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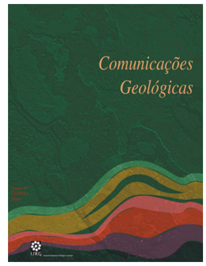
Oxidized and reduced Portuguese Variscan granites associated with W and Sn hydrothermal lode deposits: magnetic susceptibility results



Granitos Variscos portugueses oxidados e reduzidos e sua associação com mineralizações hidrotermais de W e Sn: resultados de suscetibilidade magnética

H. Sant'Ovaia[1,*], H. Martins[1], F. Noronha[1]

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Abstract: The central-northern region of Portugal mainland comprises an important W-Sn metallogenic province composed of various W, W-Sn, W-Mo and Sn hydrothermal lode deposits spatially related to Variscan granites. These granites are usually categorised into two main groups: the two-mica granites and biotite-bearing granites. As the granite series reflect redox states of their corresponding melts, the magnetite- and ilmenite-series represent oxidized- and reduced-type respectively. The mineralogical features and magnetic susceptibility (K) of the granites were examined in order to deduce the redox conditions of magma system. Despite of different petrographic and geochemical characteristics, K values in the majority of the granites studied vary from 20 to 300 × 10^{-6} SI units corresponding to reduced- or ilmenite-type granites. The oxidized-or magnetite-type granites are scarce and represented by some post tectonic biotite granites with K values ranging from 15 to 20 × 10^{-3} SI units. Major W and Sn ore deposits are related to two-mica and biotite-rich granites both corresponding to reduced ilmenite-bearing granites; W-Mo lode deposits are in place related with biotite-rich granites belonging to oxidized series (i.e. magnetite or titanomagnetite-bearing granites).

Keywords: Variscan granites, magnetic susceptibility, hydrothermal lode deposits.

Resumo: A região centro-norte de Portugal continental inclui uma importante província metalogénica de W-Sn constituída por vários depósitos hidrotermais de W, W-Sn, W-Mo e Sn espacialmente relacionados com granitos Variscos. Estes granitos são usualmente divididos em dois grandes grupos: granitos de duas micas e granitos biotíticos. Neste estudo, a suscetibilidade magnética (K) de corpos ígneos representativos destes dois grupos foi avaliada com a finalidade de inferir as condições redox atingidas durante a génese e evolução magmática. Apesar das diferenças geoquímicas e petrográficas, K varia entre 20 e 300 × 10^{-6} SI para a maioria dos granitos estudados, compatível com a sua natureza reduzida e presença de ilmenite. Os granitos com magnetite, ou ditos oxidados, são raros, sendo representados por alguns corpos biotíticos pós-tectónicos com valores de K compreendidos entre 15 e 20 × 10^{-3} SI. As mineralizações de W e Sn relacionam-se com granitos de duas-micas ou biotíticos, ambos pertencentes ao grupo dos granitos com ilmenite. As mineralizações de W-Mo associam-se a granitos biotíticos pertencentes ao grupo dos granitos oxidados, isto é, com magnetite ou titanomagnetite.

Palavras-chave: granitos Variscos, suscetibilidade magnética, mineralizações hidrotermais.

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1. Introduction

The relative abundance of magnetic and weakly magnetic minerals in granites can be assessed in terms of the whole-rock magnetic susceptibility (K). Indeed, magnetic susceptibility of granites has been successfully used in previous studies as a petrographic index to distinguish between magnetite-series and ilmenite-series (e.g. Ishihara, 1977; Takahashi *et al*., 1980). Magnetic susceptibility of magnetite-bearing granite series corresponds to K values above 3.0 × 10^{-3} SI; for the ilmenite-granite series it stands ≤ 3.0 × 10^{-3} SI (Ishihara, 1977). The main source of the magnetic susceptibility in magnetite-series granites is magnetite and titanomagnetite; for the ilmenite-series granites the magnetic response is function of the ferromagnesian silicates plus ilmenite abundances.

The oxidation state can be roughly indicated by the presence of certain oxide accessory mineral phases, the magnetite- and ilmenite-bearing series corresponding to oxidized- and reduced-type, respectively (e.g. Takagi, 2004). Each type of granite can also be related to particular metal enrichments and/or associations (Takagi & Tsukimura, 1997; Kumar, 2010).

In Portugal mainland, the prevailing Sn and W lode deposits are distributed all through the Central Iberian Zone (CIZ), forming the so-called "Iberian Sn-W metallogenic province" (Neiva, 1944), included in the "Northern Province "(Thadeu, 1965) characterised by the presence of various W, W-Sn, W-Mo and Sn hydrothermal ore-systems. These systems occur where Variscan granites intrude marine series, with ages ranging from Precambrian to the Silurian-Devonian (e.g. Neiva, 1944; Thadeu, 1973, 1977); it seems that the binary granite-metasedimentary rock is essentially to the development of these ore deposits. Furthermore, granites can act as an important source of metals and/or source of heat needed to sustain the hydrothermal system for a significant time range (e.g. Boiron *et al*. 1996; Mateus & Noronha, 2001, 2010). The Portuguese Variscan granites are usually categorised into two main groups: two-mica granites and biotite granites (Ferreira *et al*., 1987). Considering this classification, Sn mineralization in pegmatites and aplites are mainly related with two-mica evolved granites; the Sn and W hydrothermal lode deposits and occurrences are locally related to both granite groups (e.g. Noronha *et al*., 2006; Mateus & Noronha, 2010).

