amphibole-bearing unit of clear I-type affinity in the SCS area (Villaseca et al. 1998). These granites plot along a mixing line of meta-igneous rocks from different crustal levels (Fig. 9), due to their almost constant εNd values, which are very similar to those of the CIZ felsic meta-igneous protoliths (Beetsma 1995; Villaseca et al. 1998, 1999; Castro et al. 1999). The Porriño unit also plots close to the mixing line suggesting a slightly higher contribution (50 60%) of this more radiogenic meta-igneous component (Fig. 9). This is in agreement with the highest P, Pb and ASI values shown by the Porriño granites within the studied GNP I-type granites (Table 2). In any case, the involvement of metasedimentary sources in the genesis of the studied granites is precluded with the available isotopic data and, thus, their I-type classification is reinforced.

## Thermal aspects of melt generation

The results of the present study suggest that the sources of I-type granites included basic-intermediate to felsic meta-igneous protoliths. The dehydration melting of biotite- and hornblende-bearing rocks is widely suggested as an important anatectic crustal process giving rise to significant granite melt fractions when high thermal conditions (800 to 975°C) have been attained at depth (e.g. Patiño Douce et al. 1990; Singh and Johannes 1996; Sisson et al. 2005). Two critical factors for reaching high-T conditions in an intra-continental orogenic event are: i) the value of maximum crustal thickening attained during the collision, and ii) the crustal heat production rate (Patiño Douce et al. 1990). The Iberian continental crust was considerably thickened during the Hercynian collision either in the GNP area (> 70 km, Martínez Catalán et al. 1999) or in central Spain (up to 80 km after Barbero and Villaseca 2000). This factor of doubling the original crustal thickness is a requisite for widespread anatexis (e.g. Thompson and England 1984). Moreover, the internal radiogenic heat production within this thickened crust is very high in the CIZ: 2.35 2.60 $\mu Wm^{-3}$ for metamorphic rocks, 3.23 $\mu Wm^{-3}$ for granites, and 0.98 1.04 $\mu Wm^{-3}$ for the felsic SCS lower crust (averages from: Bea et al. 2003; Villaseca et al. 2005). Temperatures in excess of 900°C at lower crustal levels could have been attained as exemplified by the estimated *P-T* range for the deep-seated meta-igneous granulites of the SCS (900 to 1000°C; Villaseca et al. 2007; Villaseca and Orejana 2008). Thermal modelling of some Hercynian collision areas using less heat productive crustal materials and lower thickening factors than those estimated here, suggest that granite magmatism does not require a significant addition of heat from mantle sources (e.g. Gerdes et al. 2000; Bea et al. 2003). Thermal aspects suggest a suppressed mantle contribution, which is in agreement with geochemical features of studied I-type granites.

## Geodynamic framework

Based on the position of ophiolitic rock sequences, two Hercynian sutures have been identified in the boundaries

