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A new style of Ni-Cu mineralization related to magmatic breccia pipes in a transpressional magmatic arc, Aguablanca, Spain

Abstract The Aguablanca deposit represents a new style of magmatic Ni Cu mineralization in discordant sulfide rich pyroxenitic breccia pipes. The orebody is hosted by Variscan calc alkaline diorites and gabbros which intruded during an oblique subduction/collision event. Transpressional transtensional left lateral structures facilitated the intrusion of primitive magmas to shallow depths in the crust. A two stage genetic model is proposed. In the first stage, a transitional deep magma chamber formed. The primitive magma interacted at depth with wall rocks, resulting in extensive crustal contamination, concomitant sulfide magma immiscibility and settling of orthopyroxene , clinopyroxene and sulfide rich cumulates to form a layered magmatic complex. Geochemical and mineralogical evidence, including the virtual disappearance of olivine, heavy ^{34}S values (7.4‰), distinctive Nd, Sr and Pb signatures, high Au contents, and the presence of spinel and graphite indicate a major interaction with the upper crust, probably with pyrite rich carbonaceous slates of Late Proterozoic age. The second stage was related with the emplacement of residual calc alkaline gabbroic to noritic melts and the development of an intrusive breccia containing fragments of the consolidated layered complex rocks and associated disseminated to massive sulfides.

Introduction

Magmatic Ni Cu deposits form a distinct style of mineralization which share several common features (Naldrett 1999): (1) location either at the base of stratiform magmatic complexes, sills or flows (e.g., Noril'sk) or as irregular bodies within the underlying feeder zones (e.g., Jinchuan, Voisey's Bay), (2) an association with olivine rich rocks (usually dunites and troctolites), and (3) a spatial relationship to large transcrustal faults in intraplate rifted areas. Host magmas are Mg rich and usually of basaltic, picritic or komatiitic composition (e.g., Naldrett 1981, 1999). Extensive crustal contamination seems to be a major requirement in the formation of this style of mineralization (Lightfoot et al. 1990; Ripley et al. 1999).

In this paper we describe an unusual case of magmatic Ni Cu mineralization at Aguablanca (SW Spain), in which synplutonic faults may have played a major role in the formation of the orebody. The style of Ni Cu mineralization here differs from previously described deposits and does not conform to current classifications (e.g., Naldrett 1981, 1999). The Aguablanca deposit is currently under economic evaluation. It was discovered after a regional geochemical stream sediment survey which identified significant Cu anomalies which were related to a poorly exposed gossan with minor old workings. After systematic diamond drilling up to 700 m depth, provisional geological resources are about 31 Mt @ 0.46% Cu and 0.62% Ni with Co, Au and PGE credits. Ortega et al. (1999) report grades of up to 0.15 ppm Au, 0.02% Co and up to 0.6 ppm Pt + Pd in specific zones of the orebody. Aguablanca is the only significant example of Ni Cu mineralization in SW Europe.

Regional geologic setting

The Aguablanca deposit is located in the southeastern part of the Ossa Morena Zone, one of several tectonic domains of the Iberian Massif (Quesada et al. 1991; Fig. 1). The Ossa Morena Zone was accreted to the autochthonous Iberian Terrane during Cadomian times (620 480 Ma). During the later Variscan orogeny (390 300 Ma; Eguiluz et al. 2000), the Ossa Morena Zone acted as the overriding plate during the oblique northward subduction and collision of the exotic South Portuguese Zone with the Iberian Massif. A key feature of the Ossa Morena Zone is the existence of major WNW ESE strike slip faults which have been active throughout its evolution since Late Proterozoic times. The oblique nature of the Variscan deformation explains many of the structural and sedimentary features, including the transection of folds by the associated cleavage (Apalategui et al. 1990), the intrusion of intermediate to acid epizonal plutons along oblique extensional structures (Castro 1985), and the formation of synorogenic trans

