The role of crustal contamination in the genesis of Ni-Cu sulfide ores from the Cortegana Igneous Complex (SW Spain)

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Abstract. Crustal contamination of mafic magmas with S-rich country rocks is believed to play a critical role in the formation of Ni-Cu sulfide ores in SW Spain. Whereas this process has been well recognized in the Aguablanca Ni-Cu deposit (the only economic ore of this type in SW Europe), no data existed in other less mineralized, mafic-ultramafic intrusions of the region, such as the Tejadillas prospect in the Cortegana Igneous Complex. The Tejadillas prospect is composed of igneous cumulates similar to those of Aguablanca, but their incompatible trace element abundances show more primitive patterns than those of Aguablanca. In contrast, incompatible trace element ratios of the Aguablanca rocks are much closer to the contaminant country rocks than those of Tejadillas. Therefore, we suggest that the small volume of sulfide mineralization observed at Tejadillas was the consequence of low degrees of contamination of its parental magma by S-rich country rocks. This suggest that assimilation of S-rich country rocks by mafic magmas is the key factor for the genesis of economic Ni-Cu sulfide ores in SW Spain.

Keywords. Cortegana, Tejadillas, Aguablanca, crustal contamination, Ni-Cu sulfide ores

1 Introduction

Among processes triggering sulfur saturation of mantle-derived magmas (i.e., crustal contamination, magma mixing and fractional crystallization), the assimilation of external sulfur by silicate melts from sulfide-bearing country rocks is probably the most important one, being the responsible of the formation of an important number of Ni-Cu sulfide deposits (e.g., Noril'sk, Voisey's Bay, Duluth; Barnes and Lightfoot 2005).

The role of crustal contamination has been well recognized in the genesis of the only Ni-Cu sulfide, operating mine in SW Europe, the Aguablanca Ni-Cu deposit. Sulfur saturation was achieved by the incorporation of crustal sulfur to the silicate melts from the country pyrite-rich black slates of the Serie Negra Formation (Casquet et al. 1997; Tornos et al. 2001; Piña et al. 2006, 2010). From the discovery of the Aguablanca deposit, several base-metal sulfide (BMS)-bearing mafic-ultramafic bodies have been identified in the region, such as Argallón, Brovales and Cortegana. The latter represents the most interesting one, containing ores with up to 1.36 wt.% Ni and 0.2 wt.% Cu.

The aim of this contribution is to present a comparative petrographical and geochemical study of the Ni-Cu sulfide ores in the Cortegana intrusion and those of the Aguablanca deposit, to discuss the role played by crustal contamination in the formation of the Cortegana ore.

2 The Ni-Cu sulfide ore in the Tejadillas stock

The Cortegana Igneous Complex comprises a number of small intrusive stocks, named Tejadillas, Sojalba, Merendero, Caballona and Tabaca (Fig. 1), located within the Ossa-Morena Zone of the Iberian Massif, only 65 km west to the Aguablanca deposit. Exploration was focused on the Tejadillas stock that contains the highest amounts of Ni and Cu. Although preliminary studies have showed that sulfide mineralization is much less abundant than in Aguablanca.

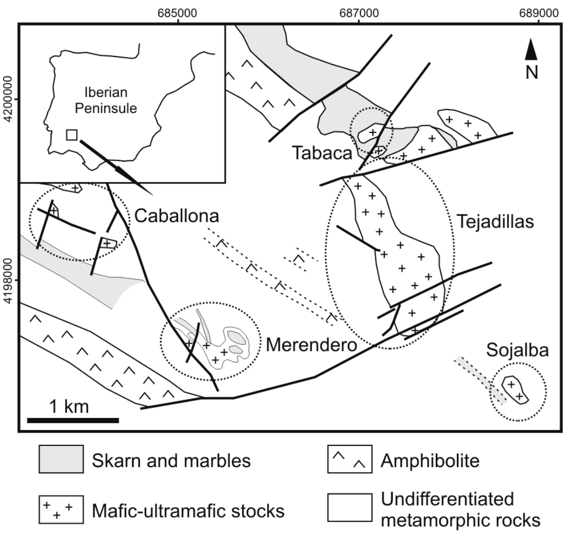

Figure 1. Squematic geological map of the Cortegana Igneous Complex showing the most important occurrences.