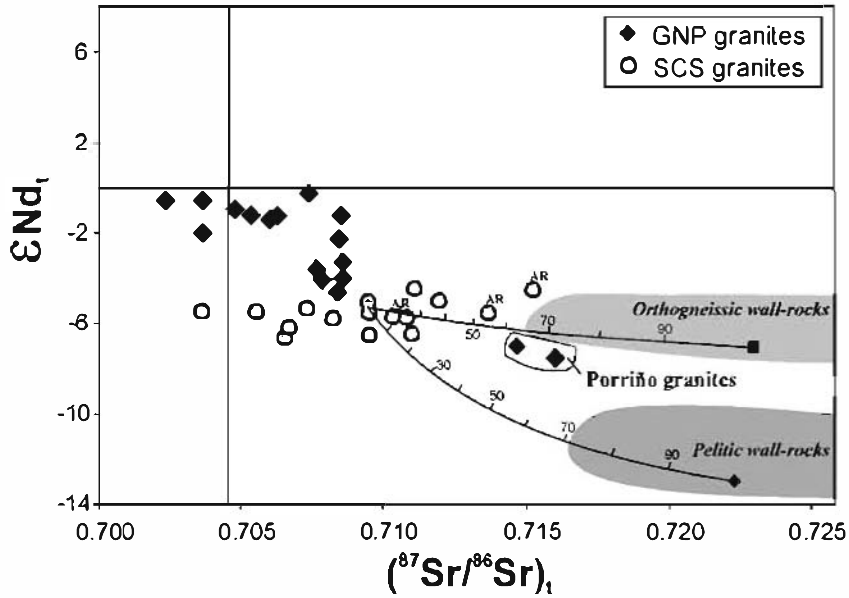


**Fig. 9** Initial $^{87}Sr/^{86}Sr$ vs initial εNd plot showing mixing lines between an average deep-seated felsic meta-igneous granulite source and two different crustal end-members: a) and average orthogneiss (data from Villaseca et al. 1998; Castro et al. 1999), b) and average pelite (data from Beetsma 1995; Villaseca et al. 1998). Felsic meta-igneous granulite composition is: $(^{87}Sr/^{86}Sr)_{300}$=0.70954, initial $\varepsilon Nd_{300}$= 5.2, Sr=282 ppm, Nd=27.8 ppm. Orthogneissic end-member composition is: $(^{87}Sr/^{86}Sr)_{300}$=0.72305, initial $\varepsilon Nd_{300}$= 6.9, Sr=107 ppm, Nd= 24.9 ppm. Pelitic end-member composition is: $(^{87}Sr/^{86}Sr)_{300}$=0.72238, initial $\varepsilon Nd_{300}$= 12.5, Sr=140 ppm, Nd=38.9 ppm. Granites marked with AR are samples from the Atalaya Real pluton in the SCS, other symbols as in Fig. 6

of the Central Iberian zone: i) the allochthonous complexes of northwestern Iberia (Galicia Tras os Montes) and ii) the strongly strike-slip reworked allochthonous units contained in the Coimbra-Córdoba shear zone (Fig. 1a).

The geological setting of the GNP granites (Galicia Tras-os-Montes zone) is complex and could have originally involved in their genesis an accreted mafic (oceanic) crust (Díaz García et al. 1999; Arenas et al. 2007). Lithospheric fragments of the Rheic ocean were accreted to the Iberian micro-continent at around 390 Ma (Arenas et al. 2007). On the other hand, the boundary between southern Central Iberian and Ossa-Morena zone is also interpreted as a suture of an oceanic realm that gently dips under the Central Iberian terrane (Simancas et al. 2002). The closure of ocean basins in both boundaries suggests a local accretion or indentation of significant meta-basic layers under the Central Iberian zone (Fig. 1b). The available isotope (Sr, Nd, Pb) data for mafic and ultramafic complexes from NW Iberia suggest that some metabasites from the accreted Rheic oceanic lithosphere may have been involved in the genesis of some GNP I-type plutons (Figs. 6 and 7), in spite of their dominant MORB-like geochemistry, illustrated by low $^{208}Pb/^{204}Pb$ ratios (Fig. 7) and highly radiogenic Nd isotope signatures (Beetsma 1995; Santos et al. 2002; Pin et al. 2002, 2006). The metabasic rocks that are more radiogenic than MORBs and have chemical signatures indicative of an involvement of a subducted component, are the most likely sources for the GNP granites. Suprasubduction ophiolitic rock-types are common in the NW allochtonous complexes (Santos et al. 2002; Arenas et al. 2007). The partial melting of these subsequently granulitized metabasic layers at mid-to-lower crustal levels, during late-Hercynian times, would also explain why these I-type granites have a more primitive isotopic composition than those from the innermost continental areas (where quartzofeldspathic rocks are dominant).

Post-kinematic "red granites" of Northern French Brittany show similar characteristics to those of the GNP granites (Fig. 1c). They are late-Hercynian in age (305 to 280 Ma, Ploumanach, Morlaix; Barriére 1980; Carron et al. 1994) and have a similar chemical composition, although Nd-Pb isotope data is not currently available. A major difference is the presence of associated gabbros, which have promoted theories for these I-type granites being generated from a single basic to acid magma fractionation (Barriére 1977) or through hybridization (Fourcade 1981). Whatever the case, the mantle contribution has been estimated to be of small proportions (Albarède et al. 1980). Oceanic lithosphere have been accreted or underthrusted in the southern Brittany terrane boundaries (e.g. Shelley and Bossière 2002) and, therefore, metabasic or related rocks would be involved in granite melt genesis, in a similar scenario to that proposed here for the Iberian terranes.