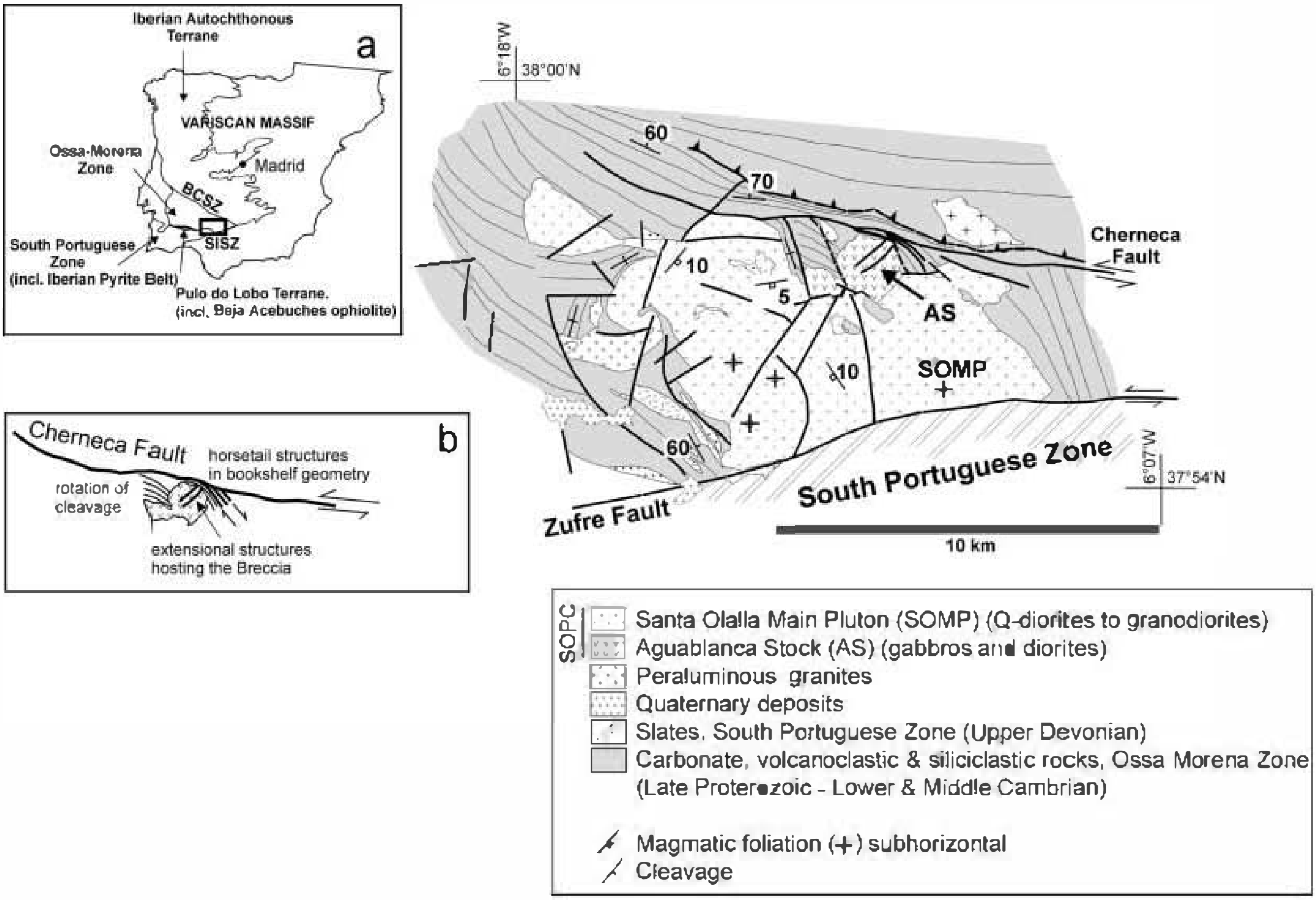

Fig. 1a, b Geological sketch of the Santa Olalla Plutonic Complex and Aguablanca Stock highlighting the structural features. The *thin lines* represent the main cleavage trends. **a** Location of the Ossa Morena Zone in the Iberian Peninsula. *BCSZ* Badajoz Córdoba Shear Zone; *SISZ* South Iberian Shear Zone. **b** Tectonic scheme of the Aguablanca Stock

tensional basins (Gabaldón et al. 1985). Transpression was also a key feature in the formation of the major ore deposits of SW Iberia, including the world class massive sulfide deposits of the Iberian Pyrite Belt as well as the Fe (Cu) skarns, Sn and Hg replacive mineralization, and gold and Zn Pb veins in the Ossa Morena Zone (e.g., Locutura et al. 1990).

The Santa de Olalla Plutonic Complex

The Santa de Olalla Plutonic Complex (SOP Complex) comprises the Santa Olalla Main Pluton and the smaller Aguablanca Stock (Casquet 1980; Fig. 1). The SOP Complex is located north of the Variscan crustal suture which separates the Ossa Morena from the South Portuguese Zones (South Iberian Shear Zone and its prolongation in the Zufre Fault). Its northern boundary is close to a narrow and high angle strike slip fault, the Cherneca Fault. The rocks of the SOP Complex intruded carbonate and calc silicate rocks, metavolcanics and slates of Late Proterozoic to Early Cambrian age which unconformably overlie a several kilometer thick sequence of Late Proterozoic, alternating, pyrite bearing black slates and quartzites with minor amphibolites (Serie Negra; Quesada et al. 1987; Eguiluz et al. 2000). The intrusion is epizonal and generated an aureole of high grade contact metamorphism, achieving local migmatization (T_{max} – 700 750 °C; P_{lit} – 0.5 1 kbar; Casquet 1980), superimposed on regional Variscan metamorphism of lower greenschist facies.

