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MINERALOGY AND SULFIDE MINERAL CHEMISTRY OF THE NEVES–CORVO ORES, PORTUGAL: INSIGHT INTO THEIR GENESIS

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ABSTRACT

Like almost every deposit in the Iberian Pyrite Belt, the Neves–Corvo deposit, in Portugal, has its own mineralogical characteristics. This is especially true for the large variety of mineral associations containing copper and tin that have been observed in the three orebodies exploited so far. Associated with the copper-rich massive lenses, unusual sphalerite + tetrahedrite–tennantite and bornite-rich discrete ore horizons have been found. Both types of ore show mineral associations similar to those described for the "tetrahedrite front" and the "bornite zone" in the Kidd Creek deposit of Ontario. The Neves–Corvo deposit is, also, the only one so far in the Portuguese sector of Iberian Pyrite Belt in which a large variety of Cu, As, Sn, Co, Bi, Te (Se) and Ag sulfosalts has been observed in stringer ores. Cassiterite occurs as large meter-sized discrete massive lenses cross-cut by chalcopyrite veins, centimetric lenses in the *rubané* ores, stringers ores at the base of massive sulfides, and centimetric clasts of cassiterite in the middle of the tin-bearing copper-rich massive sulfides. In the copper-rich and polymetallic massive ores with low contents of tin, cassiterite mainly occurs as clusters formed by fine-grained cassiterite intergrown with sphalerite and phyllosilicates. The geotectonic complexity and the scarcity of the existing geological data on the structural features of the deposit have so far not allowed the paleogeographic reconstruction of the environment of formation. However, on the basis of both the stratigraphy of the different types of ore and the textural and compositional features of the sulfides, the Sn and Cu enrichments exhibited by the polymetallic massive ores from Neves–Corvo deposit are a result of multiple metallogenetic events that took place at different times, under different thermochemical constraints. Hence the ores are ascribed to the following events: 1) deposition of the tin-rich ores, 2) protracted formation of the polymetallic massive sulfide ores, which constitute about 86% of the total Neves– Corvo resources, and 3) late anomalous Cu-enrichment, confined to discrete zones of the polymetallic massive sulfides and to zones of interaction, leading to ore enriched in bornite and in sphalerite – tetrahedrite–tennantite.

Keywords: ore petrology, mineral chemistry, sulfides, ore genesis, Neves–Corvo, VHMS deposit, Iberian Pyrite Belt, Portugal.

SOMMAIRE

Comme pour presque tous les gisements de la Ceinture Pyriteuse Ibérique, le gisement de Neves –Corvo, au Portugal, possède des traits minéralogiques qui lui sont propres. En particulier, il faut signaler la grande diversité d'associations de minéraux contenant du cuivre et de l'étain dans les trois zones minéralisées exploitées jusqu'à maintenant. Associés aux lentilles massives cuprifères, on trouve des horizons minéralisés inhabituels à sphalérite + tétraédrite–tennantite et à bornite. Les deux types de minerai possèdent des associations de minéraux semblables à celles du "front de tétraédrite" et de la "zone à bornite" à Kidd Creek, en Ontario. Le gisement de Neves–Corvo, de plus, est le seul du secteur portuguais de la Ceinture de Pyrite Ibérique à montrer une si grande variété de sulfosels à Cu, As, Sn, Co, Bi, Te (Se) et Ag dans le minerai en filaments (stringer). La cassitérite se présente en lentilles massives de dimensions métriques, recoupées par des veines de chalcopyrite, en lentilles centimétriques dans le minerai rubané, en minerai filamenteux à la base des zones de sulfures massifs, et sous forme de fragments centimétriques au sein d'amas de sulfures massifs riches en cuivre et porteurs d'étain. Dans les minerais polymétalliques riches en cuivre ayant de faibles teneurs en étain, la cassitérite se trouve surtout en groupements de grains fins en intercroissance avec la sphalérite et les phyllosilicates. La complexité géotectonique et la rareté des données géologiques à propos du contexte structural du gisement n'ont pas permis jusqu'à maintenant d'en reconstruire la paléogéographie du milieu de formation. Toutefois, à la lumière de la stratigraphie des différents types de minerai, des textures et des compositions des divers minéraux sulfurés, il semble évident que les enrichissements en étain et en cuivre subis par les minerais massifs polymétalliques à Neves–Corvo résulteraient d'événements métallogéniques multiples mais distincts. Ces événements auraient impliqué 1) la déposition de minerais riches en étain, 2) une longue période de formation du minerai sulfuré polymétallique massif, qui constitue environ 86% du minerai à Neves–Corvo, et 3) un enrichissement en Cu tardif le long de zones spécifiques dans le minerai polymétallique massif et aussi dans les zones d'interaction à bornite et à sphalérite + tétraédrite – tennantite.

(Traduit par la Rédaction)

Mots-clés: pétrologie di minerai, composition des minéraux, sulfures, genèse des minerais, Neves–Corvo, gisement de sulfures massifs dans un hôte volcanique, Ceinture Pyriteuse Ibérique, Portugal.