Ore element ratios in intrusion-related deposits are in part a function of the relative oxidation state and degree of fractionation of the associated granite suite (e.g. Blevin & Chappell, 1995; Neiva, 2002). The oxidation state in a granitic magma may be more important than the nature of the granitic source rocks on controlling the type of associated mineral deposits (e.g. Whalen & Chappell, 1988; Candela & Bouton, 1990; Neiva, 1982).

A large volume of Variscan granitic rocks outcrop in CIZ. These granites are well documented in what concerns geological mapping, petrography and geochemistry (e.g. Ferreira *et al*., 1987; Dias *et al*., 2010) but their magnetic characteristics, as well as the relationship of this feature with ore deposits, remain unknown. In this work we summarize the available magnetic susceptibility data of Variscan granites in order to analyse their correspondence to oxidized-type or reduced-type granites and, on this basis, evaluate their relation with hydrothermal ore deposits.

2. Geological Setting

Portuguese Variscan granites are synorogenic, as supported by their geological, petrographic and geochemical characteristics, and can be divided into two main groups: two-mica granites and biotite granites (e.g. Ferreira *et al*., 1987). The former group can be considered syntectonic in relation to the third phase of Variscan deformation, syn-D3, and are usually emplaced along the core of D3 regional folds, being D3 the last Variscan ductile deformation phase. Usually they are leucocratic granites with primary muscovite and biotite resulting of the crystallization of wet peraluminous magmas originated at a mesocrustal level (e.g. Ferreira *et al*., 1987; Castro *et al*. 1999). The second group, made of biotite granites, has origin on a deeper crustal level and corresponds to relatively dry magmas; when muscovite occurs in this second group, it has a secondary origin (e.g. Derré *et al*. 1982; Noronha, 1982; Almeida *et al*. 2002). The intrusion and distribution of biotite granites are mostly controlled by D3 shear zones and late-Variscan tectonic structures, so their emplacement can be syn-D3 (320-313 Ma), late-D3 (311-306 Ma), late-to-post-D3 (300 Ma), or even post-tectonic (299-290 Ma) (e.g. Dias *et al*. 2010).

All these granites are intrusive in metasedimentary rocks of different types and ages:

(1) Pre-ordovician strata comprising a monotonous mega-sequence of metapelites and metagreywackes of uncertain age, generally referred as the "Complexo Xisto Grauváquico"; and (2) Ordovician, Silurian, lower Devonian and upper Carboniferous rocks metasedimentary rocks, occasionally accompanied by metavolcanic suites.

As a result of a rapid crustal uplift occurred at ca. 300 Ma, surface heat flow anomalies were developed, enduring at least till ca. 280 Ma (Mateus & Noronha, 2010). This heat flow regime supported an extensive hydrothermal activity throughout the entire crust, involving distinct fluid sources in successively lower P-T conditions along a continuum that provided long-lived systems, some of them comprising significant amounts of ore mineral phases namely wolframite, cassiterite and sulphides (e.g. Mateus & Noronha, 2001, 2010).

3. Material and methods

In this work we summarize the magnetic susceptibility data from around 644 sampling stations and around 5152 samples on different massifs of Variscan Portuguese granites (Fig. 1 and Table 1). On Vila Pouca de Aguiar composite massif, the two main granite facies were sampled, Pedras Salgadas (PS) and Vila Pouca de Aguiar (VPA). On Castro Daire composite massif the two main facies, central and external one, were also sampled. Details and comprehensive discussion of the data used in this work can be found in Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) and Martins *et al*. (2009, 2011).

The magnetic susceptibility (K) is defined as K=M/H, the ratio of the induced magnetization (M) to the applied field (H). In International System (SI), magnetization and magnetic field are both dimensionless, although its magnitude is commonly referred to SI. In polymineralic rocks, the magnetic susceptibility is the sum of the contribution of all rock-forming minerals, so it varies with concentration and composition of those mineral phases, which may include diamagnetic, paramagnetic or ferromagnetic (s.l.) species.