The Santa Olalla Main Pluton shows normal zoning from granodiorites and monzogranites in the core to tonalites and quartzdiorites at the rim. Magmatic foliation, where present, is usually subhorizontal. The Aguablanca Stock represents an intrusion with more mafic mineral composition. It is formed dominantly of medium to coarse grained amphibole biotite (quartz) diorites with steep magmatic foliations (Dioritic Unit). At its northern edge, between the diorites and the host rocks, there is a 10 to 400 m thick sheet of coarse grained pyroxenitic gabbros (~65%), gabbronorites (~30%) and norites (~5%; Gabbroic Unit). Skarns are abundant in the carbonate country rocks (Casquet 1980). Only traces of sulfides have been reported in these skarns.

The Santa de Olalla Plutonic Complex is one of several zoned synorogenic Variscan intrusions which occur in the central area of the Ossa Morena Zone, forming a NW SE trend (Quesada et al. 1987; Sánchez Carretero et al. 1990). The entire suite consists of I type magnetite bearing plutonic rocks dominated by biotite amphibole diorites but ranging in composition from gabbros to granites. Magmatic cumulates are common in the internal zones of some intrusions, usually as olivine rich gabbros to dunites (Pons 1982; García Casquero 1995). Geochemically, the suite is defined by a high K_2O calc alkaline trend (Casquet 1980; Pons 1982; Sánchez Carretero et al. 1990). The geochemistry of the SOP Complex and the influence of crustal contamination has been reviewed elsewhere (Casquet et al. 1998; Tornos et al. 1999). Rb/Sr dating of the Santa Olalla Plutonic Complex gave an errorchrone of 359 ± 18 Ma with a high MSWD (17.1), probably caused by the widespread hydrothermal alteration and concomitant alteration of original Rb/Sr values. The more likely age of intrusion is probably similar to that of the equivalent and nearby Burguillos Pluton (338 ± 1.5 Ma; U Pb in allanite; Casquet et al. 1998).

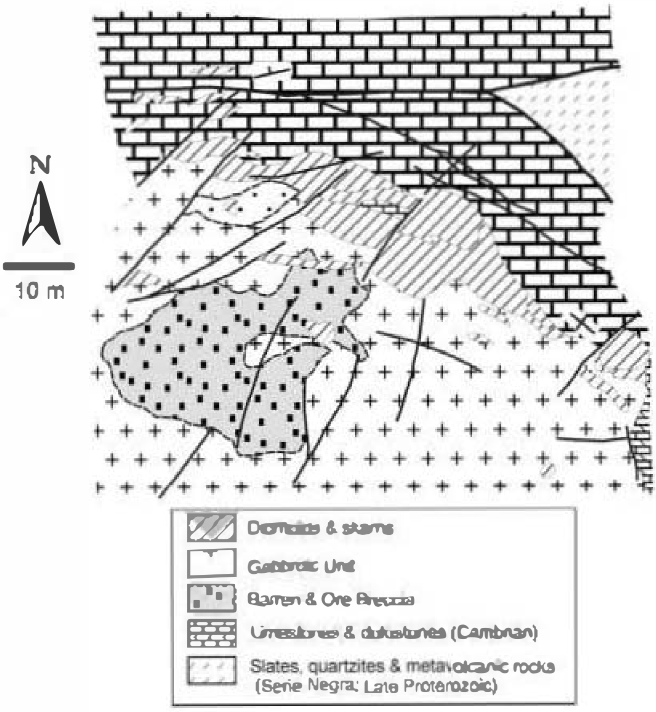

Fig. 2 Geological map of the Aguablanca orebody

The orebody

In the NE part of the Aguablanca Stock, there is a subvertical breccia body with a pipe like morphology (Fig. 2) which has been traced down to a depth of c. 700 m. The breccia is complex, chaotic and highly heterolithic. It contains variably sized (several mm to 4 m across), ellipsoidal fragments of fine grained orthopyroxenites, websterites, clinopyroxenites and some medium grained gabbros and gabbronorites, all showing cumulate textures. Olivine bearing rocks are very scarce. The main minerals are orthopyroxene (En_{76-87}), clinopyroxene (diopside salite to augite) and plagioclase. The orthopyroxenites contain some inclusions of olivine (Fo_{86-88}) rich cumulates. Mg rich phlogopite and clinoamphibole occur as intercumulus phases. All these minerals, including olivine, have low Ni contents (< 500 ppm Ni). A common accessory phase is xenolithic Cr and Ni poor Fe spinel, which occurs in clusters within plagioclase. The breccia also includes some fragments of skarn, hornfels and marble.

