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Geological setting and magnetite-ore genesis at the Corujeiras prospect (Beja, Portugal)

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ABSTRACT

Key-words: Fe-skarn; calc-silicate rocks; Beja Igneous Complex; Ossa Morena Zone.

At Corujeiras (NE Beja), several types of intermediate and felsic igneous rocks belonging to the Beja Igneous Complex intrude Pre-Variscan magnesian marbles and strongly deformed quartz-feldspathic rocks. A small Fe(-Mg)-skarn is shown to develop along the contact of hydrous (*qtz*-)monzonitic rocks with marbles, leading to extensive *mgt* formation. A prograde stage of nearly isochemichal metasomatism is responsible for an anhydrous mineral assemblage (*fo* ± *hc*) in the endoskarn at ≤ 540ºC along with the formation of diopsidic hornfels (± *Hc*) in the exoskarn. The onset of ore deposition correlates with a late-prograde stage (≤ 420ºC), when highly reactive Fe-Si-rich fluids are introduced in the endoskarn, leading also to the development of serpentine minerals (± *chn* ± *ves* ± *czo/ep*). Late retrograde stages are responsible for extensive phyllosilicate (*phl* ± *chl*) and minor amphibole (*tr* ± *cum*) formation in the exoskarn, as well as for the hydration of the remaining *fo* in the endoskarn. Evidence of minor sulphide dissemination (*po* ± *cpy* ± *py* ± *sph*), mostly in the endoskarn, exists and is also correlative of this evolving stage. The waning stages of hydrothermal activity are recorded by fracture-controlled carbonate infillings and strong hydrolysis of primary feldspars in the igneous rocks.

Introduction

The small iron deposit of Corujeiras (NE Beja) is known for several decades (Oliveira, 1992). Recent geological mapping of its involving area shows that there are several types of igneous rocks, all belonging to the Beja Igneous Complex (BIC), intruding Pre-Variscan units, namely forsteritic marbles and highly deformed quartz-feldspathic rocks. Along some contacts of these igneous bodies with marbles, typical skarn mineralogy can be observed, comprising different calc-silicate minerals, magnetite and minor sulphides. This work aims to characterise the outcropping igneous rocks and the mineralogy of the Fe(-Mg)-skarn, discussing in general terms the evolution of this ore-forming system.

Geological setting

In the Corujeiras area, six different intrusive rocks were recognised, besides Pre-Variscan marbles (variably metasomatised) and strongly deformed quartz-feldspathic rocks (Fig. 1). The detailed scale (1:5000) of the geological mapping precludes a straightforward correlation with the general lithological features proposed for the main units that commonly are used to describe BIC. The SW sector of the mapped area comprises mainly gabbroic (GB) rocks locally intruded by small bodies of microporphyritic *qtz*-monzonites (QM). These *qtz*-monzonites intrude also the microporphyritic monzonites (M) outcropping immediately north of gabbros; note that without knowing the An-content of plagioclase it is not possible to assign a dioritic or gabbroic composition to M rocks. Two types of granite rocks (PG and MG) with distinct textures, that show also different field relationships with the afore-mentioned igneous bodies, represent the late emplacement of more evolved magmas. The porphyritic granites (PG) follow a NW elongated pattern, intrude the M bodies and show a highly variable granularity. The microgranites (MG) exhibit a fine equigranular texture and form a distinct outcropping pattern suggestive of a relatively late emplacement. Several late NW-SE elongated bodies of coarse-grained granodiorites (GD) occur in the SE sector of the mapped area.

Relics of two Pre-Variscan units (including quartz-felspathic – QF – rocks and marbles – MB) outcrop also in the mapped area, being well represented in its SE sector. The QF rocks are fine-grained and show a conspicuous mesoscopic foliation; they are presumably correlative of metavolcanics and/or meta-arkoses of Late Proterozoic age (Oliveira, 1992). The MB rocks show often a well-developed metamorphic banding, usually outlined by olivine-rich bands. The calc-silicate rocks (CC) show highly variable macroscopic features, even at the outcrop-scale, depending mostly of their protolith nature. When the precursor is igneous, CC rocks display typically a pale-greenish color and a fine-grained texture where pyroxene megacrystals can be easily recognised; when carbonate-derived, CC rocks are mineralised, comprising large proportions of *fo* (or pseudomorphic serpentine aggregates with reddish or greenish color) and coarse-grained magnetite along with minor sulphide (*po* ± *cpy* ± *py*) disseminations.