The survey performed comprised 6 to 8 oriented drill-cores per site, covering as much as possible uniformly the granite plutons, according to the exposure conditions or the access conditions. Bulk magnetic susceptibility (K) and Anisotropy of Magnetic Susceptibility (AMS) were measured with an AGICO KLY-4S apparatus at the "Centro de Geologia da Universidade do Porto" and with a KLY-2 also from AGICO in Toulouse, France. For each site, the mean direction of the three principal axes of the AMS ellipsoid (K1≥K2 ≥K3) was computed with the ANISOFT software using Jelinek statistics (Jelinek, 1981). The ANISOFT software was also used to calculate the shape parameter T [=2ln(K2/K3)/ln(K1/K3)-1]. The magnetic anisotropy, expressed by the parameter Ppara% [= ((K1 - D/K3 - D) - 1) x 100, where D (= -14.6×10^{-6} SI) is the diamagnetic component carried by quartz and feldspars (Rochette, 1987)], was also computed. This parameter, together with T, describes the AMS ellipsoid (Jelinek, 1981; Hrouda, 1982).

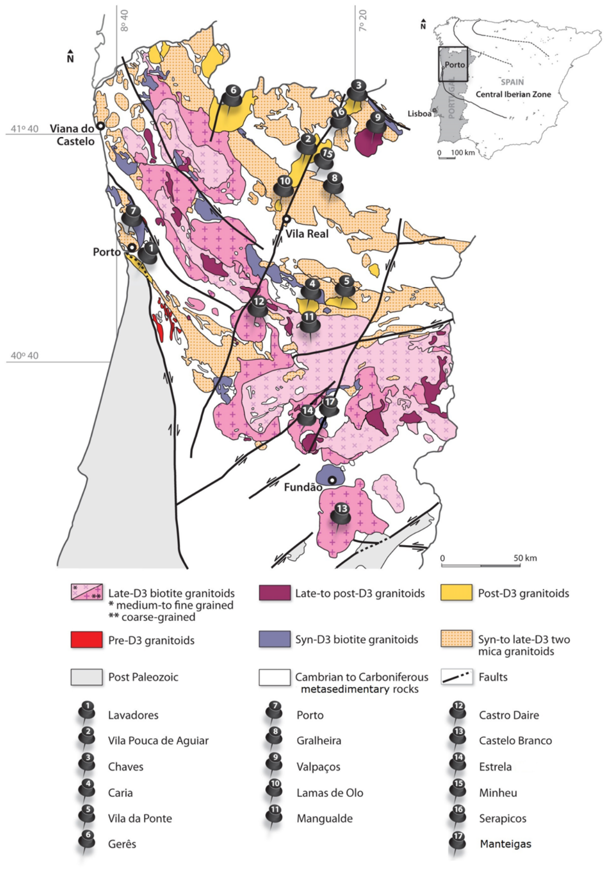

Fig.1. Distribution of Variscan granitoids in the Central Iberian Zone, Northern Portugal (Ferreira *et al*., 1987, modified) and location of the granites studied.

Fig.1. Distribuição dos granitos Variscos na Zona Central Ibérica, Norte de Portugal (Ferreira *et al*., 1987, modificado) e localização dos granitos amostrados.

Table 1. Mineralogy, texture and typology of the studied granites consider their relation with D3 Variscan deformation phase.

Tabela 1. Mineralogia, textura e tipologia dos granitos relativamente à fase D3 da deformação Varisca.

Granite	Mineralogy/Texture	Tipology
Gralheira	Two-mica medium-grained granite	Syn-to late-D_3 two-mica granitoids
Minheu/Lagoa Serapicos Porto	Two-mica medium-grained porphyritic granite	
Manteigas	Biotite porphyritic granite	Syn-D_3 biotite granitoids
Castro Daire (internal facies)	Biotite-muscovite fine-grained granite	Late-D_3 granitoids
Castro Daire (external facies)	Biotite-rich porphyritic coarse-grained granite	
Castelo Branco	Biotite-muscovite porphyritic monzogranite	
Mangualde-Trancoso	Biotite-rich medium-to fine-grained granitoids	
Serra da Estrela (Seia and Covilhã)	Biotite-rich coarse-grained and medium-to fine- grained granitoids	
Valpaços	Two-mica peraluminous porphyritic coarse-grained granite	Late-to post-D_3 granitoids
PS (VPA massif)	Biotite porphyritic medium-to fine-grained monzogranite	Post-D_3 granitoids
VPA (VPA massif)	Biotite-rich porphyritic medium-to coarse-grained monzogranite	
Vila da Ponte	Biotite-rich porphyritic medium-to coarse-grained granite	
Caria		
Chaves	Biotite-rich porphyritic coarse-medium grained granite	
Lamas de Olo		
Lavadores	Biotite-rich porphyritic coarse-grained monzogranite	
Gerês	Biotite-rich porphyritic medium-to coarse grained granite	

4. Magnetic susceptibility data

4.1. Bulk magnetic susceptibility

A summary of the statistical results obtained for the magnetic susceptibility measurements in several plutons are listed in Table 2. All the granite facies show paramagnetic behaviour (magnetic susceptibility ~ 10^{-6} SI), except for the bodies of Lavadores, Gerês and Manteigas whose magnetic susceptibility ($\geq 10^{-3}$ SI) is compatible with the presence of magnetite.

