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Hercynian Acid Magmatism and Related Mineralizations in Northern Portugal

A. Almeida[1*], H.C. Martins[1,2] and F. Noronha[1]

[1] Centro de Geologia da Universidade do Porto, Faculdade de Ciências, Pr. Gomes Teixeira, 4099-002 Porto, Portugal, E-mail: aalmeida@fc.up.pt

[2] Departamento de Geologia, Universidade de Trás-os-Montes e Alto Douro, Apartado 202, 5000-911 Vila Real, Codex, Portugal

* Corresponding author

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Abstract

Cabeceiras de Basto (CB), Vieira do Minho (VM) and Vila Pouca de Aguiar (VPA) granite plutons are located in the so-called Central Iberian Zone, northern Portugal. U–Pb zircon and monazite geochronology yielded the minimum emplacement age of 311 Ma for CB and the crystallization ages of 311 Ma for VM and 299 Ma for VPA, constraining the time interval of the third Hercynian deformation phase, relative to which these massifs can be grouped as follows: syn- to late-tectonic (CB and VM) and post-tectonic (VPA) granites.

CB is a composite peraluminous two-mica granite pluton, occupying the core of a N 130° E antiform. Geochemical and isotopic data suggest a heterogeneous crustal source of mid-Proterozoic age (1.2 Ga). The granites are specialized in Sn, Li and, to a lesser extent, W mineralizations. Fractional crystallization is the main concentrator mechanism for these elements. Late-magmatic hydrothermal alteration processes (feldspar albitization and plagioclase and biotite muscovitization) enhanced the concentration promoted by the magmatic differentiation.

Both the VM and VPA plutons are controlled by deep regional fault zones and consist of composite biotite granites, generated in the lower crust and installed in higher structural crustal levels, resulting in thermal metamorphism (P:2 kb; T: 500–600°C) capable of generating crustal convecting fluids. They are spatially related to important Sn, W and Au mineralizations. Although they are not highly specialized, they have contributed significantly as heat sources for the ore concentrations.

Key words: Hercynian granites, Li, Sn, W metallogenic specialization, Portugal, Iberian Peninsula.

Introduction

The maximum of Hercynian crustal thickening in the NW of Iberian Peninsula corresponds to the D1 and D2 Hercynian deformation phases while D3, the last ductile deformation phase, intra-Westphalian in age, marks the end of the collision process. According to their relationship with the D3 tectonic phase and their mineralogy (biotite or two-mica) the syn-orogenic granitic rocks of the Iberian Hercynian fold belt can be subdivided into three groups: (1) ante- to syntectonic biotite granites (380–345 Ma), (2) syn- to late-tectonic two-mica granites (330–305 Ma) and (3) late- and post-tectonic biotite granites (290–280 Ma) (Ferreira et al., 1987; Pinto et al., 1987). The biotite granites are calc-alkaline granites of deep crustal origin and the two-mica granites are peraluminous granites of mesocrustal origin (Capdevila et al., 1973). The events related to the D3 tectonic phase were marked by folding and shearing which controlled the granite emplacement (Noronha et al., 1981). Crustal thickening induced by these tectonic events associated with the influence of the underlying mantle has given rise to the generation of various anatectic crustal and hybrid granites (Ortega and Ibarguchi, 1990).

Genetic relationships between Hercynian acid magmatism and the spatially associated Sn, W, Li and to a lesser extent Au depositions form one of the most controversial topics in metallogeny (Tischendorf et al., 1991). Sn, Li and to a lesser extent W and Au mineralizations in northern Portugal occur almost exclusively sub-parallel to the regional Hercynian structures, associated with shear zones, following the same trend as the granites. Au mineralizations define alignments sub-parallel both to the shear zones and to post-D3 NNE-SSW structures (Noronha, 1988; Noronha and Ramos, 1993).

Geological Setting

The granite plutons selected for this study are located in the the Central Iberian Zone in northern Portugal. Two different genetic types of syntectonic granites may be distinguished: the older peraluminous type, and the younger, generally calc-alkaline to sub-alkaline type which marks the transition to the post-collision granites.

The Cabeceiras de Basto (CB) granite complex is located close to the boundary between the Minho and Trás-os-Montes provinces at about 70 km NE of Porto. The massif is NW-SE elongated, parallel to the regional structure (Fig. 1). It occupies the core of a N 130°E antiform formed during the D3 Hercynian phase and intrudes the Lower Silurian metasediments (mostly schists with subordinate quartzite and metavolcanic rocks) which were affected by the three major Hercynian folding phases (Ramos et al., 1981; Noronha, 1982, 1983; Ferreira et al., 1987). The granites constituting the complex were subsequently affected by late- to post-magmatic shear zones associated with significant hydrothermal alteration.

NE of the CB complex, in the Covas do Barroso area, an important Sn and Li vein field cross-cutting metasedimentary rocks of Silurian age is found, spatially associated with the two-mica granites. The Sn mineralization is constituted by cassiterite in aplite-pegmatite veins, most of which are controlled by the regional structure, by linear or 'en-echelon' faults, and are frequently deformed by the third Hercynian deformation phase (Noronha, 1983; Borges et al., 1979). Charoy et al. (1992) first described Li-rich aplite-pegmatite bodies in the same area. Li mineralization has different forms, as spodumene and lepidolite crystals dominantly in the pegmatitic veins, and as a phosphate of the amblygonite series both in the aplite and in the pegmatite veins. Lima (2000) described a field of Li-rich aplite-pegmatite veins following a NW-SE trend more than 20 km long, subdivided into two sectors: the western sector where only spodumene is found, and the eastern sector where petalite and eucryptite also occur. The veins are syn-tectonic (syn-D3 Hercynian deformation) and are spatially associated with the syn-tectonic (syn-D3) two-mica granites of Cabeceiras de Basto.