2.1 Petrography of the Tejadillas igneous rocks and sulfide mineralization

The Tejadillas stock consists of a poorly exposed, tabular-shaped body of roughly 1.4 km long and 0.7 km wide, formed by medium to coarse-grained igneous cumulates: hornblende peridotite, olivine gabbronorite, norite, gabbronorite, gabbro s.s. and tonalite. Norite and gabbronorite are the predominant rock-types. The contact with the country host rocks is marked by the presence of orbicular-textured rocks consisting of gabbros hosting rounded to angular xenoliths of country metamorphic rocks (mainly, calc-silicate hornfels) (Fig. 2). These xenoliths show well-marked boundaries with evidence of poor digestion by the host magmas.

Figure 2. Orbicular-textured gabbro showing centimetric size, rounded xenoliths of host metasedimentary rocks.

Primary igneous textures are well recognized in the mafic-ultramafic cumulates, although late hydrothermal alteration can partly obliterate such textures. Ultramafic rocks (i.e., hornblende peridotite and olivine gabbronorite) are made up of cumulus olivine (Fo_{83-75}), orthopyroxene (Mg# 0.79-0.86) and minor clinopyroxene (Mg# 0.85-0.87), with interculumus plagioclase (An_{88-96}), amphibole and minor phlogopite. Poikilitic textures typically consist of rounded olivines enclosed total or partially by amphibole. Nickel content in olivine is very low, commonly below 0.20 wt.%, suggesting a Ni-depleted parental magma. Gabbronorite and norite are medium-grained orthocumulates composed of variable proportions of cumulus orthopyroxene (Mg# 0.77-0.82) and clinopyroxene (Mg# 0.80-0.87), and intercumulus plagioclase (An_{75-89}), amphibole and minor quartz and phlogopite. Poikilitic textures are also common in gabbros s.s., consisting of pyroxene enclosed by plagioclase and amphibole. Tonalite is a coarse- to medium-grained leucocratic rock mainly composed of plagioclase (An_{61-50}) and quartz with minor biotite and clinopyroxene (Mg# 0.79-0.81).

Sulfide mineralization occurs in peridotite and gabbronorite-norite, being absent in the most leucocratic rock-types. Mineralogy is quite simple, consisting of pyrrhotite (> 80 vol. % of total sulfides), pentlandite and chalcopyrite. It occurs as small aggregates interstitial to silicates and, less commonly, as roughly rounded droplets within them. Sulfide mineralization typically represents less than 5 vol. % of the rocks.

2.2 Whole rock geochemistry

Twenty representative rock samples of the Tejadillas stock were analyzed at Genalysis Laboratory Services Pty. Ltd., Maddington (Western Australia). Major oxides contents were determined by X-ray fluorescence (XRF) and trace elements by inductively coupled plasma-mass spectrometer (ICP-MS) after multi-acid digestion.

Tejadillas cumulate rocks show large chemical variations in agreement with the wide range of modal composition. MgO content ranges from 12.30 to 34.79 wt.% and SiO_2 from 44.47 to 54.90 wt.%. Mg# (atomic Mg/[Mg+Fe]) is quite constant (0.75-0.83), with the highest values corresponding to hornblende peridotite (Mg# 0.83). Al_2O_3 contents are relatively low (3.60-10.64 wt.%) and all samples are relatively poor in TiO_2, MnO and alkalis (Na_2O+K_2O) (below 0.82 wt.%, 0.35 wt.% and 2.39 wt.%, respectively).

Primitive mantle-normalized, incompatible element patterns of Tejadillas cumulates are shown in Figure 3. These rocks are characterized by slight enrichment in large ion lithophile elements (LILE), Rb, Ba, Th, U, and LREE, relative to high field strength elements (HFSE) Nb, Ti, Zr, Hf, and HREE. These patterns resemble those of Aguablanca rocks (Fig. 3), but those from Tejadillas show slightly less fractionated patterns. Whereas in Aguablanca, the $(La/Yb)_{MN}$ and $(Th/Nb)_{MN}$ ratios vary from 3.8 to 8.2 and from 2.8 to 9.1, respectively, in Tejadillas these ratios range from 1.6 to 4.4 and from 0.5 to 2.6, respectively (Fig. 4).