In paramagnetic granites, the magnetic susceptibility is a useful parameter to distinguish facies in composites massifs, as is the case of the granitic bodies of Vila Pouca de Aguiar, Serra da Estrela (Seia, Covilhã), Castro Daire, Chaves, and Castelo Branco. However, when the mean magnetic susceptibility (Km) for each granite body is analysed, we observed that Gralheira, Porto, Pedras Salgadas, internal facies of Castro Daire (Alva), Minheu, Serapicos, Valpaços and Castelo Branco have Km lower than 70 × 10^{-6} SI (Table 2). The class with the high relative frequency of magnetic susceptibility (27%) is the one ranging between 71 and 90 × 10^{-6} SI which correspond to the granites of Vila da Ponte, Caria and external facies of Castro Daire (Fig. 2). This class is followed by the one ranging from 51 to 70 × 10^{-6} SI (19%), corresponding to the granites of Pedras Salgadas, internal facies of Castro Daire, Minheu, Serapicos, Valpaços and Castelo Branco. The class ranging from 91 to 110 × 10^{-6} SI has 15% of frequency and corresponds to Chaves, Mangualde-Trancoso and Serra da Estrela granites. Magnetic susceptibility increases with the increase of biotite and ilmenite contents. The two-mica granite facies display Km values scattered in the interval 30 to 70 × 10^{-6} SI and a relative frequency of 8%. The two-mica granites (muscovite > biotite) present lower values of magnetic susceptibility than biotite granites.

The ferromagnetic granites are scarce and only represented by Lavadores, Gerês and Manteigas. Nonetheless, the Manteigas and Geres massifs also have facies with a paramagnetic behaviour and so, the Lavadores granite remains as the only one that can be considered as a true magnetite-type granite according to criteria reported in Ishihara (1977), showing always magnetic susceptibility values above 10^{-3} SI. The presence of a ferromagnetic iron oxide in Lavadores was confirmed by the Isothermal Remanent Magnetization curves (Fig. 3) and magnetite was identified under reflected light microscopy (Fig. 4).

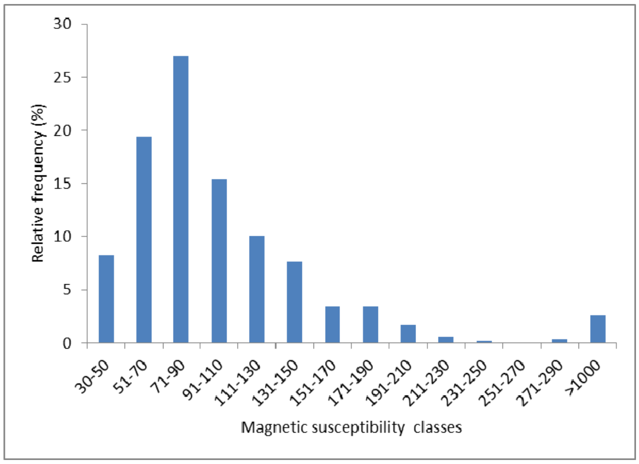

Fig.2. Frequency histogram of mean magnetic susceptibility values for the granites studied, considering the data in Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) and Martins *et al*. (2009, 2011).

Fig.2. Histograma de frequência da suscetibilidade magnética média para os granitos estudados considerando os dados reportados em Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) e Martins *et al*. (2009, 2011).

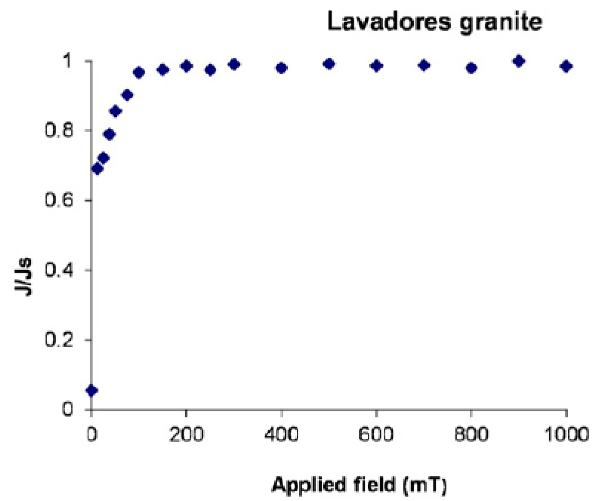

Fig.3. Isothermal Remanent Magnetization (IRM) acquisition curve for a representative sample of the Lavadores granite, according to data in Martins *et al*. (2011).

Fig.3. Curva de Magnetização Remanescente Isotérmica (MRI) para uma amostra representativa do granito de Lavadores, de acordo com dados em Martins *et al*. (2011).

Table 2. Magnetic Susceptibility (K), magnetic anisotropy (Ppara%) and shape parameter (T) data for the sampling granites. N, number of sampling sites; PS, Pedras Salgadas; VPA, Vila Pouca de Aguiar. According to data in Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) and Martins *et al*. (2009, 2011).