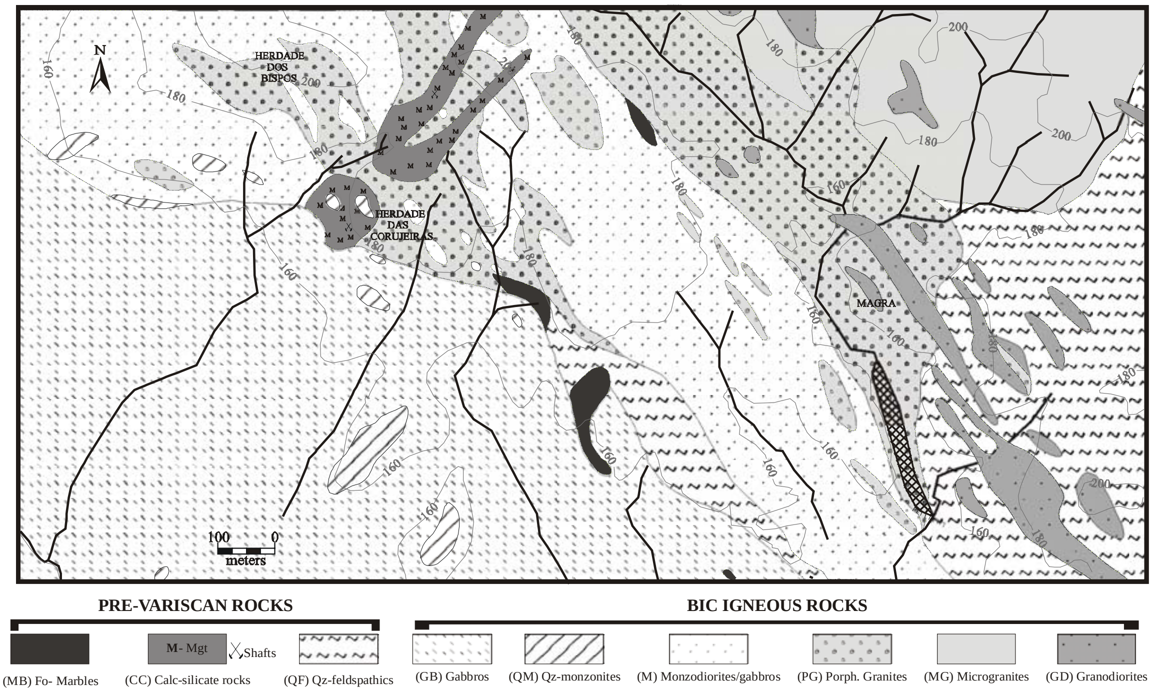

Figure 1- Geological map of the Corujeiras area. Note that the tighted-square pattern indicates a small farming damn.

Petrography and mineralogy

All the sampled igneous rocks show some degree of similarity concerning textural arrangements of the main and accessory mineral phases. Since modal proportions and textural varieties are summarised in table 1, the following description emphasises essentially their main distinctive features. Igneous rocks classification follows criteria recommended by IUGS (Le Bais & Streckeisen, 1991).

Igneous rocks with (micro)porphyritic texture (*e.g.* QM or M) have phenocrystals of (sub-)euhedral zoned plagioclase and K-feldspars. When present, clinopyroxene phenocrystals are commonly partly or totally replaced by complex aggregates of pale-green amphibole intensely chloritised (often including opaque minerals, zircon or apatite). The M rocks show, additionally, sub-idiomorphic megacrystals of dark-brown and strongly pleochroic amphibole with poikilitic texture that do no exhibit any signs of late chloritisation. The matrix of porphyritic rocks comprises a framework of K-feldspar and zoned plagioclase in variable proportions intergrown with anhedral quartz; aggregates of brown amphibole and of idiomorphic sphene crystals are also present in the matrix of some of these rocks. Rocks with granophyric textures (*e.g.* some PG and all GD) have a network of alkaline feldspar and zoned plagioclase; these minerals develop variably extensive simplectic rims with interstitial quartz. All the examined rocks record moderate to intense hydrolysis of the feldspars *s.l.*. The accessory mineral phases are usually present in variable amounts (see table 1), and form: 1) small aggregates of biotite; 2) dark-green lamellae of chlorite, often replacing biotite aggregates; 3) anhedral to subhedral opaque minerals; 4) euhedral fine-grained crystals of zircon and apatite; 5) anhedral aggregates of epidote/zoisite; and 6) interstitial muscovite, only in granitic rocks (not reported in table 1).