On the basis of the composition of the matrix, two different types of breccias can be distinguished, the Ore Breccia and Barren Breccia. The Ore Breccia has the fragments enclosed in an undeformed sulfide rich matrix. Enclosed in this breccia there are irregular, meter sized ellipsoidal massive sulfide bodies which contain only some sporadic fragments of silicate rocks. Massive sulfides in the Ore Breccia host abundant, randomly oriented crystals (1 3 mm in size) of bronzite (En_{74-87}) and diopside augite, which coalesce to form aggregates of coarse grained pyroxenites with intercumulus sulfides. The contact between the sulfides and the fragments is always sharp, the fragments showing neither interstitial sulfides nor reaction rims (Fig. 3).

The matrix of Barren Breccia is composed of coarse grained rocks similar to those of the Gabbroic Unit and containing only disseminated sulfides (1 5 vol%). The contact between the two breccias is sharp and the Barren Breccia grades outwards over a short distance into the massive Gabbroic Unit which contains only minor ultramafic fragments and disseminated sulfides. The disseminated sulfides in the Barren Breccia and the Gabbroic Unit form a halo of weak mineralization which extends for ~100 m away from the Ore Breccia. Maximum Cu + Ni grades (2.4% Cu, 5.4% Ni) are found in the core of the breccia pipe, but no systematic lateral nor vertical variation in the Cu/Ni ratio (average Ni/(Ni + Cu) – 0.6) has been found within the orebody.

Sulfides consist of early pyrrhotite intergrown with pentlandite and later chalcopyrite with minor cubanite and magnetite. There is a superimposed paragenesis with coarse grained pentlandite, chalcopyrite and pyrrhotite along with some cobaltite and graphite, in a sequence similar
and Naldrett (1997).

All the rocks of the Aguablanca Stock underwent subsolidus hydrothermal alteration. In general, the mafic rocks are more altered than the ultramafic rocks. Mafic minerals are replaced by clinoamphiboles of variable composition (actinolite, Mg hornblende and edenite pargasite), biotite phlogopite and lesser clinozoisite. Plagioclase is replaced by sericite. A second stage of hydrothermal alteration is characterized by the presence of talc, clinochlore ripidolite, calcite, illite and clay minerals. Peridotitic enclaves are replaced by serpentine, vermiculite and magnetite. K Ar dating suggests that hydrothermal alteration took place between 325 and 307 Ma (Casquet et al. 1998), well after the end of the magmatic activity.

The sulfides recrystallized during hydrothermal alteration, forming veins and masses which replace the surrounding rocks. The secondary sulfides are pyrrhotite, chalcopyrite, pentlandite and pyrite with mackinawite and bravoite, with minor Ag Bi Pd tellurides and other complex minerals of the platinum group (see Lunar et al. 1997; Ortega et al. 1999).

A remarkable feature of the mineralized area is the conspicuous subvertical NE SW (N40 55°E) orientation of layering in the gabbros and of the fragments within the breccia, subparallel to some of the faults of the area (Fig. 2). The zones of major hydrothermal alteration seem also to be controlled by these faults.

Geometry of the intrusions and structural control

Because the Santa Olalla Plutonic Complex is truncated in the southeast by the important regional Zufre Fault, its original overall geometry remains unknown. Igneous foliations in the Santa Olalla Main Pluton dip gently inwards (usually between 0 and 20°). The resulting concentric pattern inferred from foliation trajectories suggests a funnel shaped geometry, with a feeder zone to the southwest of the exposed part of the intrusion. The presence of many flat lying roof pendants visible in the area, and the horizontal attitude of most of the upper contact along the edge of the pluton indicate that the top of the pluton was almost horizontal. However, the structure of the Aguablanca Stock is different. Faint layering visible in the gabbros is very steep. The attitude of the contact turns from almost subvertical into gently outward along the northwest exposure of the pluton. Thus, a bell jar geometry with a subvertical feeding dyke seems more plausible, although the restricted number of outcrops makes it difficult to obtain a precise image of the intrusion. Geochemical continuity between the rocks of the Aguablanca Stock and those of the Santa Olalla Main Pluton suggests that the corresponding magmas were derived from a common magma chamber at depth (Casquet et al. 1998).