Tabela 2. Parâmetros de suscetibilidade magnética (K), anisotropia magnética (Ppara%) e parâmetro de forma (T) dos granitos estudados. N, número de estações de amostragem; PS, Pedras Salgadas; VPA, Vila Pouca de Aguiar. Dados reportados em Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) e Martins *et al*. (2009, 2011).

Granite	Mineralogy/ Texture	N	Magnetic Susceptibility ($K \times 10^{-6}$ SI)		Magnetic anisotropy (Ppara%)		Shape parameter (T)	
			Mean	Variation range	Mean	Variation range	Mean	Variation range
Gralheira	Two-mica medium-grained granite	3	50	48 – 52	5.4	3.2 – 6.7	0.29	0.21 – 0.36
Minheu/Lagoa	Two-mica medium-grained porphyritic granites	7	56	35 - 71	2.2	1.2 – 3.6	0.28	0.00 – 0.61
Serapicos		7	65	45 – 86	4.0	1.8 – 5.1	0.12	-0.37 – 0.62
Porto		6	47	42 – 52	5.9	1.6 – 13.1	0.23	-0.17 – 0.83
Manteigas	Biotite porphyritic granite	4	803	276-16732	7.3	3.1-16	0.22	-0.52 – 0.26
Castro Daire (internal facies)	Biotite-muscovite fine-grained granite	23	64	43 – 90	3.2	1.2 -5.4	0.32	-0.52 – 0.63
Castro Daire (external facies)	Biotite-rich porphyritic coarse-grained granite	79	86	38 – 137	3.6	1.8 – 6.1	0.25	-0.29 – 0.60
Castelo Branco	Biotite-muscovite porphyritic monzogranite	52	69	7 – 131	4.1	1.6 – 10.5	0.24	-0.19 – 0.60
Mangualde-Trancoso	Biotite-rich medium-to fine-grained granitoids	31	110	36-231	2.4	0.9-4.1	0.26	-0.20 – 0.69
Serra da Estrela (Seia and Covilhã)	Biotite-rich coarse-grained and medium-to fine- grained granitoids	197	105	21-237	3.3	1.0-8.6	0.3	-0.34 – 0.75
Valpaços	Two-mica peraluminous porphyritic coarse-grained granite	7	59	48 – 65	3.0	2.1 – 3.8	0.11	-0.08 – 0.22
PS (VPA massif)	Biotite porphyritic medium-to fine-grained monzogranite	35	68	44 – 121	2.1	1.0 – 4.9	0.23	-0.14 – 0.67
VPA (VPA massif)	Biotite-rich porphyritic medium-to coarse-grained monzogranite	81	135	60 – 218	1.0	0.6 – 2.3	0.12	-0.28 – 0.55
Vila da Ponte	Biotite-rich porphyritic medium-to coarse-grained granites	38	79	23 – 220	1.6	0.4 – 4.1	0.13	-0.89 – 0.93
Caria		42	74	57 - 92	1.9	0.8 – 3.9	0.22	-0.27 – 0.69
Chaves	Biotite-rich porphyritic coarse-medium grained granites	10	92	81 – 103	1.7	1.3 – 4.0	0.26	0.01 – 0.52
Lamas de Olo		2	179	154-217	2.5	1.5-3.5	0.05	-0.68 – 0.69
Lavadores	Biotite-rich porphyritic coarse-grained monzogranite	14	11675	1550-19303	11.6	10.3-29.8	0.09	-0.25 – 0.29
Gerês	Biotite-rich porphyritic medium-to coarse grained granite	6	800	100-1000	1.8	1.3-2.3	0.03	-0.51 – 0.64

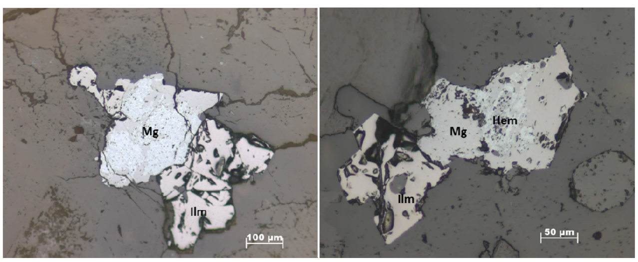

Fig.4. Reflected light microscopy images sowing magnetite (Mg), hematite (Hem) and ilmenite (Ilm) in the Lavadores granite. All photo-micrographs under crossed polars.

Fig.4. Imagens de microscopia de luz refletida, podendo observar-se magnetite (Mg), hematite (Hem) e ilmenite (Ilm) no granito de Lavadores (NX).