The Vieira do Minho (VM) massif, composed of late-Hercynian granitoids with a NNW-SSE orientation sub-

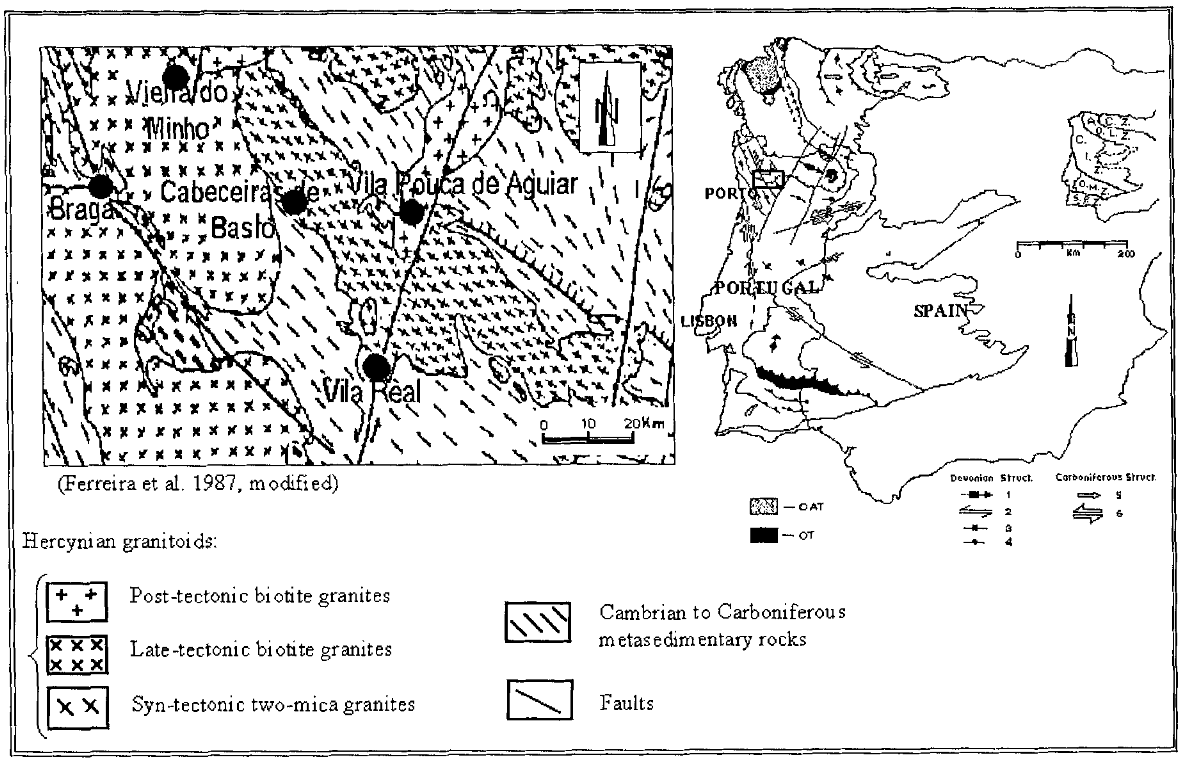

Fig. 1. Schematic geological map of the studied area around Cabeceiras de Basto, Vieira do Minho and Vila Pouca de Aguiar, northern Portugal. Map on the right side: major Variscan structures in the Iberian Peninsula. CZ–Cantabrian Zone, WALZ–West Asturian-Leonese Zone, CIZ–Central Iberian Zone, OMZ–Ossa-Morena Zone, SPZ–Southe Portuguese Zone, CAT–Continental Allochthonous Terrane, OT–Northern and Southern Ophiolitic Terranes, 1–Devonian shear sense, 2–Devonian shear zone, 3–Stretching in b, 4–Stretching in a, 5–Carboniferous shear sense, 6–Carboniferous shear zone (adapted from Dias and Ribeiro, 1995).

concordant with the regional structures (N 60 W) and whose emplacement was controlled by a regional structure, the Vigo-Amarante-Régua shear zone. This massif cross-cuts the two-mica syn-tectonic granites of the CB complex and the Silurian metasedimentary sequence (Fig. 1), being considered late-tectonic (late-D3).

The composite VM massif consists of two different units of biotite-rich porphyritic granite: the coarse-grained monzogranite of Vieira do Minho (VMG) and the medium-grained monzogranite of Moreira de Rei (MRG) with abundant microgranular enclaves, which are rare in VMG. The MRG is much more heterogeneous and a wide variation of megacryst concentrations is frequently observed and interpreted as a result of magmatic flow. A magmatic fabric defined by planar orientation of K-feldspar megacrysts is sometimes observed in both granites. This orientation is related to magmatic flow whose direction is controlled by the geometry of the intrusion. The gradational contact between the VM and the VR monzogranites indicates a synchronous emplacement (Noronha et al., 2000a). Basic rocks (norite, vaugnerite and gabbro) associated with these granites have been reported by Andrade and Noronha (1981) and Dias and Leterrier (1993).

The VPA pluton consists of a post-tectonic granite (post-D3) whose emplacement was controlled by a regional tectonic structure, the Régua-Verin fault (Noronha et al., 2000b). The pluton cross-cuts the two-mica syntectonic granite as well as the Upper Ordovician to Lower Devonian metasedimentary sequence (with evidence of D3 event) of the country rocks, by N 120°-trending D3 folds with sub-horizontal axes and a subvertical axial planar foliation within which the VPA pluton has developed a metamorphic contact aureole (Ribeiro, 1998). The VPA massif is elongated NNE-SSW perpendicular to the later regional folds (Fig. 1), being considered post-tectonic or post-D3 (Ferreira et al., 1987). The VPA pluton was nucleated in the southern portion of the major Régua-Verin fault which belongs to the D4 NNE-trending fault system and cross-cuts the whole of North Portugal. This fault system was in turn nucleated during the D3 phase of the Variscan orogeny and was reactivated in the D4 phase as a thrust fault (Baptista, 1999). This fault still manifests a seismic activity (Cabral and Ribeiro, 1993).

The VPA pluton was the object of a combined petro-structural study and magnetic fabric measurements with gravity modelling of its shape at depth, complemented by petrographic observations (Sant'Ovaia, 2000). VM and VPA massifs are spatially related with W and Au mineralizations. In the VM area, W is found as scheelite in skarn levels associated with metasedimentary rocks (Ramos et al., 1981). Au occurs in quartz veins, cross-cutting two-mica granites and metasedimentary formations. The Au mineralization is essentially late-D3, probably controlled by the fracturation system syn-D4 which has also played an important role in the emplacement of the post-tectonic granites (Martins, 1998; Noronha et al., 2000a,b).

Petrography and Geochemistry

Cabeceiras de Basto (CB) complex

The CB pluton is composed of three main petrographic types of two-mica granites: fine-grained granites, G'f (grain size: 0.5–1 mm); a medium-grained homogeneous granite, G'm (grain size: 2–4 mm) and a coarse-grained, locally porphyritic granite, G'g (grain size: 5–7 mm). The G'm and G'g granite series cross-cut the G'f type, although no clear chronology can be defined for the emplacement of G'm and G'g as the contacts between these units are always transitional (Almeida, 1994). The three granite series present hypidiomorphic granular textures and a similar mineral association including quartz, plagioclase An_1–An_6, perthitic K-feldspar (orthoclase to microcline as anhedral crystals to euhedral megacrysts), biotite and muscovite. Apatite, monazite, zircon, ilmenite, rutile, rare sillimanite and tourmaline occur as accessory minerals. Most of the studied samples exhibit, to various extents, the effects of late- to post-magmatic hydrothermal processes essentially involving sericitization of plagioclase and/or muscovitization of biotite and albitization of K-feldspars.