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INTRODUCTION

Mineralogical studies of the ores from Neves–Corvo, Portugal, took place in two main phases. From 1979 to 1988, at the time of the technical feasibility and evaluation studies of the Corvo and Graça orebodies, ore microscopy studies were made to define the mineral assemblages and textures of the various types of ore. The second phase began in 1988, at the time ore production started. They aimed to provide the know-how needed both in the optimization of ore-dressing processes and the feasibility of recovering precious and high-tech metals. The semiquantitative mineralogical methods were first used to optimize the concentration processes of the massive sulfide ores of the Aljustrel deposit, also in the Iberian Pyrite Belt (Gaspar 1984); they were further developed for the processing of the Neves–Corvo ores (Gaspar 1994, 1995, 1997, Gaspar & Pinto 1991, 1993). The chemical laboratory at the mine also provided the bulk composition of thousands of ore samples from drill cores and mine stopes.

Over the last twenty years, a large amount of information both on ore mineralogy and chemical composition of the sulfides from Neves–Corvo was produced, and a significant part of the ore-microscopy results have already been published (Gaspar 1991, 1996, Gaspar & Pinto 1991, 1993, Gaspar *et al.* 1998, Pinto *et al.* 1994, 1997, Ferreira *et al.* 1997). Most of the data on the composition of sulfides published here were obtained between 1992 and 1995 in the context of a joint Brite–EuRam II project on "New Integrated Flowsheets for Separation and Recovery of Minor Elements from Sulphides" funded by the European Union. John F.W. Bowles used a Cambridge Microscan 9 electron microprobe to perform most of the analyses during the progress of the two phases of the mineralogical studies (Mineral Sciences Ltd., Chesham, U. K., unpubl. reports). Alvaro Pinto and John F.W. Bowles used a CAMECA 55 electron microprobe at the Laboratório do Instituto Geológico e Mineiro (IGM, Porto) to characterize minerals in peculiar associations that occur in the bornite-rich massive cupriferous ores (Pinto *et al.* 1994; IGM, Mineral Sciences and SOMINCOR, unpubl. reports). Philippe Marion and Benzaazoua Mostafa of the Laboratoire Environnement et Minéralurgie (LEM–GESD, ENSG, Nancy, France) have also provided analytical data, obtained with a CAMECA SX–50 electron microprobe and with an ion microprobe (SIMS Dynamique) at the Laboratoire d'Analyse des Matériaux, Centre Universitaire, Luxembourg (Mostafa 1995; LEM, unpubl. reports).

Although most the compositional data have been obtained on sulfide samples studied by ore microscopy, they were obtained at different times, by different researchers, and at different laboratories. This fact made it impossible to achieve the desired integration of the data obtained by both studies in the timetable imposed for the accomplishment of the EurRam Project. Although the technological definition of ore types established by the SOMINCOR geologists at the mine could be used as a tool in the interpretation of the sulfide stratigraphy within each orebody, difficulties arise whenever a comparison with ore types from VMS deposits in the Iberian Pyrite Belt and elsewhere is attempted.

In the present work, an attempt is made: 1) to achieve a mineralogical characterization of the ore types as defined by the geologists at the mine through a exhaustive review of all published and unpublished mineralogical data, 2) for each generation of a given sulfide, to define the allocation of the trace elements, taking into account the type of ore in which the sulfide occurs, and thus 3) to contribute to a better understanding of the genesis of the Neves–Corvo ores through a comparison with the mineralogy and mineral chemistry data from other VMS deposits, mainly those in the Iberian Pyrite Belt (IPB) and at Kidd Creek, Ontario.

THE NEVES–CORVO DEPOSIT

Neves–Corvo is the only volcanogenic massive sulfide deposit in the IPB currently in operation in Portugal. The deposit, discovered in 1977 (Leca 1990, Leca *et al.* 1983, 1985, Carvalho 1991, Gomes 1991), consists of five polymetallic orebodies that in places show unusually high copper and tin contents. The orebodies occur at the top either of felsic volcanic rocks or black shales, on both flanks of an open southwest-plunging asymmetrical anticline (Oliveira *et al.* 1997). Recent data (Carvalho *et al.* 1997, Pinto 1999) indicate that the deposit contains in excess 270 million tonnes of massive sulfides, and estimated total resources for the orebodies are 42 Mt of copper ores at 7.6% Cu (including 4.3 Mt of tin ores at 2.7% Sn), 47 Mt of zinc ores at 6.2% Zn, 1.9 Mt of tin ores at 2.67% of Sn, and 180 Mt of pyritic ores at 0.5% Cu and 0.2% Zn. The latest assessments of the Lombador and Zambujal orebodies indicate that the total resources will increase in future, and will exceed 300 Mt of ore.

Although all the orebodies contain significant Zn, so far the deposit has been exploited only for copper and tin ores, from the Neves Norte, Corvo and Graça orebodies. The mine is currently the largest producer of these metals in Europe, with 1,092 Mt tonnes Cu and 26,200 tonnes Sn produced from 1988 to 1997 (Real & Carvalho 1997).

Like almost every deposit in the IPB, Neves–Corvo has its own mineralogical characteristics. This is especially true for the large variety of both copper and tin minerals in the three orebodies that have been exploited. Associated with discrete copper-rich massive lenses, unusual sphalerite + tetrahedrite–tennantite + stannite–kësterite ore horizons showing high contents of Zn, As, Sb, Sn, Ag and Hg have been found, mainly at Graça and, more sparsely, at Corvo. The deposit is, so far, the only one in the Portuguese sector of IPB where a large variety of Cu, As, Sn, Co, Bi, Te (Se) and Ag sulfosalts, along with Au, has been observed in stringer ores similar to the ones found by Marcoux & Leistel (1996) and Marcoux *et al.* (1996) in the Spanish sector. For the first time in the IPB, a large zone enriched in bornite, along with Cu–Sn, Bi, In, Se, Ag sulfides and gold, was also found in 1993 in the Neves Norte orebody (Pinto *et al.* 1994).