The intrusive rocks of the area seem to have a major structural control. Both the Aguablanca Stock and the magmatic breccia have a shape and orientation consistent with their formation along subvertical extensional zones associated with left lateral shearing (Fig. 1). Other local structural indicators, such as (1) the rotated cleavage around the pluton, and (2) the presence of antithetic (dextral) NW SE strike slip faults with a bookshelf geometry in the eastern part of the pluton confirm such a model. Both pull apart structures and releasing bands related with the curvature of the Cherneca Fault appear to have allowed the magmas to intrude at shallow crustal levels.

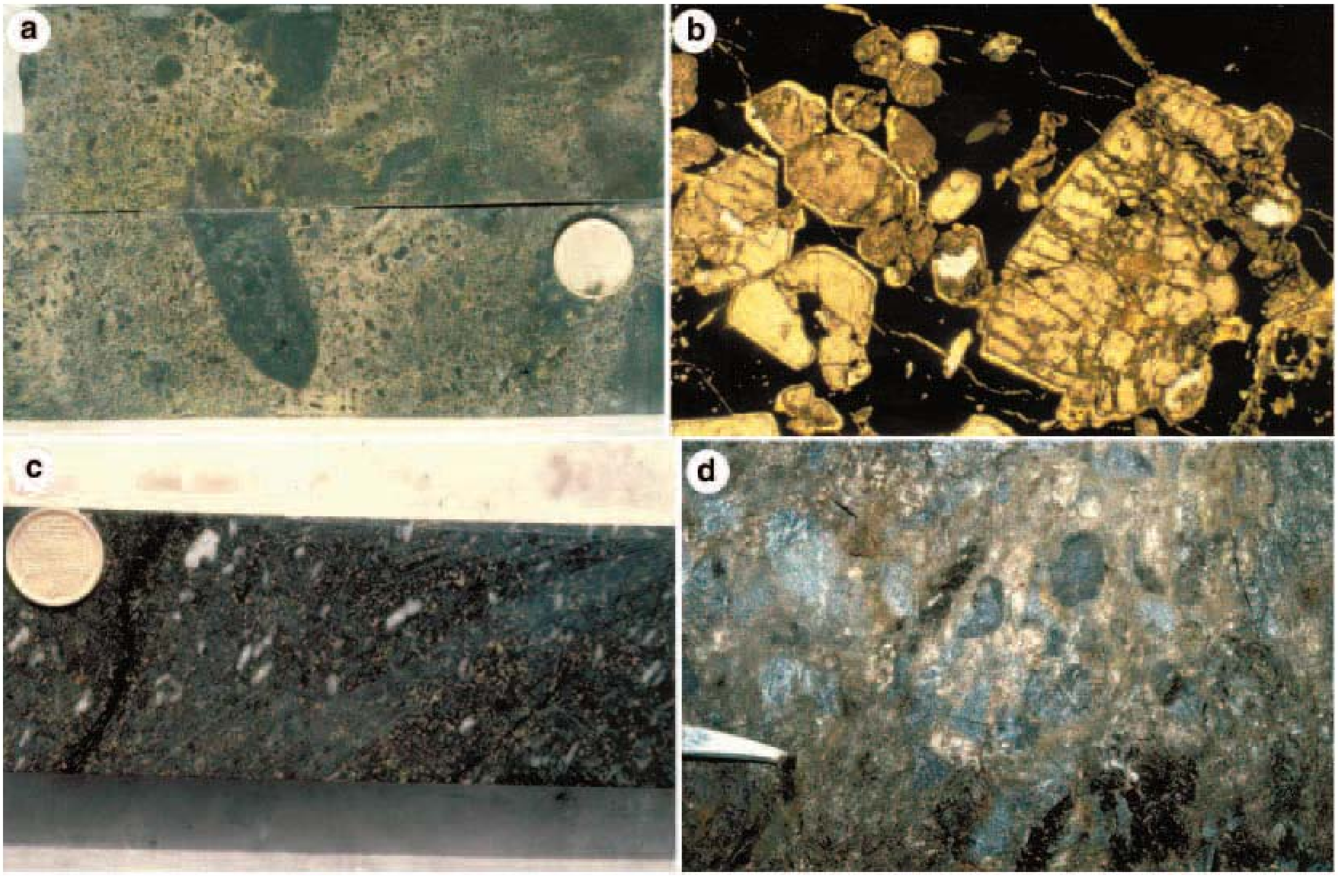

Fig. 3a d Textures of the mineralized samples. a Semi massive ore in the ore breccia including fragments of fine grained pyroxenites and large isolated crystals of pyroxenes with equivalent composition. b Intercumulus sulfides supporting large isolated and unoriented crystals of ortho and clinopyroxene. The pyroxenes contain inclusions of biotite phlogopite and a rim of clinoamphiboles due to late retrograde alteration. Field of view: 2.5 mm. c Gabbronorite of the Gabbroic Unit hosting disseminated mineralization. d Breccia Ore, including fragments of fine grained and barren pyroxenites supported by massive sulfides