The geochemistry of the three granite types indicates almost identical peraluminous compositions ($1.2 < A/KCN < 1.4$). However, they can be separated according to their K/Na ratios (G'g: 1.9–2.2, G'm: 1.4–1.6, G'f: 1.3–1.5), their REE ranges (G'f: 71–284 ppm, G'm: 43–92 ppm, G'g: 39–126 ppm) and their Zr contents (G'f: 74–195 ppm, G'm: 49–94 ppm, G'g: 46–88 ppm) (Almeida, 1994).

Excluding samples significantly affected by hydrothermal alteration (muscovitization and/or albitization), each of the granite suites from the CB complex displays short but well-defined chemical and mineralogical evolution trends for major and trace elements, with increasing Si contents, decrease in Fe, Mg, Ca, REE, Zr and Mg/(Mg+Fe) ratios of the biotite and primary muscovite, while alkali contents remain almost constant. Such trends may be related to a crystal fractionation of magmas during their emplacement. A crystal fractionation model has been calculated by the least square mixing method of Wright and Doherty (1970), using major element compositions from the least and most evolved samples of each suite and from compositions of their main mineral phases (biotite, plagioclase and

K-feldspar) obtained by electron microprobe analyses (Almeida, 1994). A good Σr^2 was calculated for each granite type, respectively with the value of 0.32, 0.15 and 0.37 for G'f, G'm and G'g, being the respective weight fractions of melt remaining (F) 91.3 %, 89.7 % and 90.7 % (Table 1).

Vieira do Minho (VMG) and Moreira de Rei (MRG) granites

The VMG and MRG are classified as monzogranites based on petrography and chemistry. They exhibit a porphyritic hypidiomorphic granular texture and contain quartz, perthitic K-feldspar (orthoclase and microcline), plagioclase (oligoclase-andesine) and biotite. Muscovite is also present but rare. Apatite, zircon, monazite and ilmenite are found as accessory minerals. Since the granites are late-tectonic in nature the main differences between the two granites are found in microscopic deformation features which are more pronounced in VMG. They consist of sub-granulation of quartz, undulatory extinction in quartz, biotite and some muscovite and bending of biotite cleavages and of plagioclase twin planes. The quartz is anhedral, typically interstitial, and shows an important recrystallization process, mainly in VMG. The plagioclase An_{34}–An_{15} is zoned and sometimes exhibits myrmekitic rims intergrown with intergranular albite An_2–An_5. Albitization is also revealed by the presence of minor albite crystals that have grown inside the K-feldspar megacrysts. Crystals with more sodic composition An_{12}–An_9 are observed in the matrix. The biotites in both granites have a composition typical of the alumino-potassic series and define an evolution trend characterised by a decrease in Mg contents whereas total Al increases, suggesting an internal evolution by fractional crystallisation.The biotite compositions of the two granites

Table 1. Crystal fractionation model for Cabeceiras de Basto granite complex based on the least square mixing method.

	Original magma	Remaining magma	Calculated remaining magma			
G'f granites	2	113		Biotite	Plagioclase	K-feldspar
SiO_2	72.95	74.49	74.99	39.47	67.22	64.56
Al_2O_3	15.36	15.05	14.90	20.75	20.56	18.24
FeO_t	2.08	1.23	1.13	21.87	n.d.	0.02
MnO	n.d.	0.02	0.02	0.28	n.d.	n.d.
MgO	0.47	0.30	0.30	4.48	n.d.	n.d.
CaO	0.42	0.56	0.44	n.d.	1.14	0.01
Na_2O	2.89	2.94	2.92	0.06	11.0	0.68
K_2O	5.47	5.21	5.06	10.64	0.06	16.48
TiO_2	0.36	0.20	0.26	2.44	0.02	n.d.
%		F=91.3		4.78	1.85	2.07
Σr^2			0.32			
G'm granites	79	104		Biotite	Plagioclase	K-feldspar
SiO_2	73.08	74.68	74.77	36.85	67.60	64.68
Al_2O_3	15.83	15.39	15.41	19.91	20.04	18.47
FeO_t	1.65	1.08	1.08	24.65	0.02	n.d.
MnO	0.03	0.04	0.03	0.37	n.d.	n.d.
MgO	0.27	0.22	0.13	5.62	n.d.	n.d.
CaO	0.43	0.22	0.43	n.d.	1.08	0.01
Na_2O	3.21	3.30	3.02	0.14	11.21	0.97
K_2O	5.21	4.89	4.89	10.03	0.06	15.87
TiO_2	0.29	0.16	0.25	2.43	n.d.	n.d.
%		F=89.7		2.76	4.15	3.42
Σr^2			0.15			
G'g granites	13	65		Biotite	Plagioclase	K-feldspar
SiO_2	73.27	75.26	75.37	37.75	67.78	65.00
Al_2O_3	15.44	15.15	15.16	19.22	19.98	18.14
FeO_t	2.16	1.08	1.09	23.81	0.08	n.d.
MnO	0.03	0.05	0.02	0.24	n.d.	n.d.
MgO	0.55	0.20	0.29	5.85	n.d.	n.d.
CaO	0.25	0.14	0.27	n.d.	1.06	n.d.
Na_2O	2.60	3.26	2.79	0.07	11.01	0.37
K_2O	5.34	4.74	4.76	10.36	0.10	16.48
TiO_2	0.36	0.12	0.25	2.71	n.d.	n.d.
%		F=90.7		5.63	0.87	2.78
Σr^2			0.37			

differ mainly in their Mg content (VMG, XMg: 0.30–0.38; MRG, XMg: 0.38–0.45) (Martins and Noronha, 2000).

VMG and VRG are slightly peraluminous monzogranites (10<A<40 where A=Al-(K+Na+2Ca) with VMG having the higher values. These granites have a potassic signature with K_2O/Na_2O ratio ranging from 1.57 to 1.84 in VMG and from 1.51 to 1.70 in MRG.