The large contents of tin, mainly observed in the Corvo and Graça orebodies, reflects the occurrence of a complex suite of mineral associations formed by cassiterite and tin sulfides. Cassiterite occurs as large meter-sized discrete massive lenses cross-cut by chalcopyrite veins, as centimetric lenses in the *rubané* ores, in stringers ores at the base of massive sulfides, and as centimetric clasts of cassiterite in the middle of the tin-bearing copper-rich massive sulfides. In the Cu-rich massive ores with contents of tin less than 1%, cassiterite mainly occurs as clusters formed by fine-grained cassiterite (mostly <150 μm) intergrown with sphalerite and phyllosilicates. In such ore, stannite and kësterite are the most widespread tin sulfides, occurring as a replacement both of cassiterite and sphalerite.

The generally vertically stacked lenses of massive Cu-rich ores have copper contents, mineralogical associations and textures that do not conform to those observed in Cu enrichments solely due to the so-called metal zone-refining process.

THE GEOLOGICAL CONTEXT

The Iberian Pyrite Belt, a major geotectonic unit of the Iberian segment of the Hercynian fold belt, extends in an approximately E–W-trending arc through southern Portugal and Spain for about 230 km, over a width ranging from 35 to 50 km. The IPB corresponds to an area of Devonian–Carboniferous volcanic and sedimentary rocks containing a large number of volcanic-rock-hosted massive sulfides (VHMS) that have been mined since the transition from Neolithic to Chalcolithic times (Rothenberg & Blanco-Freijeiro 1982, Gaspar 1996). The volcanic rocks of the IPB are a heterogeneous assemblage of felsic to mafic volcanic and volcaniclastic rocks, mainly rhyodacite and basaltic pillow lavas, with lesser volumes of andesitic rocks (Schermerhorn 1975b, Routhier *et al*. 1980, Leistel *et al.* 1994, Mitjavilla *et al.* 1991, Carvalho *et al.* 1999). Regional metamorphic grade in the IPB in general increases from zeolite facies in the south through prehnite-pumpellyite to greenschist facies in the north (Schermerhorn 1975a, Munhá 1983, 1990).

The tectonic setting of the IPB has been a matter of great controversy, and several models have been proposed: an accretionary prism related to a north- or northeast-dipping zone of subduction located southwest of the South Portuguese Zone (Carvalho 1972, Bard *et al.* 1973, Thiéblemont *et al.* 1994, Carvalho *et al.* 1999), an intracontinental back-ark basin (Munhá 1983, Ribeiro & Silva 1983), or a zone of northeastward subduction starting in the Late Devonian followed by oblique continental collision during Famenian to Middle Westphalian times (Ribeiro *et al.* 1990, Quesada 1991, Silva *et al.* 1990, Dias & Ribeiro 1995, Mitjavilla *et al.* 1991). Palynological dating of hanging-wall rocks indicates a Strunian age (*i.e.*, latest Devonian, transitional to Carboniferous) for the Neves–Corvo deposit (Pereira *et al.* 1996).

DESCRIPTION OF THE OREBODIES

Mineralization at Neves–Corvo led to five lens-shaped bodies of massive sulfides, namely Neves, Corvo, Graça, Lombador and Zambujal (Fig. 1). Recent assessments of reserves indicate that the orebodies are not linked only by thin strips of mineralized rocks, as formerly assumed. Actually, the orebodies form an almost continuous complex volume of mineralized rock showing a large spectrum in both style of mineralization and geological structure (A. Ferreira, pers. commun., 2001). The orebodies are distributed on both flanks of an open, asymmetrical anticline that plunges to the southeast; they are located at depths of 230 to about 1000 m below surface. As a result of the Hercynian orogeny, the five orebodies are now composed of block-faulted compartments that are mostly formed of replicates of vertically stacked lenses. Disruption and tectonic deformation of both the ore lenses and stockworks have been observed. All these facts render rather difficult a reconstruction of the original paleogeography of the deposit.

The Corvo orebody measures 1100 by 600 m, with a maximum thickness of 95 m. It is located on the northeastern flank of the anticline, with a NE–SW elongation, and it dips 25 to 30° to the northeast. The depth below the surface varies from 230 to 1100 m along dip. Vertically stacked lenses of massive cupriferous ores having a lens of barren pyrite at the top mainly make up the orebody. In 1986, during extensive underground drilling and underground mapping aimed at an evaluation of copper ore reserves, large massive lenses of cassiterite were found at the northern end of a corridor along a N–S lineament. The assay data also show that the Cu, Sn and Zn contents successively decrease from the first basal cupriferous ores to the lens located at the top. The Corvo orebody is also characterized by a horizon (the *rubané* unit) located at the top of the massive sulfides, consisting of chloritic shales, interbedded with sulfides, cassiterite, jasper and carbonates. Most of the polymetallic (Cu, Zn) massive sulfide ores that have high Zn contents have been developed laterally at the southern end of the orebody, with the exception of small lenses that occur interspersed with barren pyrite at the top of cupriferous ore. At the base of Corvo, massive cassiterite and stringer ores with a distinct style of mineralization have also been observed (Figs. 2, 3).