Regional studies have shown that the Ossa Morena Zone experienced an important episodic left lateral displacement during the Variscan Orogeny. Most of the displacement took place along the old Cadomian suture (Badajoz Cordoba Shear Zone) but Quesada et al. (1987) and Roberta et al. (1991) have shown that significant displacement occurred along other WNW ESE structures. In this context, the Cherneca Fault probably acted as a second order, deep left lateral shear zone, favoring the formation of extensional structures and concomitant intrusion of igneous rocks.

Genesis of the mineralized breccia

The association of the mineralization with zoned pipe like discordant breccia bodies makes the Aguablanca orebody rather similar to the Voisey's Bay deposit (Li et al. 2000). It could well represent a feeder conduit of an overlying pluton which now has eroded away. However, the geologic position and the dominance of cumulate pyroxene rich fragments in the breccia may indicate that the position of the pipe is different

posed magmatic stratiform complex. Layers of pyroxenite and minor peridotite, gabbro and norite, interbedded with one or more stratiform bodies of massive sulfides, were the source of the fragments now seen in the breccias.

Different mechanisms can explain the rupture of the stratiform magmatic chamber and formation of the breccia pipe. Simple opening of a zone of weakness related to a tensile fracture within the chamber could produce enough lateral overpressure to inject the sulfide magma into the open space. Alternative, equally valid models include tectonic squeezing or seismic pumping.

Most of the rocks in the stratiform complex had already crystallized when they were incorporated in the breccia. However, the sulfides do not show any evidence of subsolidus deformation, indicating that their emplacement was in a plastic state, most probably as large immiscible blebs in the host gabbros. The related coarse grained pyroxene crystals could be interpreted as megacrysts trapped at depth by the molten sulfides (Arndt, personal communication). The temperature of injection of the breccia is consistent with that of the intrusion of the host Gabbroic Unit and the high grade contact metamorphism. The consolidation of the breccia probably took place at temperatures above the mss solidus (near 1,000 °C) but below the ortho and clinopyroxene solidus (about 1,200 1,400 °C).

In the Santa Olalla Plutonic Complex, the Sr and Nd isotopic compositions suggest an evolution which can be modeled by a combination of fraction

cesses (Casquet et al. 1998). The major geochemical difference between the Aguablanca Stock and equival t Variscan intrusions in the Ossa Morena Zone is the high $^{87}Sr/^{86}Sr_i$ and low $^{143}Nd/^{144}Nd_i$ of the mafic rocks in the Aguablanca Stock, which have $^{87}Sr/^{86}Sr_i$ and $^{143}Nd/^{144}Nd_i$ values which plot between those of the unmineralized Variscan plutons of the area and the host metasedimentary rocks (Casquet et al. 1998; Tornos et al. 1999). These compositions suggest that the magma assimilated sediments broadly equivalent to those hosting the Aguablanca Stock (Fig. 4). Mixing with upper crustal rocks is also evident in the isotopic compositions of sulfur

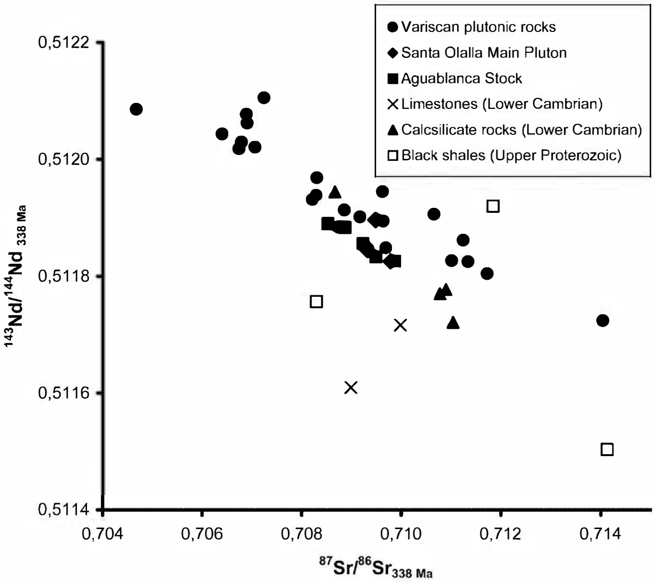

Fig. 4 $^{143}Nd/^{144}Nd$ vs $^{87}Sr/^{86}Sr$ ratios at 338 Ma for igneous rocks of the Ossa Morena Zone and host Upper Proterozoic Lower Cambrian sediments and volcanic rocks. The data from the Aguablanca Stock and Santa Olalla Main Pluton plot between those of uncontaminated plutons and the host rocks (modified from Tornos et al. 1999, with data from Casquet et al. 1998)