The dispersed geographical distribution of the post-Hercynian I-type granites in western Europe (Fig. 1c) contrasts with other european Hercynian I-type granite belts (Finger and Steyrer 1990). Moreover, S- and I-type granites intruded coevally in the Iberian and Brittany peninsulas at the same emplacement level. It seems that, rather than a tectonic control in a specific geodynamic setting, or outlining the closure of a suture zone, the presence of I-type granites would be related to differences in composition of the protoliths involved at partial melting scenarios. In this regard, the isotopically more primitive Hercynian I-type granites (e.g. GNP granites) show a good geographical relationship with accreted peri-oceanic lithosphere and, consequently, they might be derived from more metabasic sources.

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## References

Abdel-Rahman AM (1994) Nature of biotites from alkaline, calc-alkaline, and peraluminous magmas. J Petrol 35:525–541

Albarède F, Dupuis C, Taylor HR Jr (1980) $^{18}O/^{16}O$ evidence for non-cogenetic magmas associated in a 300-Ma-old concentric pluton at Ploumanac'h (Brittany, France). J Geol Soc London 137:641–647

Arenas R, Martínez Catalán JR, Sánchez Martínez S, Fernández-Suárez J, Andonaegui P, Pearce JA, Corfu F (2007) The Vila de Cruces ophiolite: a remnant of the early Rheic ocean in the variscan suture of Galicia (Northwest Iberian Massif). J Geol 115:129–148

Barbero L, Villaseca C (2000) Eclogite facies relics in metabasites from the Sierra de Guadarrama (Spanish Central System): *P-T* estimations and implications for the Hercynian evolution. Mineral Magaz 64:815–836

Barriére M (1977) Le complexe de Ploumanac'h, Massif Armoricain. Thèse Doctoral, Université de Brest, 291

Barriére M (1980) Les granitoïdes paléozoïques armoricains. In: Autran A, Dercourt J (eds) Evolutions géologiques de la France. Mém BRGM 107: 56–63

Bea F, Montero P, Molina JF (1999) Mafic precursors, peraluminous granitoids, and late lamprophyres in the Avila batholith; a model for the generation of Variscan batholiths in Iberia. J Geol 107:399–419

Bea F, Montero P, Zinger T (2003) The nature, origin, and thermal influence of the granite source layer of Central Iberia. J Geol 111:579–595

Bellido F, Brandle JL, García Garzón J, Lasala MJ, Reyes J (1990) Estudio petrológico y geocronológico del plutón granítico de Neira. Cuad Lab Xeol Laxe 15:25–40

Bellido F, Brandle JL, Lasala M, Reyes J (1992) Consideraciones petrológicas y cronológicas sobre las rocas graníticas Hercínicas de Galicia. Cuad Lab Xeol Laxe 17:241–261

Bernard-Griffiths J, Peucat JJ, Sheppard S, Vidal Ph (1985) Petrogenesis of Hercynian leucogranites from the southern Armorican Massif: contribution of REE and isotopic (Sr, Nd, Pb and O) geochemical data to the study of source characteristics and ages. Earth Planet Sci Letters 74:235–250

Beetsma JJ (1995) The late Proterozoic/Paleozoic and Hercynian crustal evolution of the Iberian Massif, N Portugal, as traced by geochemistry and Sr-Nd-Pb isotope systematics of pre-Hercynian terrigenous sediments and Hercynian granitoids. Ph. D. Thesis, Vrije Universiteit, Amsterdam, pp 223

Capdevila R, Floor P (1970) Les différents types de granites hercyniens et leur distribution dans le nord-ouest de l'Espagne. Bol Geol Miner España 81:215–225

Capdevila R, Corretgé G, Floor P (1973) Les granitoïdes varisques de la Meseta Ibérique. Bull Soc Géol France 15:209–228