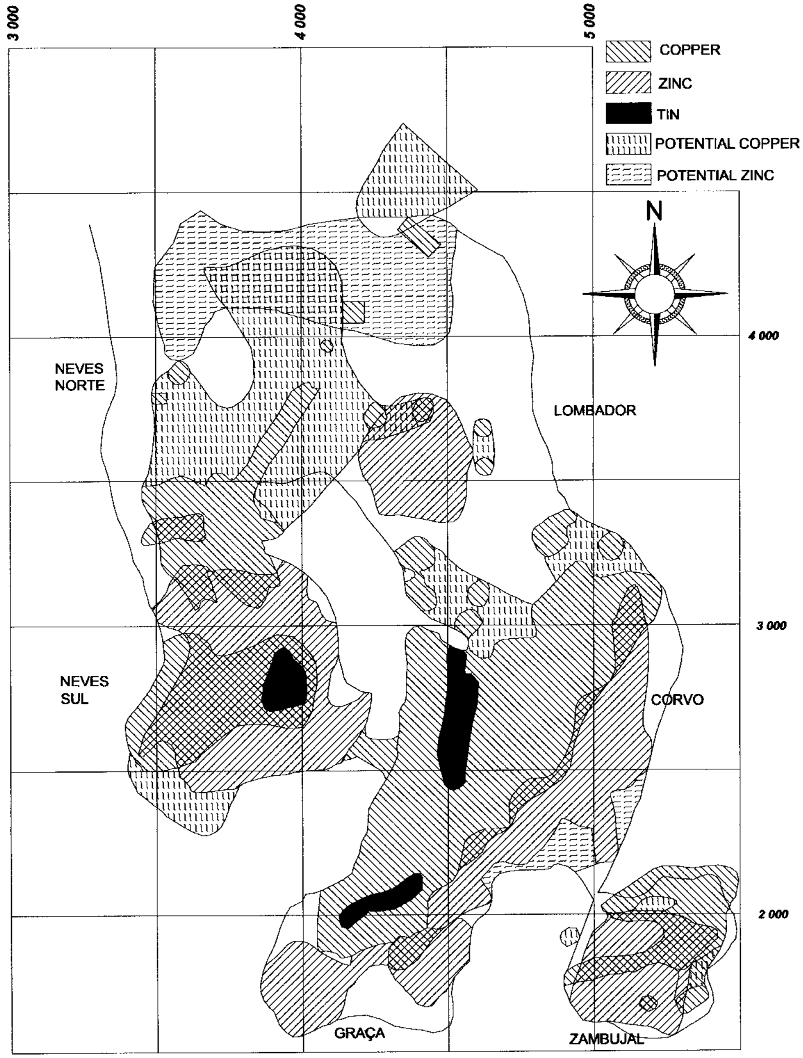

FIG. 1. Plan of the Neves–Corvo mine lease-area showing the distribution of copper, tin and zinc ores in the five orebodies that form the deposit. Source: SOMINCOR, Geological Department (2001).

The Graça orebody is located on the S–SW flank of the main anticline, and dips 70° in the upper part, becoming subhorizontal at depth. The massive sulfides extend over a length of 700 by 500 m in width, with a maximum thickness of 80 m, at depths of 250 to 425 m below the surface. As at Corvo, three vertically stacked lenses formed by cupriferous ores with massive pyrite at their top have been observed at Graça. The lenses of massive pyrite with low Cu and Zn contents constitute about 90% of the ore. The three lenses have a decreasing Cu content from the base to the top of the orebody (Fig. 4). Cassiterite is present only as fine disseminations in the massive cupriferous sulfides, and its distribution seems confined to a corridor that shows the same strike as the occurrence of cassiterite in the Corvo orebody. Significant lenses of polymetallic massive sulfide have been developed laterally to the southwest of the massive cupriferous ores, on strike with the polymetallic massive sulfides at Corvo. The cupriferous massive sulfide ore of Graça has the highest average Cu grade of all the orebodies (Fig. 5). Assays show that in some places, the cupriferous massive ore also