Vila Pouca de Aguiar (VPA) pluton

The VPA pluton is zoned and mainly composed of two granite types distinguished macroscopically by their grain size and biotite contents, with no clear-cut contacts between them. The Vila Pouca de Aguiar granite (VPAG), forms 70% of the whole massif, and the Pedras Salgadas granite (PSG) forms most of the remainder. A third minor type, the Gouvães da Serra granite (GSG), which cannot be represented at the map scale of figure 2, is very similar to and occurs south, southwest and east of the pluton. All the granite types are more or less porphyritic (Martins, 1998). VPAG is a medium-grained biotite-rich monzogranite and contains microgranular magmatic tonalitic to granodioritic enclaves (Gomes, 1990). PSG is a medium- to fine-grained biotite monzogranite, more leucocratic than the other types, with no enclaves. GSG is a coarse-grained biotite monzogranite. In the field, these rocks appear as almost isotropic although some planar organization marked by K-feldspar megacrysts and biotite flakes may be observed, particularly to the south of the VPA pluton.

The three granites have porphyritc hypidiomorphic granular texture with K-feldspar and occasional plagioclase megacrysts. Biotite is the only ferromagnesian phase. Accessory minerals include zircon, apatite, allanite and ilmenite and rare monazite in PSG.

Quartz is typically anhedral, and occurs both as large crystals and interstitially. In GSG and PSG, quartz is usually subrounded. Plagioclase is euhedral to subhedral and shows normal zoning patterns from andesine cores and oligoclase rims, although more sodic compositions may be found in intergranular crystals, in rims of albite composition that surround plagioclase and in myrmekitic intergrowths. In GSG and PSG the plagioclase is also zoned but from oligoclase cores to albite rims. The albitization processes (under subsolidus condition) are common near the contacts and within K-feldspar crystals which consist of perthitic microcline or orthoclase. Microcline can be present as megacrysts of an earlier growth stage or as interstitial crystals of later formation. They are subhedral

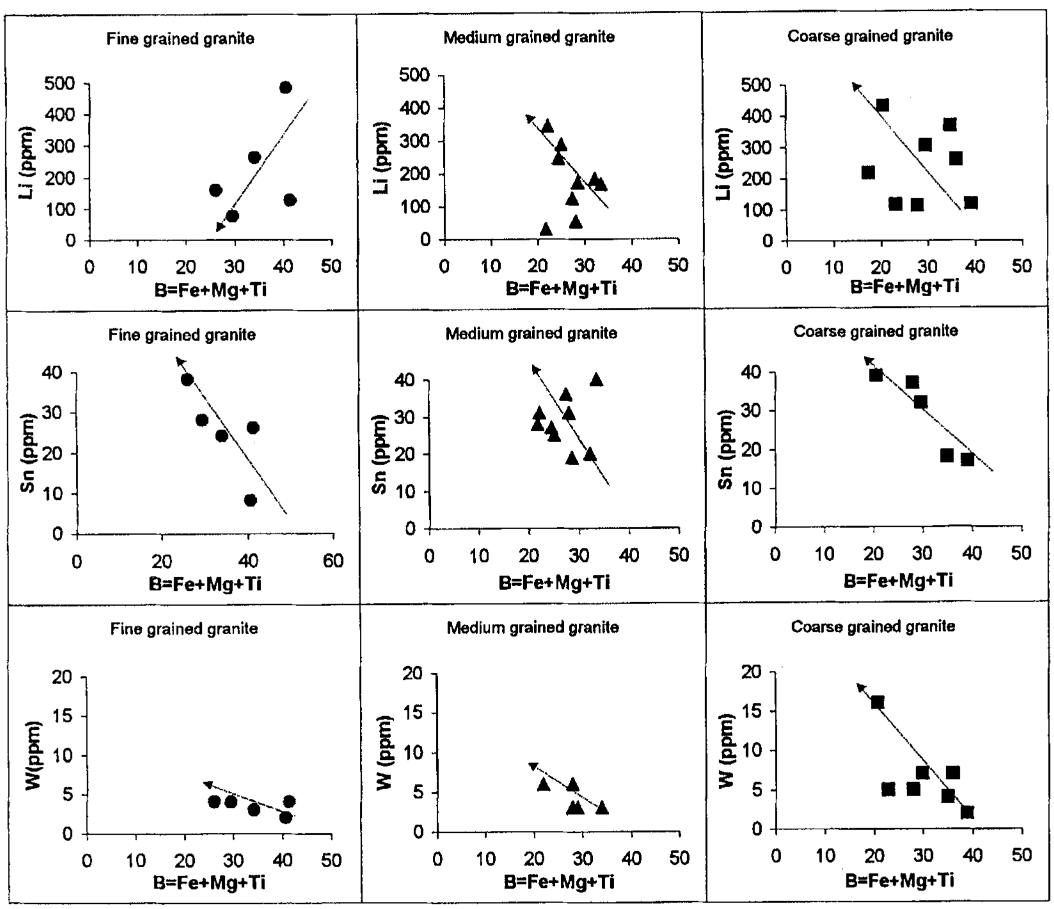

Fig. 2. Behaviour of Li, Sn and W with the differentiation parameter B=Fe+Mg+Ti of the least altered samples of CB two-mica granites.

or anhedral, respectively, cross-hatched twinned and the megacrysts contain inclusions of plagioclase with albite rims, concentrically distributed biotite and quartz. Biotite occurs as subhedral crystals with reddish-brown to pale-yellow pleochroism. It sometimes forms polycrystalline aggregates and is locally altered to chlorite. Epidote, sphene and rutile are formed as a consequence of chloritization of biotite. The biotites of VPAG ($0.31<XMg<0.37$) and GSG ($0.25<XMg<0.28$) show an evolution characterised by a decrease in Mg content whereas total Al increases. This internal evolution can be interpreted as a result of magmatic differentiation. In contrast, the biotites in PSG ($0.26<XMg<0.32$) are distributed along an almost vertical trend which is characterised by a marked increase in Al whereas Mg content remains almost constant (Martins and Noronha, 2000). The biotites from VPAG and GSG have a sub-alkaline affinity while the biotites from PSG are alumino-potassic in the Al_t-Mg diagram (Nachit et al., 1985).

In VPA and GS granites the microgranular enclaves show a porphyritic texture with quartz, andesine-oligoclase or labradorite-oligoclase phenocrysts, orthoclase, perthitic microcline, biotite and hornblende. The most common accessory minerals are apatite (needles), sphene, zircon and ilmenite (Gomes, 1990).

A total of 54 representative samples of Cabeceiras de Basto complex (Almeida, 1994), 39 of Vieira do Minho and 33 of Vila Pouca de Aguiar (Martins, 1998) have been analysed for major, trace and rare earth elements by inductively coupled plasma atomic emission spectrometry, ICP-AES and ICP-MS (Govindaraju and Mevelle, 1987) at the CRPG, Nancy, France, with a precision of 10% for major and most trace elements and 5% for rare earth elements. Whole rock analyses of major, trace and rare earth elements of the granites from the three studied granite complexes are given in table 2, taking into account a selection of the least and the most evolved samples of the more relatively unaltered samples of each granite facies.