Igneous-derived calc-silicate rocks show abundant diopsidic pyroxene (Fig. 2A) forming massive aggregates of small grains (0.5 mm). Locally, megacrystals of diopside with centimetric dimension occur, sometimes associated to coarse aggregates of hercynite. The pyroxene frequently exhibits anomaly high interference colours due to late hydration; amphibole grains are also observed and display optical features that suggest the presence of cummingtonite. The matrix of these calc-silicate rocks is essentially composed of plagioclase frequently masked by a pervasive alteration that includes aggregates of heterogeneous composition and very variable granularity (phlogopite + tremolite ± chlorite ± clay minerals); late intergranular veins are sealed by similar mineral assemblages. Subhedral clinozoisite, anhedral aggregates of epidote, and subhedral magnetite are the main accessory minerals.

CLASSIFICATION	**QM**	**M**	**PG**		**GD**	
TEXTURAL VARIETIES	*microporph. (interstitial)*	*microporph.*	*granophyric*	*porphyritic (microporph.)*	*granophyric*	*granophyric*
Qtz *(M)*	9.3	10.7	36.8	23.5	17.8	32.15
K-feldspar *(P) / (M)*	4.3 / 22.8	6.9 / 16.9	0 / 42.3	8.6 / 46.9	0 / 14.9	0 / 14.1
Pg *(P) / (M)*	10 / 30.5	23.2 / 25.3	0 / 6.6	11.6 / 1.5	0 / 42.4	0 / 37.8
Fresh Cpx *(P)*	1.9	0	0	0	0.2	0.1
Chl I *(M)* / II *(M)*	4.5 / 1.2	0 / 3.2	3.3 / 0.5	2 / 1.5	4.5 / 0	9.75 / 0
Bt *(M)*	0	2.8	7.7	1.6	0	1
Brown *(M)* / Green Amph *(P)*	0 / 11.8	(F) 4.3 / 4.1	0 / 0	0 / 0	13 / 6	2.2 / 1.6
Accessory phases *(M)* / Opq	2.2 / 1.5	1.3 / 1.3	2.6 / 0.2	1.4 / 1.4	1.2 / 0	1.1 / 0.2

Table 1- Modal proportions of examined igneous rocks. Other studied samples where not modally analysed due to their very fine granularity; gabbros and microgranites where not sampled. *P* indicates phenocrystals, while *M* matricial minerals; Chl I: early chlorite generation; Chl II: chlorite related with retrogradation processes. Accessory phases: *ep + czo + ap + zrn*.