and lead. The $\delta^{34}S$ values of the sulfides (7.4 ± 0.4‰; $n = 19$) are intermediate between those of juvenile sulfur and those of the Upper Proterozoic siliciclastic sediments (7 21‰; Tornos and Velasco, unpublished data). The lead isotope signatures of the ore ($^{206}Pb/^{204}Pb = 18.27$ 18.43; $^{207}Pb/^{204}Pb = 15.61$ 15.65) are similar to those of the host rocks and also typical of rocks from orogenic settings with lead derived from the host rocks (Tornos et al. 1998). Additional evidence for upper crustal contamination includes the high orthopyroxene/olivine ratio of the igneous rocks, the presence of enclaves of sedimentary rocks in the Aguablanca Stock, and the abundance of spinel in the gabbros.

The commonly accepted mechanism of formation of magmatic Ni Cu mineralisation is the incorporation of external sulfur from the host rocks via magmatic assimilation or metamorphic sulfur devolatilization (Naldrett 1999; Ripley et al. 1999). Extensive interaction with the underlying pyritic black slates of the Serie Negra was probably the critical mechanism promoting sulfide immiscibility. These rocks have locally significant copper and gold contents (Locutura et al. 1990), and their assimilation may have been responsible of the relatively high gold contents of the ore ($Au/Au_{chondrite} = 5.6$) and the presence of graphite in the late magmatic assemblages. We propose that the enrichment of silica, sulfur and alkalis associated with the assimilation of sediments resulted in the generation of an immiscible sulfide liquid and a silica rich, chalcophile element depleted magma which afterwards crystallized to form pyroxenites at the bottom of the magmatic chamber and feeder zones. Assimilation of large quantities of slates would have increased the iron and sulfur contents of the igneous rock, producing the observed low (chalcopyrite + pentlandite)/pyrrhotite ratios (0.1 0.2) in the ore. Naldrett (1999) has emphasized the importance of feeder zones for contamination. This author pointed out that in a conduit, the relative proportion of exposed wall rock is higher than in a magma chamber, and suggested that this leads to enhanced partial melting and assimilation of crustal rocks. The moderately high Cu/(Cu + Ni) ratio of the ore (0.40) indicates that the parental magma was relatively evolved (MgO close to 7%) when compared with other mafic rocks which host Ni Cu sulfide deposits (Scoates and Mitchell 2000).

Local derivation of sulfur during skarn formation seems very unlikely. The skarns are always separated from the mineralization by barren igneous rocks. The gabbros cut across the metasomatic zoning, suggesting that the skarns formed before the magmatic mineralization. Furthermore, where the mafic rocks show a high degree of interaction with the host carbonates, the resulting rocks (endoskarns and Ca rich gabbros) are always barren (Casquet 1980; Tornos et al. 1999).

Conclusions

The Aguablanca ore deposit probably represents a type of igneous rock hosted Ni Cu mineralization not described to date, related to a polyphase and syntectonic magmatic activity which led to the formation of discordant breccia pipes. Important aspects of this deposit include the extensive crustal contamination, the strong structural control, and the evolution in a dynamic magmatic setting. The geotectonic position, in an active continental margin and associated with potassic calc alkaline magmatic rocks, is also unusual.

The mineralization is thought to be directly related to the Variscan transpressional tectonics in SW Iberia. In this context, extensional zones related to large and deep strike slip faults favored the episodic intrusion of primitive mafic mantle derived magmas into the upper crust. The geological and structural relationships suggest a complex two stage magmatic evolution. The first stage involved extensive assimilation of pyritic black slates in a conduit system connected with a mid crustal magma chamber. Crustal contamination resulted in the segregation of immiscible sulfides from the resulting hybrid magma. This contamination was crucial in the genesis of the deposit, as it inhibited the formation of olivine at the very early stages. The magma then rose and ponded in an overlying magma chamber. Fractional crystallization generated a stratiform magmatic complex containing mafic and ultramafic cumulates and interbedded massive sulfides, a classical magmatic Ni Cu deposit (Fig. 5).