4.2. Magnetic anisotropy and shape parameter

Magnetic anisotropy can be used as a "marker" for the deformation experienced by granite mushes during their crustal emplacement and further cooling. Magnetic anisotropy can thus be correlated with the finite deformation of a rock, as record by mineral fabrics. This correlation depends on many factors (such as the strain rate, temperature, mineralogical composition and grain size of the rock), and therefore only a qualitative equivalence may generally be established. Post-tectonic granites as those of Vila Pouca de Aguiar, Pedras Salgadas, Chaves, Caria, Vila da Ponte and Lamas de Olo have a magnetic anisotropy equal or below 2.5% (Fig. 5), which corresponds to a deformation hardly visible to the naked eye. Nevertheless, at microscopic scale, these granites display almost ubiquitous magmatic to submagmatic microstructures (rare wavy extinction in quartz, erratic subgrain boundaries in quartz and, eventually, folded or kinked biotites) (Fig. 6). Syntectonic two-mica granites, such those of Porto and Gralheira showing high to medium temperature solid-state deformation microstructures (like squareshaped quartz subgrains, recrystallized quartz grains, coupled by kinked biotites and bands of quartz surrounded by mica flakes), display a magnetic anisotropy between 5% and 6% (Fig 5 and Fig. 6). Minheu/Lagoa granites are considered as syn-to late-D3 two-mica granitoids; however, in Fig.5, they are part of the post-tectonic group due to its low magnetic anisotropy (2.2%).

The magnetic anisotropy of the Lavadores granite is always higher than 10% (Table 2). This feature, however, reflects the presence of rough alignments of magnetite co-existent with magmatic to submagmatic microstructures.

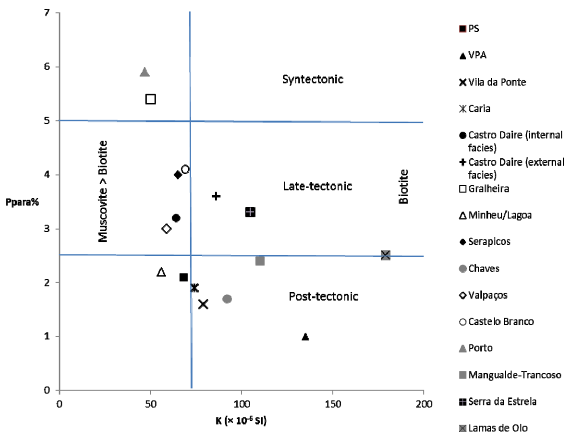

Fig.5. Plot of the relation between mean magnetic susceptibility (K) and magnetic anisotropy (Ppara%) for the paramagnetic granites. PS, Pedras Salgadas; VPA, Vila Pouca de Aguiar. Gerês, Manteigas and Lavadores granites are not represented. According to data in Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) and Martins *et al*. (2009, 2011).

Fig.5. Relação entre suscetibilidade magnética média (K) e anisotropia magnética (Ppara%) nos granitos paramagnéticos estudados. PS, Pedras Salgadas; VPA, Vila Pouca de Aguiar. Os granitos do Gêres, Manteigas e Lavadores não estão representados.
Dados reportados em Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) e Martins *et al*. (2009, 2011).

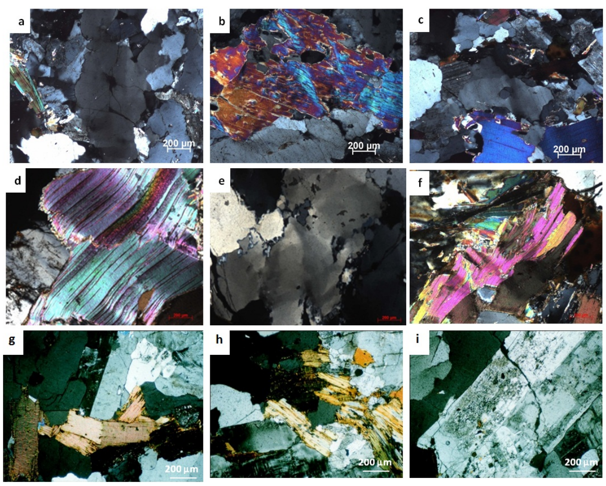

Fig.6. Microstructures observed in some of the granites studied. All photo-micrographs under crossed polars. (a), (b) and (c) Porto granite (Ppara= 5.9%); (d), (e) and (f) Castelo Branco granite (Ppara= 4.1%); (g), (h) and (i) Vila Pouca de Aguiar granite (Ppara= 1.0%). In Porto and Castelo Branco, the microstructures are characterized by subgrain boundaries in quartz and folded or kinked micas. In Vila Pouca de Aguiar, the quartz and feldspar grains do not show any crystal-plastic deformation or recrystallization evidence or any particular mineral preferred orientation. According to data in Sant'Ovaia *et al*. (2000, 2008) and Dória *et al*. (2009).

Fig.6. Microestruturas observadas em alguns dos granitos estudados. (a), (b) e (c) Granito do Porto (Ppara= 5.9%); (d), (e) e (f) Granito de Castelo Branco (Ppara= 4.1%); g), (h) e (i) Granito de Vila Pouca de Aguiar (Ppara= 1.0%). No Porto e em Castelo Branco, as microestruturas são caracterizadas por subgranulação no quartzo e "kinks" nas micas. Em Vila Pouca de Aguiar, os grãos de quartzo e de feldspato não apresentam sinais de deformação plástica ou de recristalização, nem há qualquer tendência para a orientação dos minerais. Dados reportados em Sant'Ovaia *et al*. (2000, 2008) e Dória *et al*. (2009).