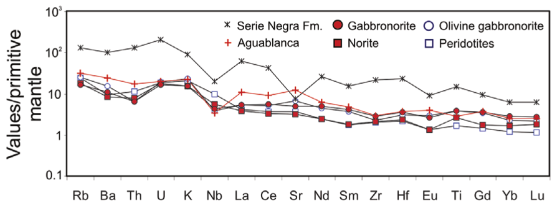

Figure 3. Primitive mantle-normalized trace element patterns for Tejadillas rocks. Patterns were drawn from the average values for each different lithology. The average composition of the Aguablanca gabbronorite is from Piña et al. (2006) and of the country rocks from the Serie Negra Formation is from Pereira et al. (2006).

3 Discussion

In the Aguablanca ore deposit, sulfide segregation was caused by the external addition of crustal sulfur from the S-rich black shales of the Late Neoproterozoic, Serie Negra Formation (Casquet et al. 2001). The 15-25 km-thick, Serie Negra Formation represents the most important formation of the Ossa-Morena Zone. It is formed by several graphite- and pyrite-bearing rock-types including metacherts, quartz phyllilites, mica schist, metagreywackes and paragneises (Pereira et al. 2006). Sulfur content is variable but can reach up to 3000 ppm S (R. Piña unpublished data). Evidence of the crustal origin of S in Aguablanca includes sulfur isotope compositions (close to + 7.4 ‰, Casquet et al. 2001), lead isotope signatures ($^{206}Pb/^{204}Pb$ = 18.27–18.43, $^{207}Pb/^{204}Pb$ = 15.61–15.65, similar to those of the Serie Negra country rocks; Tornos and Chiaradia 2004) and systematic enrichment of the Aguablanca rocks in Pb, LILE, and LREE relative to HFSE and HREE (Piña et al. 2006).

The comparison of trace element geochemistry between Aguablanca and Tejadillas rocks suggests that crustal contamination processes were much less prevalent in Tejadillas. Although the primitive mantle-normalized trace element patterns of the Aguablanca and Tejadillas rocks are comparable (Fig. 3), suggesting that they crystallized from similar parental magmas, the Aguablanca rocks show slightly more fractionated incompatible trace element patterns than those of Tejadillas cumulates. Furthermore, the shape of the patterns of the Aguablanca rocks resembles those of the Serie Negra Formation (Fig. 3), suggesting that the crustal component in Aguablanca is higher than in Tejadillas.

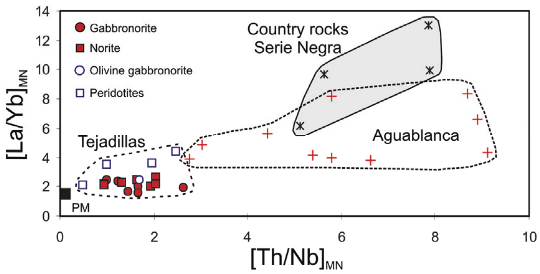

Figure 4. $[La/Yb]_{MN}$ vs $[Th/Nb]_{MN}$ diagram for the Tejadillas and Aguablanca rocks. Data for Aguablanca are from Piña et al. (2006).

The extent of crustal contamination can be estimated by using the $(La/Yb)_{MN}$ versus $(Th/Nb)_{MN}$ diagram (Fig. 4). These ratios are very sensitive indicators of crustal contamination and their representation along with the ratios of possible contaminants is very useful to constrain the degree of contamination. Thus, Figure 4 includes the composition of igneous rocks from Aguablanca and Tejadillas, as well as the average ratios of distinct rock-units of the Serie Negra Formation (Pereira et al. 2006) as possible contaminants. Rocks from Aguablanca plot close to the field of country rocks whereas those from Tejadillas plot toward the composition of primitive mantle. This difference strongly suggests that the Aguablanca magmas were more contaminated with sulfur-rich country rocks than the Tejadillas magmas or at least, that the contamination process in Aguablanca was more homogeneous and widespread than in Tejadillas. This conclusion agrees with that of Tornos et al. (2006) who suggested a lower degree of contamination in the Cortegana rocks than in Aguablanca based on sulfur isotope data obtained on sulfide disseminations ($\delta^{34}S$ values range from -0.1 to +3.1 ‰).

4 Conclusions

The very low degree of crustal contamination of parental silicate melts is a key factor to understand the scarce formation of Ni-Cu sulfides ores in the Tejadillas cumulates. This observation along with the close relationship between crustal contamination and Ni-Cu mineralization in the Aguablanca deposit suggest that assimilation of S-rich sedimentary rocks by mafic-ultramafic melts constitute the most favourable target for exploration of new Ni-Cu sulfide ores in SW Iberia.

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