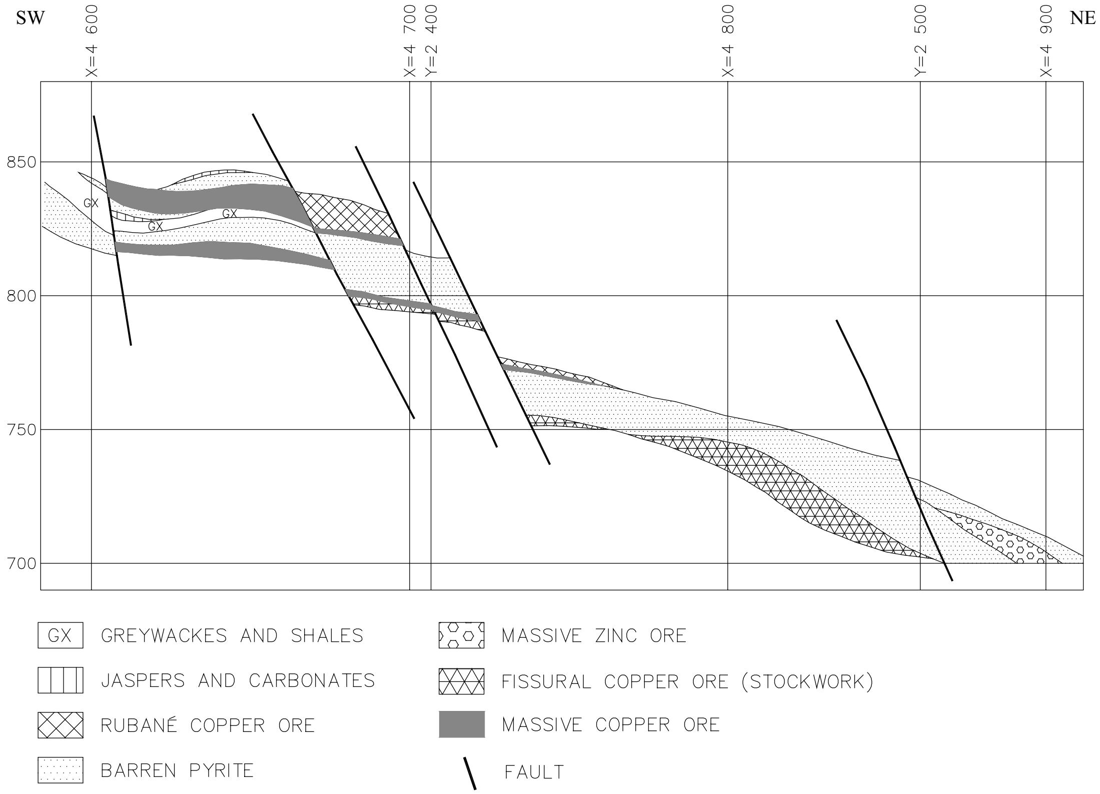

FIG. 2. Cross-section of the Corvo orebody showing the vertical and lateral distribution of the different types of ore: *rubané* copper ore (RC type), barren pyrite (ME type), massive copper ore (MC type), massive zinc ore (MZ type) and fissure-bound copper ore (FC type). Source: SOMINCOR, Geological Department (2001).

contains unusual contents of Zn, As, Sb, Hg, Ag and Sn. These unusual cupriferous massive sulfides correspond to a cupriferous subtype of ore, which can be found locally in the Corvo orebody as well. Stringer ores in the Graça massive ores have only a limited expression at the base of the ore in the southwestern sector of the orebody. Minor late N–S subvertical faults are the extension of faults observed at the surface. Minor E–W faults contain veins of carbonates, quartz and chalcopyrite.

Neves was initially assumed to be a single 700 × 1200 m subhorizontal orebody with a thickness up to 55 m, located on the crest of the main anticline and elongate in a NNW–SSE direction, dipping 5 to 15° to the northeast in its northern part (Fig. 6). Chemical analytical results and logging of drill cores have shown that the orebody actually consists of two linked bodies, Neves Norte and Neves Sul. Neves Norte consists of cupriferous massive sulfides and massive pyrite with low copper and zinc contents, showing the same kind of metal zonation as at Corvo and Graça. At the base of the copper-rich sulfide mounds, interaction zones of stringer ores with massive sulfides contain a zone rich in bornite along with chalcopyrite, carrollite, and copper-rich tennantite, in addition to Cu–Sn, Bi, In, Se, Ag sulfides and gold. The same association of minerals was later found to occur both at Corvo and Graça (Pinto *et al.* 1994, 1995, 1997, Pinto 1999). Neves Sul consists of zinc-rich polymetallic ores with minor amounts of massive cupriferous ores and tin ores. Although they contain much less copper, the ores display the same pattern of base-metal zonation as already described for the Neves Norte, Corvo and Graça orebodies, with copper at the base and zinc and pyrite at the top of the ore lenses (Gaspar & Pinto 1991). Massive pyrite constitutes only 30% of the Neves Sul orebody.

Lombador and Zambujal are the least known orebodies. Lombador occurs on the northeastern flank of the anticline, at a depth of 500 m, and extends as a 1300 × 650 m lens in a NW–SE direction, with a thickness of up to 100 m. It consists mostly of polymetallic massive sulfides rich in zinc. Zambujal has a slight E–