Metasomatised carbonate rocks (Fig. 2B) comprise a matrix of magnesite with rhodochrositic molecular contents not exceeding 2.7% (EPMA). The matricial carbonates do not show evidence of dynamic recrystalisation processes (such as triple point junctions) but distorted lamellae due to intracrystaline deformation are common. Forsterite occurs as individual anhedral (usually rounded) grains or make up aggregates that form irregular, millimetric bands. Olivine hydration can be moderate to complete, leading to serpentine growing in well-developed pseudomorphic textures of hourglass or mesh type. Locally, serpentine minerals are shown to develop non-pseudomorphic textures of interlocking or interpenetrating types (sometimes cut by ribbon-veins), indicating some degree of recrystalisation of early aggregates. In some samples, very fine-grained carbonate masses ($CaCO_3 \approx 10wt\%$) invade extensively serpentine aggregates. Non-mineralised samples show accessory amounts of hercynite (as isolated subhedral grains or randomly distributed aggregates that contain oriented magnetite exsolutions), clinozoisite and rare vesuvianite. Anhedral (rounded) grains or aggregates of chondrodite are present in some samples; this mineral is possibly more abundant than what is displayed in figure 2B, because microcrystalline grains of talc forming ribbon-like aggregates with rounded morphology are probably a product of chondrodite retrogradation. Massive magnetite aggregates include interstitial olivine relics and pseudomorphic serpentine masses; irregular and millimetric aggregates of magnetite are randomly scattered in ore-poor samples. The available EPMA data shows that the magnetite chemical composition is close to the ideal composition: $Fe^{3+}_{1.90}Al_{0.07}Fe^{2+}_{0.95}Mg_{0.08}Mn_{0.01}O_4$. Pseudo-cubic exsolutions (?) of dark grey colour and very low reflectance where observed in the magnetite, following no particular crystallographic orientation; EPMA data shows that these exsolutions (?) are of aluminous pleonasts (hercynite-spinel *s.s* solid solution) with an average chemical composition $Fe^{3+}_{0.09}Al_{1.91}Fe^{2+}_{0.22}Mg_{0.78}O_4$. Sulphides are, in general, scarce and consist of small (< 0.5 mm) anhedral grains of *po*, *cpy*, *py* and *sph*; more uncommon sulphide and sulphosalt phases were also detected as exsolutions in *py* or tiny isolated crystals, but still await proper chemical characterisation. Late veins with coarse-grained carbonate infillings cut all the previously referred mineral assemblages.

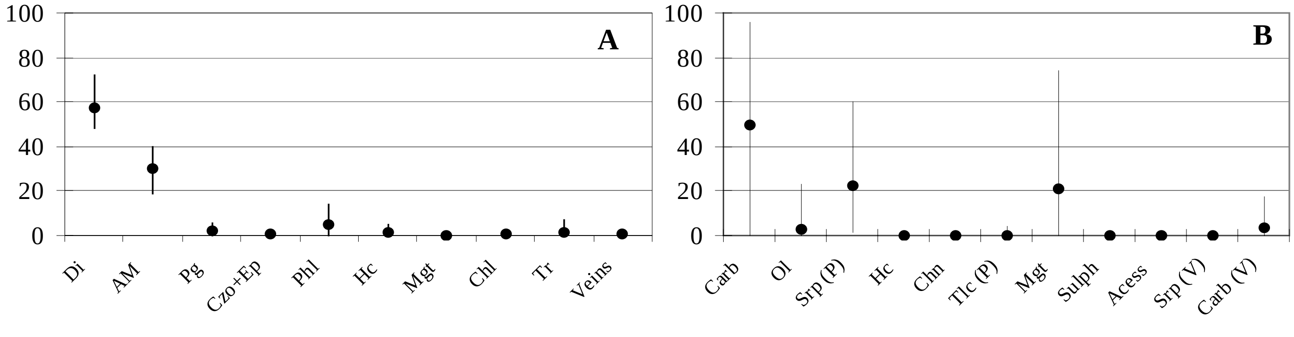

Figure 2- Average and range of modal proportions for variably mineralised CC rocks. **A-** Igneous-derived CC rocks; AM- altered *pg* matrix; **B-** Carbonate-derived CC rocks. Carb- Carbonate; P- resulting of pseudomorphic substitution of *srp* or *chn*; Acessory mineral phases = *czo + ves + cum*; Sulphide - *Sulph*; Vein infillings - V.

Discussion

At Corujeiras, the spatial association of igneous rocks of intermediate composition with the mineral assemblage that forms the calc-silicate rocks, clearly indicates that we are in presence of a Fe(-Mg)-skarn that resembles those usually found in continental magmatic arc settings (Einaudi *et al.*, 1981). The outcropping conditions and the preliminary nature of the present study do not support a direct relationship with a particular igneous rock of the mapped suite. However, according to the most common association reported for these skarn types, QM and/or M rocks are the most plausible possibility. Also according to calc-silicate rocks mineralogy, two distinct precursors can be inferred, one of igneous affiliation and other of metasedimentary (carbonate) nature; therefore, these two different calc-silicate rocks should represent an endoskarn and exoskarn, respectively, sharing a common evolution.