U–Pb Zircon and Monazite Geochronology

A U–Pb geochronological study was carried out on three zircon fractions and on one fraction of monazite from the CB pluton (Almeida et al., 1998), on three zircon fractions and on one fraction of monazite for VM pluton and on

Table 2. Major (wt.%) and trace element (ppm) data of selected granite samples from Cabeceiras de Basto, Vieira do Minho and Pedras Salgadas plutons.

	Cabeceiras de Basto						Vieira do Minho				Vila Pouca de Aguiar					
	G'f		G'm		G'g		VMG		MRG		VPGA		PSG		GSG	
	2	113	79	104	8	65	39	22	25	24	74-3	74-15	60-18	61-6	88-1	61-11
Wt%																
SiO_2	70.51	72.57	70.84	73.30	71.44	72.77	67.74	72.56	69.74	70.34	70.72	72.24	73.00	74.40	73.66	74.92
TiO_2	0.36	0.19	0.28	0.16	0.28	0.12	0.60	0.32	0.56	0.51	0.39	0.31	0.19	0.15	0.21	0.13
Al_2O_3	14.74	14.66	15.34	15.11	14.64	14.65	15.17	13.86	14.28	14.11	14.51	13.35	13.57	13.48	13.44	13.13
Fe_2O_3t	2.01	1.33	1.78	1.18	1.97	1.15	4.19	2.50	3.44	3.34	3.08	2.22	1.76	1.62	1.99	1.63
MnO	0.03	0.02	0.03	0.04	0.02	0.06	0 .04	0.02	0.04	0.05	0.06	0.05	0.04	0.03	0.03	0.03
MgO	0.45	0.29	0.26	0.22	0.44	0.19	0.91	0.44	0.96	0.81	0.79	0.51	0.32	0.26	0.40	0.18
CaO	0.41	0.55	0.42	0.22	0.64	0.14	2.08	1.12	1.77	1.58	1.99	1.54	1.18	1.04	1.20	0.76
Na_2O	2.79	2.86	3.11	3.24	3.04	3.15	3.12	2.91	3.02	3.00	3.68	3.54	3.52	3.45	3.55	3.63
K_2O	5.28	5.08	5.05	4.80	5.22	4.58	4.91	5.15	4.97	4.94	4.41	4.47	4.52	4.47	4.61	4.71
P_2O_5	0.34	0.38	0.36	0.34	0.44	0.37	0.26	0.20	0.29	0.29	0.12	0.14	0.07	0.07	0.08	0.04
L.I.	1.75	1.58	1.58	1.48	1.41	1.59	0.65	0.68	0.65	0.71	0.62	0.61	1.12	0.85	0.67	0.65
Total	98.67	99.51	99.05	100.09	99.54	98.77	99.63	99.76	99.72	99.68	100.37	98.98	99.29	99.82	99.84	99.81
ppm																
Ba	327	202	241	98	220	61	826	394	614	497	330	362	295	277	238	99
Rb	468	389	306	453	322	592	232	280	317	319	233	251	237	237	254	294
Sr	133	44	70	30	51	25	208	102	177	146	69	113	70.4	65.6	61	29
Zr	195	74	94	49	88	46	285	150	226	211	169	153	106	100	136	100
Y	12.4	9.9	10	9	8.4	8.6	28	14	18	17	36	38	40	27	41	59
La	61.4	15.7	20.5	7.9	9.9	7.3	57.9	31.78	50.42	45.54	28.77	27.32	26.11	24.4	30.67	25.85
Ce	139.8	34.8	41.7	19.3	21.6	17.6	115.48	63.84	99.33	90.33	66.48	66.23	55.4	48.24	57.31	63.77
Nd	60.5	16.2	18.9	8.0	9.0	7.0	50.44	27.79	41.41	38.65	27.47	25.12	25.52	21.07	28.27	26.14
Sm	11.3	3.9	4.2	2.3	2.4	2.0	10.26	6.32	8.22	7.73	6.45	6.05	6.12	4.88	6.35	6.97
Eu	0.9	0.4	0.6	0.3	0.3	0.2	1.59	0.87	1.22	1.03	1.04	0.94	0.7	0.55	0.54	0.28
Gd	5.7	2.8	3.1	2.1	2.1	1.8	7.93	5.14	5.97	5.74	6.11	5.64	5.6	4.16	5.98	7.1
Dy	2.4	1.8	2.0	1.6	1.6	1.4	5.98	3.64	3.82	4.08	5.91	5.68	6.56	4.68	6.34	8.82
Er	1.0	0.7	0.8	0.6	0.6	0.7	2.68	1.37	1.66	1.71	3.28	3.26	3.97	2.66	3.81	5.73
Yb	0.8	0.5	0.6	0.4	0.4	0.6	2.97	1.11	1.74	1.74	3.35	3.59	4.91	3.55	4.22	6.75
ΣTR	283.8	76.8	92.4	42.5	47.9	38.6	255.23	141.86	213.79	196.55	148.86	143.83	134.89	114.19	143.49	151.41

four zircon fractions for the VPA pluton (Martins, 1998). The separation methods involved the use of heavy liquids, followed by electromagnetic separation (Frantz separator) and hand picking under the binocular microscope. The chemical analyses were performed at the CRPG, Nancy, France. The zircon fractions were submitted to air-abrasion (Krogh, 1982) to eliminate the external zones of the crystals where Pb loss may have been present. The chemical preparation included warm washing of the zircon and monazite fractions by 3N HNO_3, HF digestion at 240°C and 3N HCl dissolution of the fluorides at 180°C in teflon bomb (Parrish, 1987) and separation of Pb and U by elution on anionic resin of two aliquots (one with addition of a mixed ^{208}Pb–^{235}U spike) according to Krogh (1973). Mass spectrometry was performed on a Finnigan Mat 262 for Pb and on a Cameca TSN 206 for U. The measured atomic ratios were corrected for blank, initial common lead compositions (Stacey and Kramers, 1975) and mass-fractionation (using NBS 983 standard). The U–Pb analytical points of the CB pluton define a very good reverse discordia (MSWD = 0.15) with a lower intercept at 311±1 Ma, with monazite almost concordant (Almeida et al., 1998). This age is interpreted as the minimum emplacement age of the CB pluton and is in good agreement with the Westphalian age (305–316 Ma), for D3 Hercynian tectonic phase. The reverse discordia presenting an upper intercept at 1207± 8 Ma reveals the presence of an inherited Pb component of Proterozoic age.