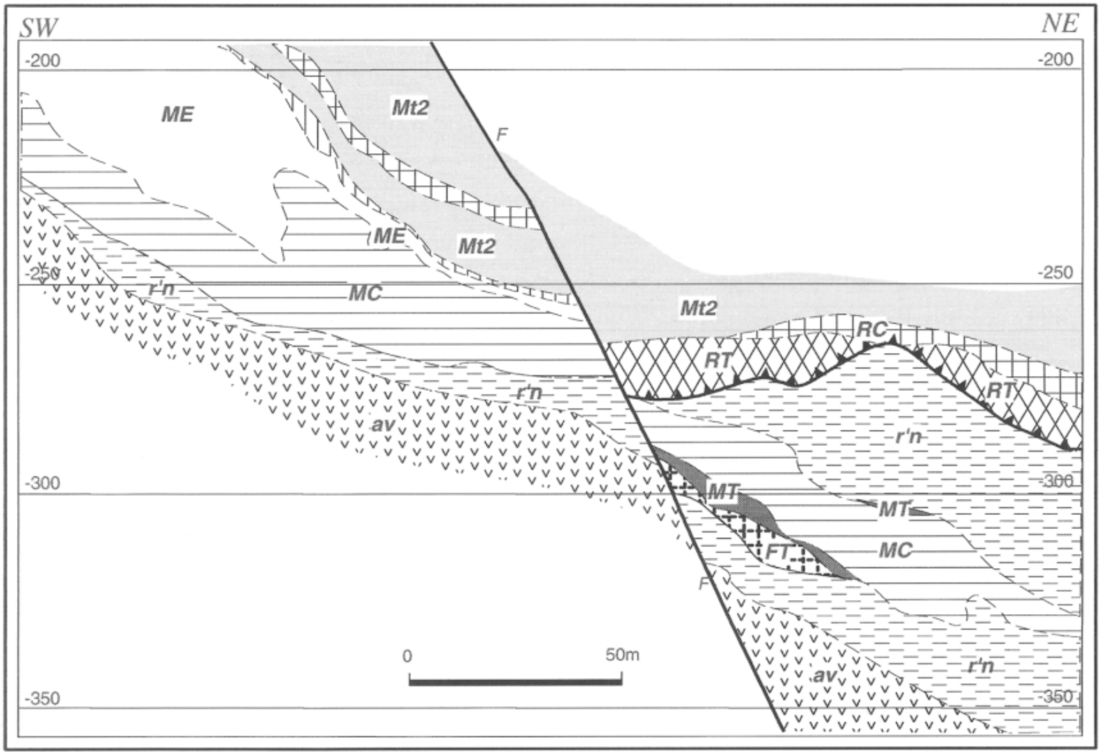

FIG. 3. Cross-section of the Corvo orebody showing at its northeastern end the distribution of the various tin ores (MT, RT and FT types) in relation to the copper-rich ores (MC and RC types). Mt2: greywakes and shales of the Mértola Formation; r'n: black pyritic shale; n: black shales of Neves Formation; av: felsic Mt2 volcanic rocks. Taken from Cabri *et al.* (1998).

W elongation and is located at a depth of 300 to 450 m at the southeastern end of the anticline. The dimensions are 550 × 600 m along dip, with a maximum thickness of 50 m. From the first reports on the drill core, it was considered as mainly formed of massive pyrite ores (60%) and polymetallic ores with very low copper and zinc contents. However, the latest drilling has shown that some rich cupriferous massive ores also occur.

ORE TYPES AND METAL ZONATION

As a result of the early assessment of the Neves–Corvo deposit, four different types of ore were recognized: massive sulfides, fissural, rubané and breccia ores (Albouy *et al.* 1981, Leca *et al.* 1983). The *fissural* type corresponds to stringer ore occurring either in black shales or in felsic volcanic footwall rocks. They can extend for up to 50 m below the *massive sulfides*, and many appear as sulfide layers subparallel to the contact of the main lens of massive sulfide. The *rubané* ore, best developed in the hanging wall of the massive sulfide lens at Corvo, consists of chloritic shales interbedded with sulfides (mainly chalcopyrite), cassiterite, jasper and carbonates. The *breccia* ores consist of decimeter- to meter-size clasts of felsic rocks interspersed with thick sulfide intervals. The breccia ores were once considered to be of epiclastic origin (Albouy *et al.* 1981, Leca *et al.* 1983), but they currently are regarded by some mine geologists as fissural ores.

Although the occurrence of metal-zoning patterns was recognized from the very beginning, the scarcity of information concerning both the original form of the orebodies and how they have been disrupted by Hercynian deformation led SOMINCOR geologists to create an alternative subdivision of the ore types to that first proposed. Taking mostly into account the contents of Cu, Zn, Pb and Sn, a technological classification of the ore types has been established to facilitate the estimation of reserves and the exploitation of the copper- and tin-rich ores (Richards & Sides 1991, Carvalho & Ferreira 1993, Carvalho *et al.* 1997).

The letter M in front of abbreviations indicates massive sulfide mineralization, to distinguish it from the copper and tin ore occurring both in the *rubané* (R) and *fissural* (F) types recognized in some of the deposits. To arrive at a valid estimate of reserves, these technological definitions of ore type have been used as a basis for geological interpretation of the sulfide stratigraphy