Carron JP, Guen Le, de Kerneizon M, Nachit H (1994) Variscan granites from Brittany. In: Keppie JD (ed) Pre-Mesozoic Geology in France. Springer Verlag, Berlin, pp 231–239

Casillas R, Vialette Y, Peinado M, Duthou JL, Pin C (1991) Ages et caracteristiques isotopiques (Sr-Nd) des granitoides de la Sierra de Guadarrama occidentale (Espagne). Abstract Séance spec. Soc. Geol. France à la memoire de Jean Lameyre

Casquet C, Montero P, Galindo C, Bea F, Lozano R (2004) Geocronología $^{207}Pb/^{206}Pb$ en cristal único de circón y Rb-Sr del plutón de La Cabrera (Sierra del Guadarrama). Geogaceta 35:71–74

Castro A, Patiño Douce AE, Corretgé LG, de la Rosa J, El-Biad M, El-Hmidi H (1999) Origin of peraluminous granites and granodiorites, Iberian Massif, Spain: an experimental test for granite petrogenesis. Contrib Mineral Petrol 135:255–276

Champion DC, Chappell BW (1992) Petrogenesis of felsic I-type granites: an example from northern Queensland. Trans R Soc Edinburgh:Earth Sci 83:115–126

Chappell BW (1999) Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. Lithos 46:535–551

Cuesta A (1991) Petrología granítica del plutón de Caldas de Reis (Pontevedra, España). Estructura, mineralogía, geoquímica y petrogénesis. Ediciós do Castro, serie Nova Terra 5:363

Cuesta A, Gallastegui G (2004) Magmatismo de la zona Centro-Ibérica: Galicia Occidental. In: Vera (ed) Geología de España. IGME-SGE, Madrid. pp 96–100

Dias G, Leterrier J, Mendes A, Simoes PP, Bertrand JM (1998) U-Pb zircon and monazite geochronology of syn- to post-tectonic Hercynian granitoids from the Central Iberian Zone (Northern Portugal). Lithos 45:349–369

Díaz García F, Arenas R, Martínez Catalán JR, González del Tánago J, Dunning GR (1999) Tectonic evolution of the Careón ophiolite (Northwest Spain). A remnant of oceanic lithosphere in the Variscan Belt. J Geol 107:587–605

Donaire T, Pascual E, Pin C, Duthou JL (1999) Two-stage granitoid-forming event from an isotopically homogeneous crustal source: The Los Pedroches batholith, Iberian Massif, Spain. Geol Soc Amer Bull 111:1897–1906

Downes H, Shaw A, Williamson BJ, Thirlwall MF (1997) Sr, Nd and Pb isotopic evidence for the lower crustal origin of Hercynian granodiorites and monzogranites, Massif Central, France. Chem Geol 136:99–122

Fernández-Suárez J, Dunning GR, Jenner GA, Gutiérrez-Alonso G (2000) Variscan collisional magmatism and deformation in NW Iberia: constraints from U-Pb geochronology of granitoids. J Geol Soc London 157:565–576

Fernández-Suárez J, Arenas R, Jeffries TE, Whitehouse MJ, Villaseca C (2006) A U-Pb geochronological study of zircons from a lower crustal xenolith of the Spanish Central System: a record of Iberian lithospheric evolution from Neoproterozoic to the Triassic. J Geol 114:471–483

Finger F, Steyrer HP (1990) I-type granitoids as indicators of a late Paleozoic convergent ocean-continent margin along the southern flank of the central European Variscan orogen. Geology 18:1207–1210

Fourcade S (1981) Geochimie des Granitoïdes. Ph D Thesis, Université de Paris 7, Paris. pp 189

García Garzón J (1987) Datación por el método de Rb-Sr de dos muestras de granito de Galicia: granito tipo Padrón y granito tipo Porriño. Bol Geol Min España 98:107–110

García de Madinabeitia S (2002) Implementación y aplicación de los análisis isotópicos de Pb al estudio de las mineralizaciones y la geocronología del área Los Pedroches-Alcudia (Zona Centro-Ibérica). Ph D Thesis, Universidad del Pais Vasco, Bilbao, pp 217