An early prograde anhydrous stage is responsible for widespread forsterite and diopside development in the exo- and endoskarn, respectively. Hercynite is ubiquitous in both rock types, incorporating the Al-impurities preexistent in the marbles. Considering the protolith nature and new-formed minerals, this stage is nearly isochemical and can be envisaged as nearly contemporaneous of magma emplacement. Effects of this stage are much more extensive in marbles, as expected, developing a widespread metamorphic aureole containing minor hornfels; however, without mineral chemistry data it is impossible to ascribe all the observed forsterite to the metamorphic event intimately related to the genesis of this skarn.

Forsterite is very sensitive to retrogradation processes, particularly if they involve hydration, and there is a positive correlation between the ratio of serpentinised/fresh olivine and magnetite enrichment, suggesting that ore genesis and early hydration processes are nearly synchronous. This indicates also that the introduction of exotic chemical components, particularly Fe in the marbles, can be envisaged mainly by fluid-aided rather than diffusion processes. The genesis of magnetite is thus a consequence of the introduction of Fe-enriched, Mg-depleted fluids (compatible with *qtz*-monzonitic magma compositions) that are simultaneously responsible by extensive serpentinisation processes. The absence of mineral phases that effectively can incorporate iron in this Mg-calc-silicate paragenesis explains the ease in which this mineral forms in this chemical environment; the bulk oxidation state of the system must be therefore compatible with the amount of Fe^{3+} needed to form such quantities of magnetite, thus, at least along *QMF* buffer. The serpentinization process also marks the most significant introduction of silica in the carbonate environment. Other mineral phases related with the late-prograde ore forming stage are *chn, ves* and *ep/czo*.

The hydrous character is significant in all the observed igneous rocks, as recorded by the relative abundance of hydrated minerals, ascribable both to late magmatic (*e.g. bt*, brown *amph*) and retrogradation processes (*e.g. chl* I and II, green *amph*). A significant part of the aluminum carried by the ore-fluid will be at first incorporated in Al-pleonasts (within *mgt*) and hercynite. During the late retrogradation stage, correlative of the system cooling, *phl ± amph* develop along with extensive hydrolysis of minerals pre-existent in the endoskarn. The growing of *tlc + srp* (preferentially vein hosted) in the endoskarn marks this evolving stage, the coeval carbonates being more Ca-enriched and occurring as fracture-controlled infillings or as disseminations over serpentine and magnesite matrix. The disseminated sulphides so far recognized are believed to form during this late retrogradation stage; *py-sph* in calcite vugs and *cpy* intergrown with serpentine pseudomorphic aggregates are the most significant examples.

Tentative temperature estimates for the major evolving stages can be made on the basis of the compiled data available for similar occurrences, assuming low pressure (Einaudi *et al.*, 1981). The geological evidence of a relatively shallow hypabissal environment supports this assumption. Pressure constraints are imposed mainly by the readjustments related to the intrusion of different igneous bodies, the volatile partial pressures apparently playing a minor role during fluid migration, as suggested by the abundancy of late carbonate veins in the (mineralised) exoskarn; in the endoskarn, late hydrated minerals also seal veins but carbonates are rare. At constant pressure, the shifting of X_{CO2} in the hydrothermal fluid significantly lowers the temperature of formation of the most common calc-silicate minerals. T-X_{CO2} diagrams for water-rich fluid compositions in the system Ca-Mg-Si-C-O-H (using $X_{CO2} \leq 0.1$, compatible with the present case) suggest that the mineral assemblage formed during the early prograde stage requires temperature conditions ≤ 540ºC. Thermodynamic calculations indicate also that during serpentinization of a *fo*-bearing Mg-skarn, $X_{CO2} < 0.05$ and $t < 420$ºC, thus providing a rough estimate for the maximum temperature compatible with magnetite development. The lower threshold for the main retrograde stage should be constrained by the *phl-amph-tlc* stability fields; residual heat dissipated during the waning stages of system cooling is still responsible for significant hydrothermal activity, leading to Ca-rich carbonate formation and widespread hydrolysis of the igneous rocks and hornfels.

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