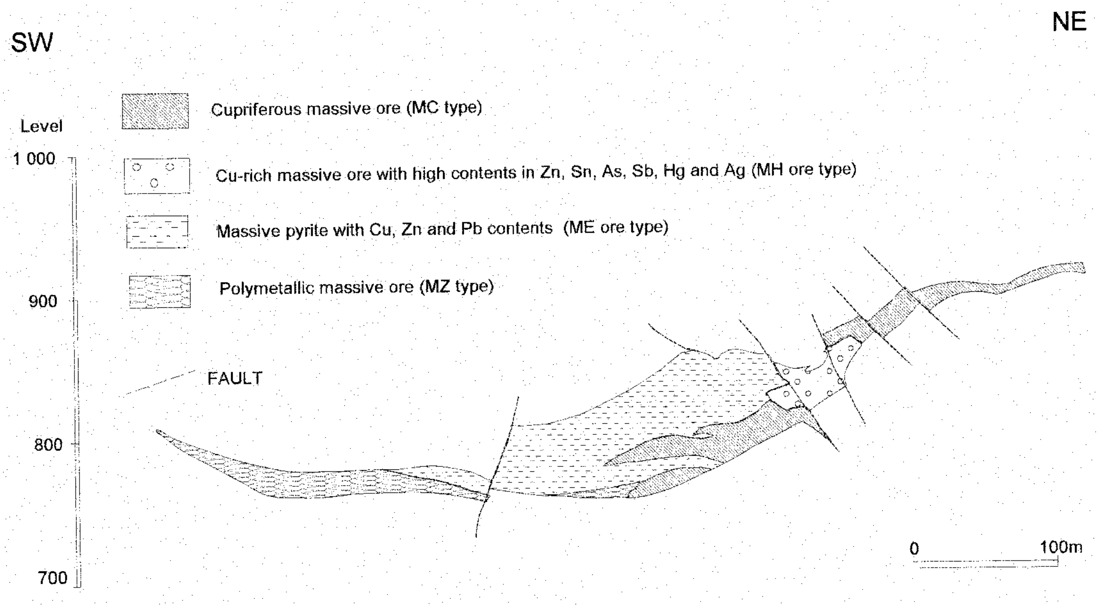

FIG. 4. Transverse section 6 from Graça showing significant polymetallic massive sulfide lenses (MZ ore type) that have been developed laterally to the southwest of both the massive pyritic ore (ME type) and the cupriferous massive ores (MC type). Discrete lenses of the MH subtype occur locally on the middle of MC ores, mostly close to later faults. After Richards & Ferreira (1992).

within each orebody. Solely on the basis of the main metal present of economic interest, there are four types of massive ores, namely: massive sulfides with high copper content (MC), massive cassiterite ores (MT), massive sulfides with high copper and tin contents (MS), massive sulfides with high zinc content (MZ), as well as massive pyrite with low contents both of copper and zinc (ME). To facilitate the estimation of ore reserves and a selective exploitation of the copper and tin ores for each type, cut-off grades of these metals have been established (Table 1).

MINERALOGY AND GEOCHEMISTRY OF THE ORES

The copper-rich massive sulfide ores (MC type)

The ores from Neves–Corvo show a large variety of mineralogical associations that differ according to the type of ore in which they usually occur (Table 2). The Cu-rich massive sulfide ores (MC type) mostly consist of massive chalcopyrite, with pyrite as the second most voluminous sulfide. In some places, the amount of chalcopyrite may even exceed the optimum proportion of Cu in the copper concentrates treated at the plant. The later massive chalcopyrite is the most abundant mineral; it replaces the original massive sulfide ores, mainly formed of pyrite and sphalerite. Pyrite in relics of primitive ore shows fine-grained, colloform and annealed crystals intergrown with chalcopyrite and sphalerite (Fig. 7). Sphalerite commonly shows edivence of *chalcopyrite disease* and, in some cases, has been completely replaced by chalcopyrite. Hydrothermal leaching of sphalerite, as described by Eldridge *et al.* (1983), is commonly observed, resulting in a major loss of Fe, dropping from about 6% down to 0.6%. Some of the leached crystals of sphalerite show mostly in their core a strong red coloration, probably due to high contents of Hg (up to 1,800 ppm). Cassiterite in massive copper ores occurs as fine euhedral to subhedral crystals that are invariably intergrown with sphalerite (Fig. 8). The intergrown cassiterite and sphalerite commonly occur along with rutile in a matrix of phyllosilicates that form lenses or discontinuous layers in the massive chalcopyrite. The size of the cassiterite crystals has not allowed a full study of trace-element concentrations. However, ore microscopy studies have shown without question that this kind of cassiterite was formed at the same time as the zinc-rich polymetallic ores and before the massive chalcopyrite. Remobilized chalcopyrite also occurs intergrown with pyrite, tennantite, tetrahedrite and Cu–Sn sulfides, forming bands.