García-Moreno O, Corretgé LG, Castro A (2007) Processes of assimilation in the genesis of cordierite leucomonzogranites from the Iberian Massif: a short review. Canad Mineral 45:71–85

González del Tánago J, Pérez-Soba C, Villaseca C (2004) Minerales accesorios de Nb-Ta-Ti e Y-REE-Th-U en el plutón granítico de La Pedriza, Sistema Central Español. Geotemas 6:57–60

Gerdes A, Wörner G, Henk A (2000) Post-collisional granite generation and HT-LP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith. J Geol Soc London 157:577–587

Jahn B, Wu F, Chen B (2000) Massive granitoid generation in Central Asia: Nd isotope evidence and implication for continental growth in the Phanerozoic. Episodes 23:82–92

Jiménez San Pedro R (2003). El complejo filoniano tardihercínico asociado al batolito de Los Pedroches (Zona Centro Ibérica, España). Ph D Thesis, Universidad del Pais Vasco, Bilbao. pp 459

Liew TC, Finger F, Höck V (1989) The Moldanubian granitoid plutons of Austria: Chemical and isotopic studies bearing on their environmental setting. Chem Geol 76:41–55

Martínez Catalán JR, Arenas R, Díaz García F, Abati J (1999) Allocthonous units in the Variscan Belt of NW Iberia. Terranes and accretionary history. In: Sinha AK (ed) Basement tectonics. Kluwer Academic, Dordrecht, pp 65–84

Martins HCB (1998) Geoquímica e petrogénese de granitóides biotíticos tarditectónicos e post-tectónicos. Implicaçoes metalogenéticas. Ph D Thesis, Universidade de Tras-os-Montes e Alto Douro, Vila Real. pp 288

Mendes AC, Dias G (2004) Mantle-like Sr-Nd isotope composition of Fe-K subalkaline granites: the Peneda-Gêres Variscan massif (NW Iberian Peninsula). Terra Nova 16:109–115

Michard-Vitrac A, Albarède F, Allégre CJ (1981) Lead isotopic composition of Hercynian granitic K-feldspars constrains continental genesis. Nature 291:460–464

Moreno-Ventas I, Rogers G, Castro A (1995) The role of hybridization in the genesis of Hercynian granitoids in the Gredos Massif, Spain: inferences from Sr-Nd isotopes. Contrib Mineral Petrol 120:137–149

Nachit H, Razafimahefa N, Stussi JM, Carron JP (1985) Composition chimique des biotites et typologie magmatique des granitoïdes. Comp Rendus Acad Scie Paris 301:813–818

Patiño Douce AE, Humphreys ED, Johnston AD (1990) Anatexis and metamorphism in tectonically thickened continental crust exemplified by the Sevier hinterland, western North America. Earth Planet Sci Letters 97:290–315

Pérez-Soba C (1991) Petrología y geoquímica del Macizo granítico de La Pedriza, Sistema Central Español. Ph D Thesis, Universidad Complutense, Madrid. pp 225

Pérez-Soba C, Villaseca C (2009) Petrogenesis of highly fractionated I-type peraluminous granites: La Pedriza pluton (Spanish Central System). Geol Acta

Pin C, Paquette JL, Santos Zalduegui JF, Gil Ibarguchi JI (2002) Early Devonian supra-subduction zone ophiolite related to incipient collisional processes in the Western Variscan Belt: the Sierra de Careón unit, Ordenes Complex, Galicia. Geol Soc America Spec Paper 364:57–71

Pin C, Paquette JL, Ábalos B, Santos JF, Gil Ibarguchi JI (2006) Composite origin of an early Variscan transported suture: Ophiolitic units of the Morais Nappe Complex (north Portugal). Tectonics 25:TC5001. doi:10.1029/2006TC001971

Reyes J, Villaseca C, Barbero L, Quejido AJ, Santos JF (1997) Descripción de un método de separación de Rb, Sr, Sm y Nd en rocas silicatadas para estudios isotópicos. I Congr Ibérico Geoquim Abstracts 1:46–55