The data on the three zircon fractions of the VM pluton define a good normal discordia (MSWD = 0.25) with an upper intercept at 311±2 Ma, which agrees with the age of 312±2 Ma obtained from monazite (Martins et al., 1999). As this pluton cross-cuts the CB pluton, this age cannot be considered as the emplacement age which must be younger, to be in accordance with the geological and structural data. Dias et al. (1998) suggested a U–Pb age of 306–307 Ma in similar granites of a surrounding area.

The U–Pb zircon data for VPA post-tectonic pluton define a normal discordia (MSWD = 1.28) with an upper intercept age of 299±3 Ma which is in good agreement with the whole-rock Rb–Sr age of 299± 9 (MSWD = 1.73) and can be interpreted as the emplacement age (Martins, 1998).

Metallogenic Specialization

Li, Sn, W, F and K/Rb data obtained on the three granite massifs (Table 3) show that only the syn-tectonic massif of Cabeceiras de Basto samples can be ascribed as 'specialized' according to Tischendorf (1974, 1977). The Sn, Li and W contents of the Cabeceiras de Basto granites fall within the ranges 8–68 ppm, 107–482 ppm and 1.3–18 ppm, respectively (Almeida, 1994). These values are higher than the average values assumed for normal granites (3, 40 and 1.5 ppm, respectively). Li analyses carried out in the biotite of the three granite types G'f, G'm and G'g from the CB complex yielded, respectively, the following range of values: 2370–3890 ppm, 780–1360 ppm and 1160–1520 ppm.

The behaviour of Li, Sn and W in the least altered samples of the two-mica granites of Cabeceiras de Basto, according to the differentiation parameter B = Fe+Mg+Ti, expressed by the number of millications in 100 g of rock (La Roche, 1964), illustrates the role of the primary magmatic evolution in the concentration of such elements in the granites (except for Li in G'f granite series) from fine to coarse porphyritic granite types (Fig. 2). The behaviour of Li in the fine-grained granite type G'f, decreasing with B parameter, suggests that biotite is the main carrier for Li in this granite, in accordance with the primary magmatic evolution. The trend exhibited by the primary evolution is affected by the alteration processes. The albitization of feldspars promotes a more regular correlation with Sn in the three CB granite types, whereas muscovitization seems to induce some dispersion (Fig. 3).

Although there are no known gold mineralizations spatially related with the CB two-mica granite complex the Au contents, ranging from 2 to 17 ppb, deserve attention (Table 4). The higher values occur in the medium and coarse-grained granites, but no clear relationship with

Table 3. Sn, Li, W, F and K/Rb data for three granite massifs, compared with the parameters proposed by Tischendorf (1974, 1977) for specialized granites.

	Specialized granites (Tischendorf, 1974, 1977)	Syn-tectonic granites Cabeceiras de Basto	Late-tectonic granites Vieira do Minho	Post-tectonic granites Vila Pouca de Aguiar
ppm				
Li	220± 100	94–482	64–138	99–195
Sn	30± 20	8–68	6.5–19	10–26
W	7± 3	1.3–16	1.3–3.2	0.8–6.8
F	3700± 1500	800–3000	1250–1900	570–1050
K/Rb	<100 (min. 20)	59–137	125–186	127–169

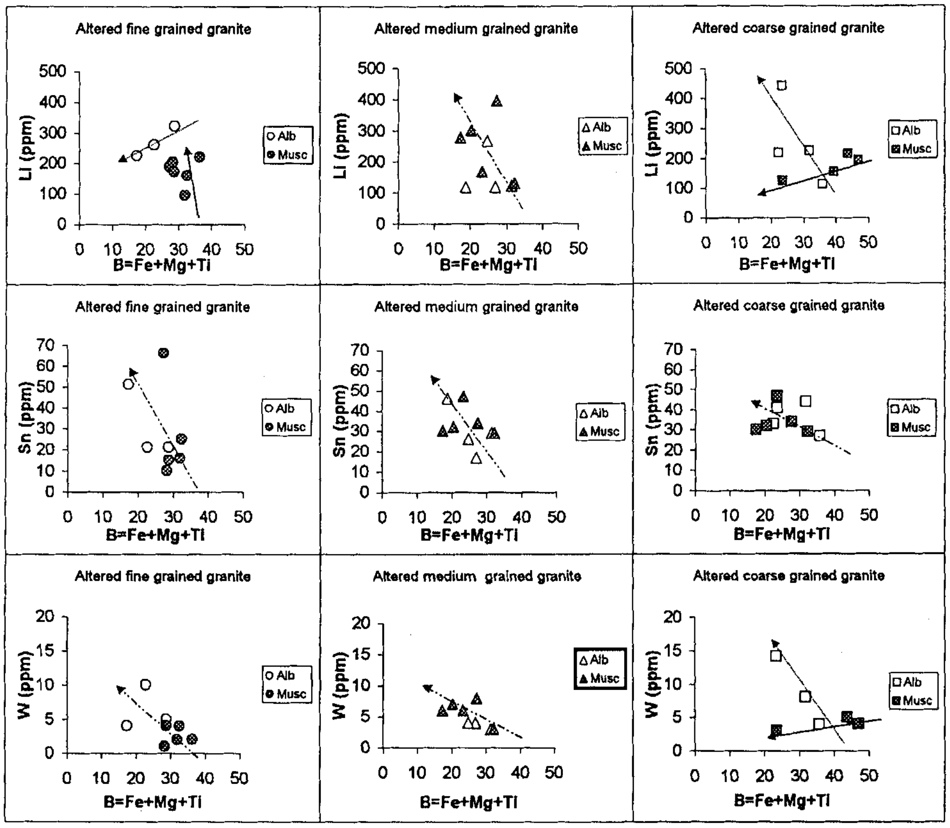

Fig. 3. Behaviour of Li, Sn and W with the differentiation parameter B = Fe+Mg+Ti, of samples of the CB two-mica granites affected by hydrothermal alteration processes. Alb–albitization, Musc–muscovitization. Suggested variation trends with B evolution parameter: bold arrow–muscovitization, dotted arrow–albitization, dashed arrow–global trend.

Table 4. Sn, Li, W, F, Au and specialization parameters for Cabeceiras de Bastogranites.