A second tectonic event then injected the residual melts and partially consolidated cumulates high into the crust. Partially crystallized cumulates were broken up and were forcibly injected to epizonal levels, a process probably favored by the presence of the molten sulfides. Sulfides reached the emplacement level as the matrix of the breccia but also as large massive blebs.

The Aguablanca deposit formed in a calc alkaline intrusion located in a transtensional structure within a Variscan magmatic arc. Transpressional transtensional settings are now interpreted as being of major interest and are thought to control the location of a wide variety of mineral deposits, including mesothermal gold veins, epithermal gold, volcanic and shale hosted massive sulfides, and porphyry copper districts. However, there is no previous evidence that they were implicated in the formation of magmatic Ni Cu mineralization. Ni Cu ores related to synorogenic plutonism are rare and only a few examples have been described previously (e.g., Vakkerlien, Thompson et al. 1980; Moxie Pluton, Thompson 1984).

The geologic setting of the Aguablanca deposit indicates that magmatic Ni Cu deposits are not solely restricted to basaltic flows, stratiform complexes or anorthositic belts. They can also form within the more mafic rocks in active continental margin settings, the only major prerequisites for ore formation being the relationship with major crustal faults and the existence of strong crustal contamination. If this model holds true, it can help exploration for other unpredicted breccia pipes and underlying stratiform complexes in the Ossa Morena Zone or similar terranes. The conditions which led to the formation of the Aguablanca deposit should not be unique, and deposits of similar style may be more common than is currently recognized.

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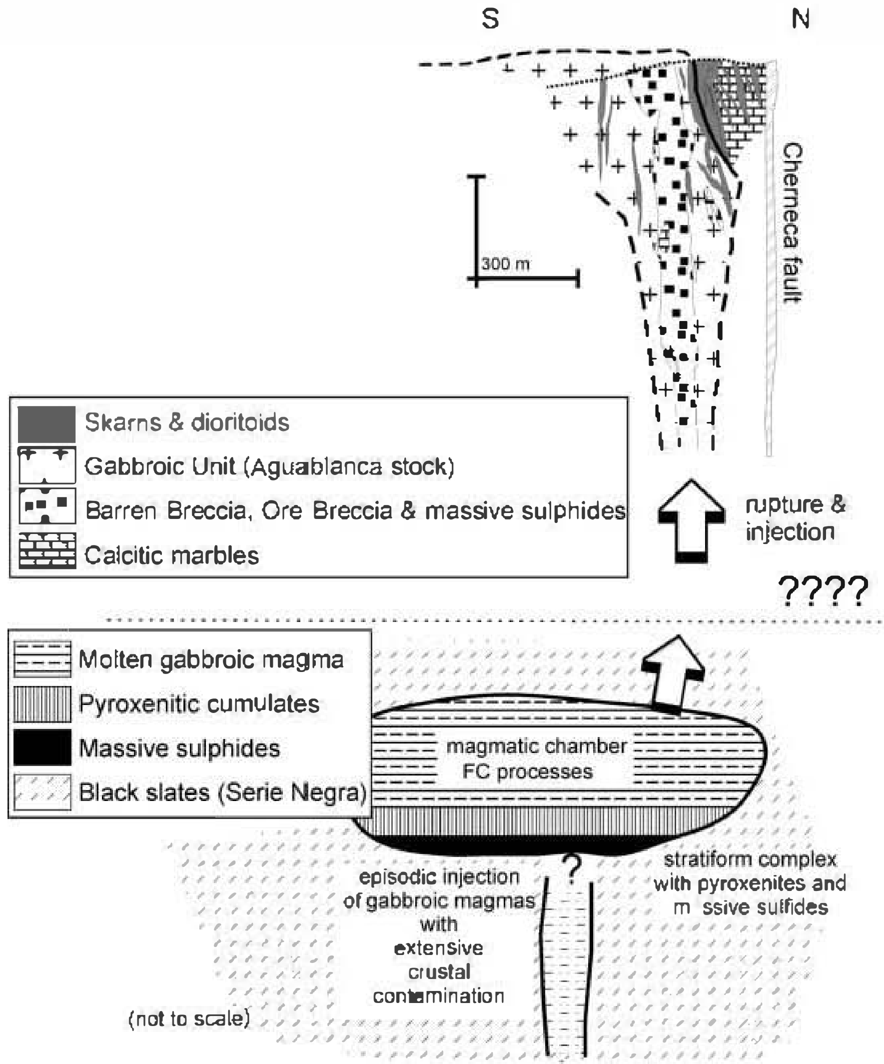
Fig. 5 Conceptual geological model for the genesis of the Aguablanca orebody with a two stage ore forming process. *FC* Fractional crystallization



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