The shape parameter T is quite variable; however, the average values are always higher than zero, suggesting the presence of oblate AMS ellipsoids due to the magnetocrystalline anisotropy of biotite (Fig. 7).

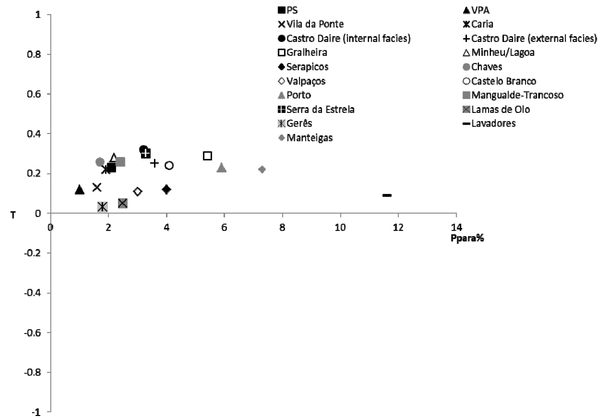

Fig.7. Plot of the relation between magnetic anisotropy and shape (T), showing dominant oblate ellipsoids. According to data in Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) and Martins *et al*. (2009, 2011).

Fig.7. Relação entre anisotropia magnética e parâmetro de forma (T) mostrando elipsoides dominantemente achatados. Dados reportados em Sant'Ovaia & Noronha (2005), Correa-Ribeiro *et al*. (2008), Dória *et al*. (2009), Sant'Ovaia *et al*. (2000, 2008, 2010) e Martins *et al*. (2009, 2011).

5. Hydrothermal ore systems

Figure 8 represents the distribution of the main W and Sn ore deposits and occurrences located in the Portuguese segment of the Central Iberian Zone (e.g. Derré, 1982; Pereira *et al*., 1993; Noronha *et al*., 2006; Mateus & Noronha, 2010). These ore showings are mostly composed of quartz lodes. W-Mo deposits are characterized by the presence of wolframite and scheelite as the main ore minerals of the oxide stage (that may also include cassiterite), besides of molybdenite and chalcopyrite in the sulphide stage. In W lode deposits, chalcopyrite is the main sulphide. In the case of W (Sn) deposits, the oxide stage is characterised by the occurrence of wolframite, as the main mineral phase, together with cassiterite. However, in Sn (W) and Sn deposits the cassiterite prevails largely to other phases.

The W-Mo hydrothermal quartz lodes are related to the Gerês post-tectonic granites (Noronha, 1982); even so, it must be emphasized that this ore type was also exploited during the Second World War at Vila Nova de Gaia (Canelas), being in this case associated with the Lavadores granite (Carta Mineira de Portugal, Folha Norte, 1960). The Sn, Sn (W) and W deposits are related to granites of different types, two-mica and biotite granites, with different ages (e.g. Mateus & Noronha, 2010).

6. Discussion

The magnetite and ilmenite-series are identified by their magnetic susceptibility values (e.g. Ishihara, 1977) because modal contents of magnetite in rocks are positively correlated with their magnetic susceptibility (e.g. Balsley and Buddington, 1964).

The values of magnetic susceptibility and magnetic anisotropy allowed a petrophysical characterization of the paramagnetic Variscan granites (Sant'Ovaia & Noronha, 2005) (Fig. 5). Despite of their different geological, petrographic and geochemical characteristics, K values obtained for the majority of the studied Portuguese granites range from 50 to 140 × 10^{-6} SI. The dominant paramagnetic behaviour of the granite bodies reflects the presence of ilmenite as the main iron oxide. This feature points out the reduced conditions involved in the granite melt formation during the Variscan orogeny, which is compatible with many other petrogenetic indicators so far put in evidence in various works (e.g. Ishihara, 1977; Takahashi *et al*., 1980; Neiva, 1982).