Rollinson H (1993) Using geochemical data: evaluation, presentation, interpretation. Longman Scientifical and Technical, Singapore

Santos JF, Schärer U, Gil Ibarguchi JI, Girardeau J (2002) Genesis of pyroxenite-rich peridotite at Cabo Ortegal (NW Spain): geochemical and Pb-Sr-Nd isotope data. J Petrol 43:17–43

Shelley D, Bossière G (2002) Megadisplacements and the Hercynian orogen of Gondwanan France and Iberia. Geol Soc America Spec Paper 364:209–222

Simancas F, González Lodeiro F, Expósito Ramos I, Azor A, Martínez Poyatos D (2002) Opposite subduction polarities connected by transform faults in the Iberian Massif and western European Variscides. Geol Soc America Spec Paper 364:253–262

Singh J, Johannes W (1996) Dehydration melting of tonalites. Part II. Composition of melts and solids. Contrib Mineral Petrol 125:26–44

Sisson TW, Ratajeski K, Hankins WB, Glazner AF (2005) Voluminous granitic magmas from common basaltic sources. Contrib Mineral Petrol 148:635--661

Sun SS, McDonough WF (1989) Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. Geol Soc Spec Publ 42:313–345

Thompson AB, England PC (1984) Pressure-Temperature-time paths of regional metamorphism. II. Their inference and interpretation using mineral assemblages in metamorphic rocks. J Petrol 25:929–955

Ugidos JM, Recio C (1993) Origin of cordierite-bearing granites by assimilation in the Central Iberian Massif (CIM), Spain. Chem Geol 103:27–43

Vellmer C, Wedepohl KH (1994) Geochemical characterization and origin of granitoids from the South Bohemian Batholith in Lower Austria. Contrib Mineral Petrol 118:13–32

Villaseca C, Barbero L (1994) Chemical variability of Al-Ti-Fe-Mg minerals in peraluminous granitoid rocks from central Spain. Eur J Mineral 6:691–710

Villaseca C, Herreros V (2000) A sustained felsic magmatic system: the Hercynian granitic batholith of the Spanish Central System. Trans R Soc Edinburgh: Earth Sci 91:207–219

Villaseca C, Orejana D (2008) Rutilos ricos en Zr incluidos en granates de xenolitos granulíticos de la corteza inferior del Sistema Central Español: implicaciones geodinámicas. Geogaceta 44:31–34

Villaseca C, Eugercios L, Snelling N, Huertas MJ, Castellón T (1995) Nuevos datos geocronológicos (Rb-Sr, K-Ar) de granitoides hercínicos de la Sierra de Guadarrama. Rev Soc Geol España 8:129–140

Villaseca C, Barbero L, Rogers G (1998) Crustal origin of Hercynian peraluminous granitic batholiths of Central Spain: petrological, geochemical and isotopic (Sr, Nd) constraints. Lithos 43:55–79

Villaseca C, Downes H, Pin C, Barbero L (1999) Nature and composition of the lower continental crust in central Spain and the granulite-granite linkage: inferences from granulitic xenoliths. J Petrol 40:1465–1496

Villaseca C, Orejana D, Pin C, López-García JA, Andonaegui P (2004) Le magmatisme basique hercynien et post-hercynien du Système Central Espagnol: essai de charactèrisation des sources mantelliques. Comp Rend Geosciences 336:877–888
Villaseca C, Orejana D, Pérez-Soba C, Reyes J (2005) Estimación del régimen térmico y producción de calor de los niveles litosféricos del Sistema Central Español. Geogaceta 38:215–218
Villaseca C, Orejana D, Paterson BA, Billström K, Pérez-Soba C (2007) Metaluminous pyroxene-bearing granulite xenoliths from the lower continental crust in central Spain: their role in the genesis of Hercynian I-type granites. Eur J Mineral 19:463–477
Zeck HP, Wingate MTD, Pooley G (2007) Ion microprobe U-Pb zircon geochronology of a late tectonic granitic-gabbroic rock complex within the Hercynian Iberian belt. Geol Mag 144:157–177