	Gf	Gf*	Gf**	Gm	Gm*	Gm**	Gg	Gg*	Gg**
Sn	8–38	21–51	10–66	19–40	17–46	29–47	17–68	27–44	13–16
Li	107–482	225–322	94–220	183–345	117–267	130–395	187–433	112–442	126–215
W	2–4	4–10	1–4	3–8	3–4	3–8	2–18	4–14	3–4
F	0.08–0.28	0.17–0.30	0.08–0.20	0.09–0.20	0.13–0.17	0.11–0.14	0.11–0.30	0.20–0.29	0.09–0.17
Au	<2–4	<2	<2–9	<2–16	5–7	5–17	<2–16	7	<2
K/Rb	88–115	67–93	96–125	88–137	84–117	76–116	64–135	59–87	99–113
Mg/Ti	0.6–2.3	1.0–6.5	0.7–2.5	0.9–1.9	1.4–3.7	0.4–2.1	0.8–1.9	1.0–2.6	0.7–1.5

* = Albitized samples, ** = Muscovitized samples, Sn, Li and W in ppm, F in %, Au in ppb.

the magmatic evolution, represented by the decreasing of B parameter for the non-altered samples, or with the F contents, both for non-altered and the late-magmatic processes, can be drawn, although there seems to be a slight variation concerning the coarse-grained granite type (Fig. 4). These observations indicate processes probably independent of the granite evolution, as far as the genesis of gold is concerned.

The comparative study of the behaviour of Li, Sn and W with F contents shows a positive correlation both in the least altered samples and in those affected by albitization of the feldspars and muscovitization of plagioclase and biotite (Figs. 5 and 6). According to the relatively regular behaviour of Sn, Li and W with F it is suggested that F may have been a vehicle for transporting these elements.

Calculations of log fH_2O/fHf and log fO_2 in biotite of the CB two-mica granites yielded respectively, 3.5 and –16 (Almeida, 1994), very close to the values calculated for similar two-mica granites, associated with Sn,W mineralizations in northern Portugal (e.g., Neiva, 1983; Dias, 1987).

The geochemical data for VM and VPA granites show that they are not strongly differentiated. On the other hand, Sn, W and Li contents are lower than typical specialized granites. However, the biotite granites, particularly the post-tectonic granites, are of primordial metallogenic importance as an indispensable source heat for the efficient circulation of the mineralizing fluids, which in turn mobilized and deposited the ore forming elements (Martins, 1998; Noronha et al., 2000a,b).

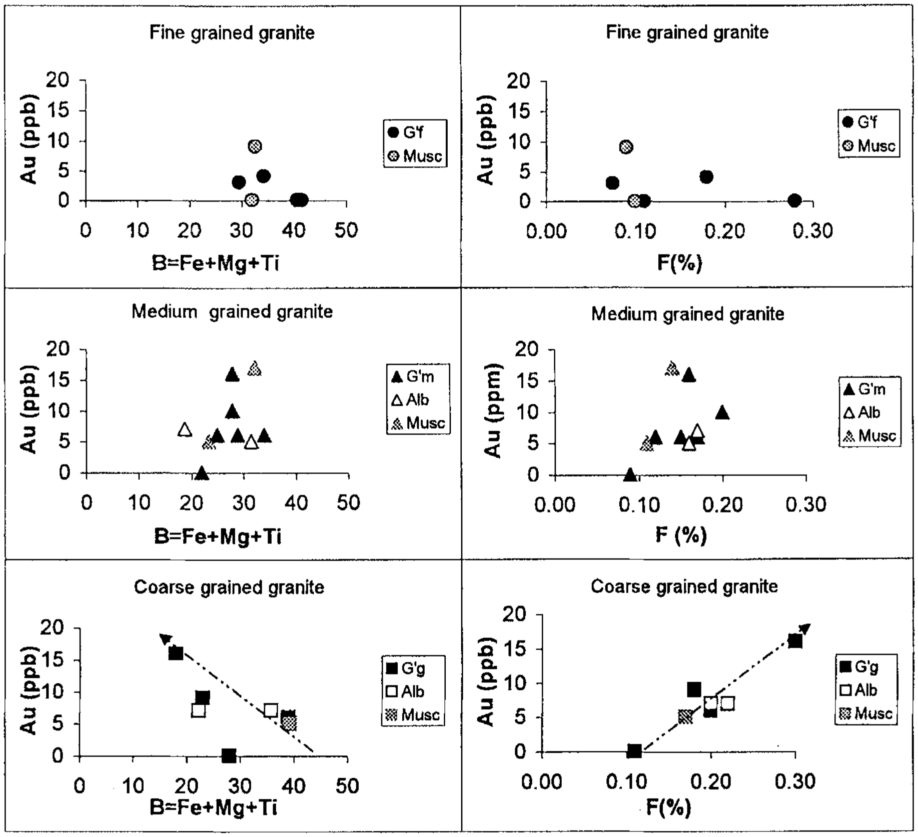

Fig. 4. Behaviour of Au with the differentiation parameter B = Fe+Mg+Ti in the CB two-mica granites. G'f – Least altered fine-grained granite, G'm – Least altered medium-grained granite, G'g – Least altered coarse-grained granite, Alb – albitization, Musc – muscovitization.

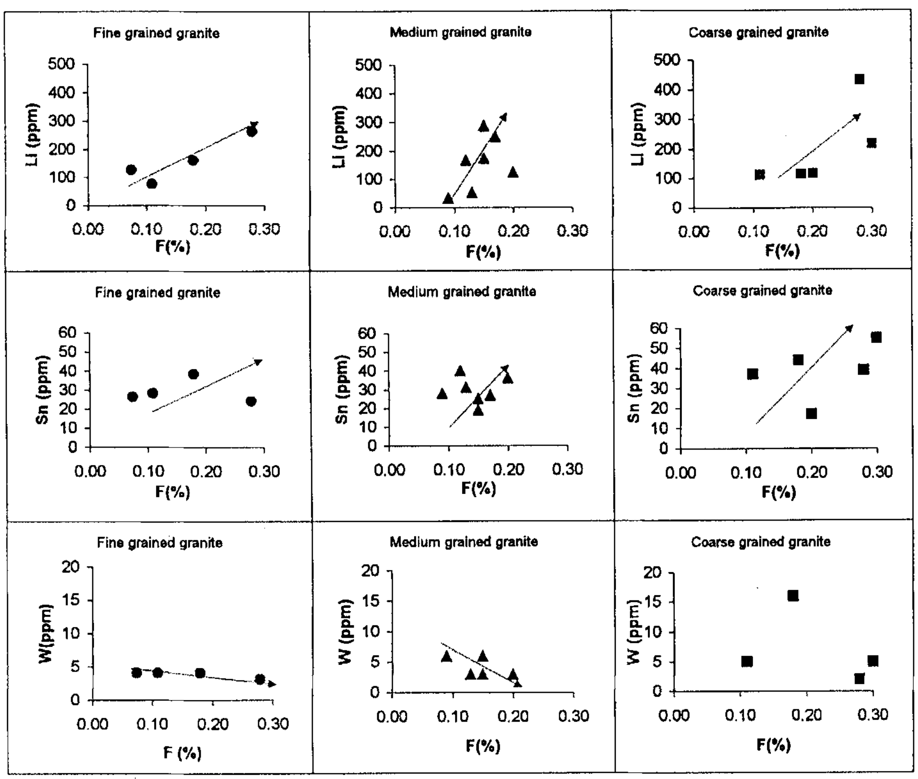

Fig. 5. Behaviour of Li, Sn and W with F of the least altered samples of the CB two-mica granites.