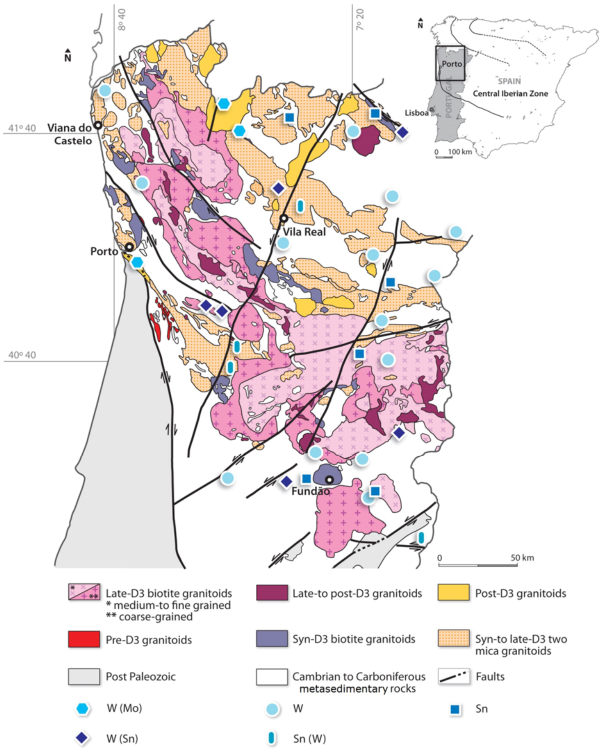

Fig.8. Location of the main W, Sn and Mo ore occurrences in Central Iberian Zone. Adapted from Derré (1982), Pereira *et al*. (1993), Noronha *et al*. (2006) and Mateus & Noronha (2010).

Fig.8. Localização das principais ocorrências de W, Sn e Mo na Zona Centro-Ibérica. Adaptado de Derré (1982), Pereira *et al*. (1993), Noronha *et al*. (2006) e Mateus & Noronha (2010).

The two-mica (muscovite > biotite) granites show magnetic susceptibility values ranging between 30 to 70 × 10^{-6} SI which are lower than values displayed by the biotite-rich facies scattered within the interval of 70 and 250 × 10^{-6} SI. The syntectonic two-mica granites (Porto and Gralheira) are different and should be distinguished from other two-mica granites, where muscovite can have a primary or secondary origin (like some late-tectonic and post-tectonic granite bodies). These granites are usually misclassified and a common mistake is to preclude an igneous protholith on the basis of their peraluminous chemistry and presence of muscovite (Blevin & Chappell, 1995). Post-tectonic granites as those of Vila Pouca de Aguiar, Pedras Salgadas, Caria, Vila da Ponte, Chaves and Lamas de Olo have a magnetic anisotropy lower than 2.5%. For the syntectonic granites of Porto or Gralheira, the magnetic anisotropy ranges between 5% and 6%. In the late to post-tectonic granite bodies, such as those of Castro Daire, Valpaços, Castelo Branco, Mangualde-Trancoso or Serra da Estrela granites, the magnetic anisotropy falls within the interval 2.5% and 5%.

The magnetite-bearing granites are scarce but represented at Lavadores, Gerês and Manteigas. Even so, only the Lavadores body could be considered as a true magnetite-type granite (K >3.0 × 10^{-3} SI) in face of its K, comprised between 1550 and 19303 × 10^{-6} SI.

Magnetite and ilmenite-series granitoids are primarily ruled by the prevailing fO_2 (Ishihara, 1977). Carmichael (1991) established that the redox states of silicic and basic magmas are inherited from their respective source regions. Our results indicate that the redox states of granitic magmas are essentially intrinsic in nature, reflecting the redox states of magma source regions. Nevertheless some granites may acquire their oxidation or reduction state due to specific physic-chemical conditions. Processes of magma mixing and mingling that occurred in an open system can also play an important role in increasing the oxidizing conditions of magma chambers. Therefore, the oxidizing conditions of granite melts belonging to the magnetite-type series can be higher due to the occurrence of mafic and felsic magma interaction in an open system (Kumar, 2010). In the Portuguese cases studied, Gerês and Lavadores are examples were the presence of mafic enclaves (Mendes & Dias, 2004; Silva, 2010) can justify their particular behaviour.

The distributions of the two granitic series are, generally, closely linked to the metallogenic provinces: sulphide-rich deposits, such as Cu, Pb, Zn, and Mo, tend to develop in association with magnetite-granitic bodies, while oxide-rich deposits, such as W and Sn, are related to ilmenite-series granitic rocks (e.g. Ishihara, 1977, 1981; Candela & Bouton, 1990; Takagi & Tsukimura, 1997; Takagi, 2004). In Portuguese examples, the W-Mo deposits are related to magnetite-type granites, whereas the Sn, Sn (W), W (Sn) and W hydrothermal lodes are related to ilmenite-type granites.

7. Conclusions

All the studied granites show paramagnetic behaviour (magnetic susceptibility ~ 10^{-6} SI), except for the bodies of Lavadores, Gerês and Manteigas whose magnetic susceptibility ranging from 15 to 20 × 10^{-3} SI units is compatible with the presence of magnetite. Despite of different petrographic and geochemical characteristics, K values in the studied paramagnetic granites vary from 20 to 300 × 10^{-6} SI units corresponding to reduced- or ilmenite-type granites.

Major W and Sn ore deposits are related to two-mica and biotite-rich granites both corresponding to reduced ilmenite-bearing granites; W-Mo lode deposits are related with biotite-rich granites belonging to oxidized series.

Magnetic susceptibility measurements, being a powerful tool to identifying the magnetite- and ilmenite-granite series is strongly recommended in granitoid studies and mineral exploration.

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