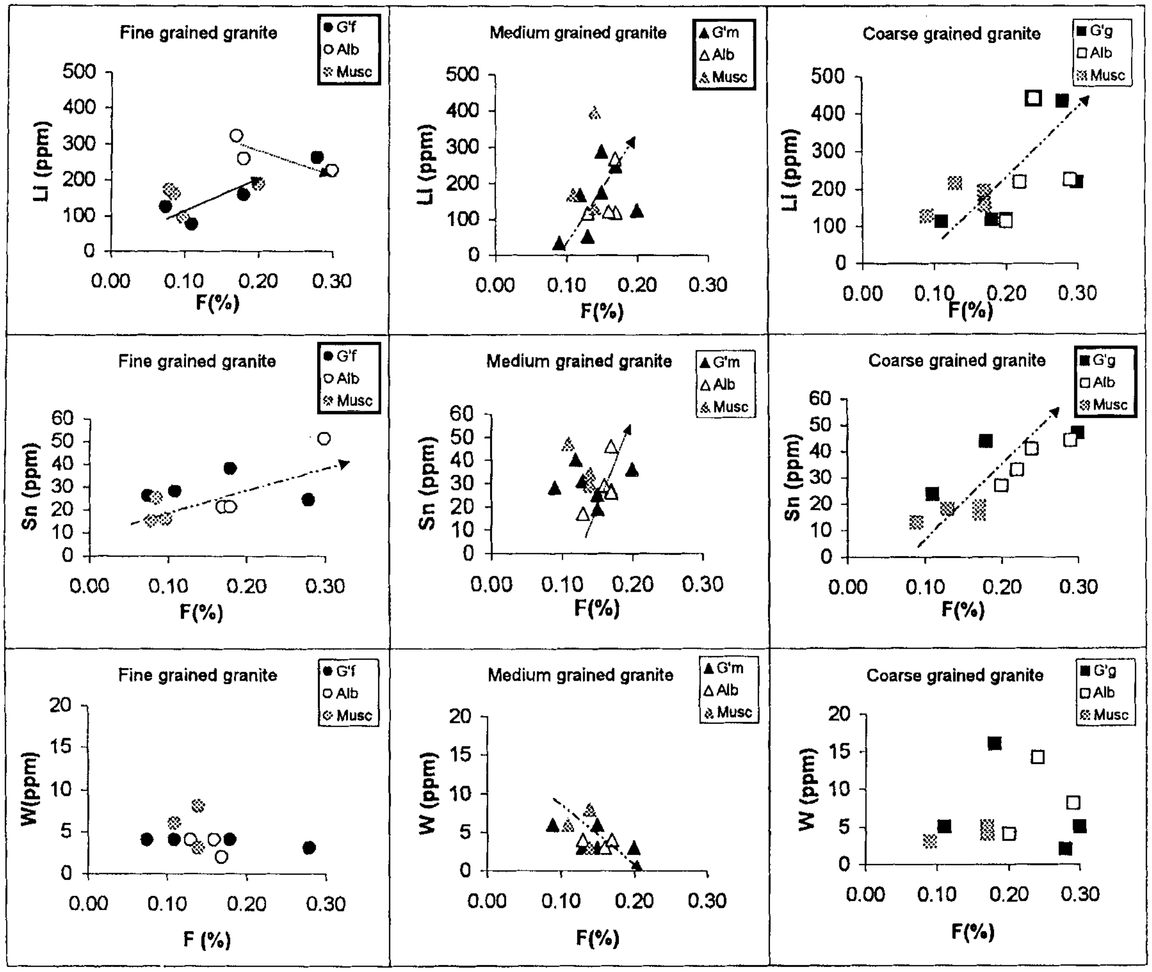

Fig. 6. Behaviour of Li, Sn and W with F, of samples of the CB two-mica granites affected by hydrothermal alteration processes, compared with the least altered samples. G'f – Least altered fine-grained granite, G'm – Least altered medium-grained granite, G'g – Least altered coarse-grained granite, Alb – albitization, Musc – muscovitization. Arrows suggesting variation trends with F as in figure 3.

Discussion and Conclusions

Li, Sn and W contents in the three granite types of Cabeceiras de Basto massif (G'f, G'm and G'g) allow their characterisation as 'specialized' granites. Magmatic differentiation by fractional crystallization process seems to be the main concentrating mechanism for the three elements (with an exception of Li in G'f). A positive correlation between F with Li, Sn and W in the granites and in the pegmatite with lepidolite suggests that F may be the vehicle for those elements, in particular, for Sn.

Late-magmatic hydrothermal alteration processes enhance the primary evolution. Albitization performs a relevant role in Sn concentration and, to a lesser extent, in Li, whereas muscovitization of plagioclase seems to improve W concentration.

The role of HF and O fugacities of the parental magma in the specificity of the mineralizations has been pointed out by Förster and Tischendorf (1989). On the other hand, a low redox state, near the QFM buffer, must have provided favourable conditions for efficient Sn accumulation during melt differentiation (Förster and Tischendorf, 1989; Lehmann, 1990).

Geological and geochemical evidence suggest that the Li-bearing aplites and pegmatites in Covas do Barroso and Alvão areas, respectively NE and SE of the Cabeceiras de Basto two-mica complex, may be spatially and genetically related with the two-mica granites of CB complex, the scarcity of amblygonite and Li-rich micas, contrasted to the widespread occurrence of spodumene, being evidence for low fluorine activity during magma crystallization (Lima, 2000).

Au behaviour in the studied two-mica granites is independent of the primary evolution and of the late-alteration processes. However, the relatively higher contents in the coarse-grained granite may be interpreted as the result of a better fluid circulation of gold-bearing fluids through coarser textured rocks, suggesting as well a stronger Au deposition in these rocks.

Although VM and VPA biotite granite composite massifs are not clearly specialized in Li, Sn or W they are spatially related to important Sn, W and Au mineralizations. Their generation in the lower crust and installation in high structural crustal levels make them responsible for a thermal metamorphism (P: 2kb, T: 500–600°C) capable of generating crustal convecting fluids which acted as a heat source for the genesis of ore concentrations.

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