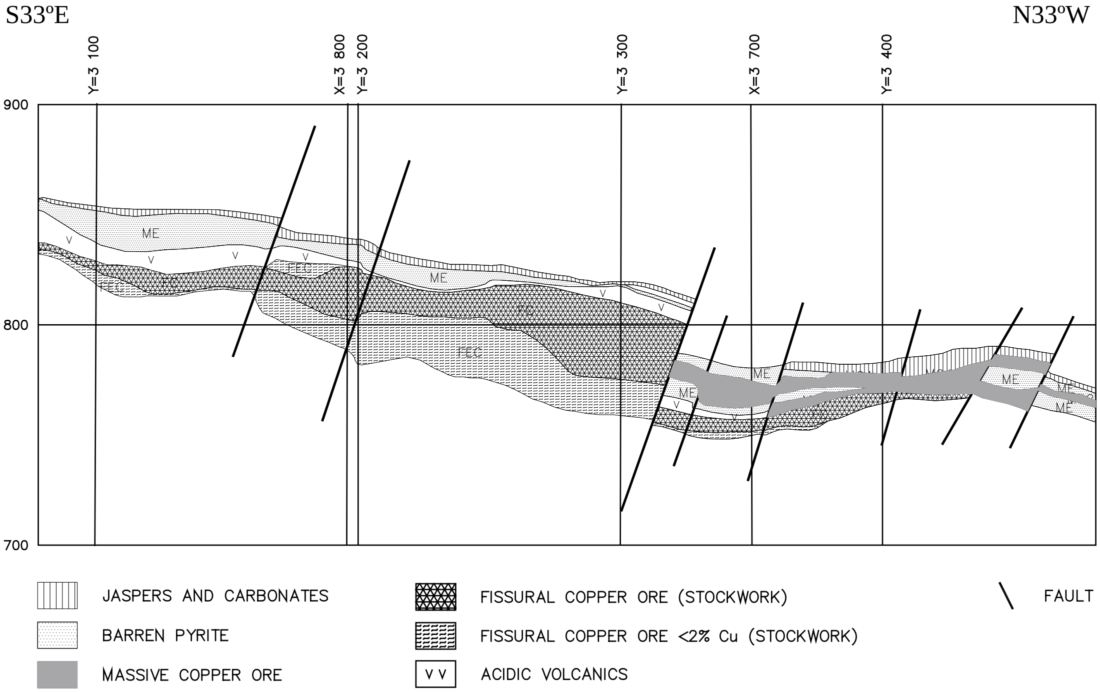

FIG. 5. Longitudinal section 3, Neves Norte deposit. The bornite-rich MC ores are located in the northwestern part of the transverse section. Centimeter-size lumps occur along with Cu–Sn, Co, Bi, In, Se, Ag sulfides and gold wherever the fissure-bound copper-rich ores (FC) underlie the copper-rich massive sulfides (MC). ME: barren pyrite; MC: massive copper ore; FC: copper-rich fissure-bound ore; FEC: fissure-bound ore with <2% Cu. Source: SOMINCOR, Geological Department (2001).

As the copper-rich massive ores (MC) are mainly a result of the intensive replacement of the original polymetallic massive ores by chalcopyrite, the data on bulk compositions obviously vary depending on the extent of replacement. Bulk compositions of MC ores, provided in 1991 by SOMINCOR, indicate average contents of 10.5% Cu, 1.5% Zn, 0.5% Sn, 41 ppm Hg, 50 ppm Ag, 829 ppm Sb and 2,933 ppm As, and the gold contents are mostly close to 0.5 g/t in the copper-rich massive sulfide ores from Corvo, Graça and Neves Norte orebodies. Chalcopyrite from the MC ore could have significant contents of Sn, Hg and In. Although chalcopyrite could carry up to 1,800 ppm indium, significant amounts could also occur in sphalerite, stannite, kësterite, cassiterite, tetrahedrite and tennantite as well. Pyrite in some cases shows high Co and Se contents. The higher Co contents could reach up to 10% in the core of some pyrite crystals, with a strong decrease toward the rim. Similar enrichments in Co were observed in euhedral crystals of arsenopyrite as well. Sphalerite is present in several generations, and with large variations in trace-element concentrations. Where partly replaced by chalcopyrite, it commonly shows a considerable decrease in Fe. Some sphalerite crystals observed under the microscope are almost transparent. Available data on the mineral chemistry of the Neves–Corvo ores shows that pyrite, chalcopyrite, sphalerite, tetrahedrite, tennantite, cassiterite and copper–tin sulfides have different trace-element signatures according the type of ore (Table 3).

The tin-bearing cupriferous massive ore (*MS type*)

The tin-bearing cupriferous massive ore (MS type) that occurs mostly in the Corvo orebody actually corresponds to a subtype of the massive copper-rich ore (MC). The two ores differ only by the fact that the MS ore has higher copper and tin contents. The enrichment in Sn shown by the MS ore is mainly a result of the widespread occurrence of tin sulfides and the inclusion of millimetric to centimetric clasts of cassiterite similar to that occurring in large lenses both at the top and bottom of the MC massive cupriferous ores (Fig. 3). Tin is mostly carried by cassiterite, but stannite, kësterite, stannoidite and mawsonite are present in variable proportions. For the most part, the tin sulfides result from the replacement of both from cassiterite and sphalerite. Because the MS ore is a subtype of the MC ore, fine-grained euhedral crystals of cassiterite intergrown with sphalerite, as already described for the MC ore, have been observed as well. Galena, arsenopyrite, löllingite, bournonite, meneghinite, betekhtinite, rutile, pyrrhotite, hematite, and magnetite occur as minor minerals in MS ores. Continuous bands of sphalerite replaced by kësterite (Fig. 9) and exsolution-related lamellae of mawsonite in stannoidite and blebs of chalcopyrite at the contact of kësterite with stannoidite are widespread.

Average bulk-compositions for the MS ores exploited in 1991 show average contents of 15.2% Cu, 1.2% Zn, 1.8% Sn, 50 ppm Hg, 57 ppm Ag, 789 ppm Sb and 2,057 ppm As. Data on the composition of chalcopyrite, sphalerite, tennantite, cassiterite, mawsonite and stannoidite occurring in MS ores are provided in Table 3.

Copper-rich massive sulfides with high contents in Zn, Hg, Ag, As, Sb and Sn (*MH type*)

The Graça and Corvo orebodies mainly consist of discrete lenses with distinct compositions: massive pyrite with low contents in Cu, Zn and Sn (ME ore), massive copper-rich sulfides (MC ore) and tin-bearing massive copper-rich ore (MS ore). However, in both orebodies, particularly at Graça, the ore lenses classified as belonging to the MC ore themselves show a peculiar stratigraphy involving intercalated horizons with high contents of Zn, Hg, Ag, Sb and As. Mine geologists classified them as belonging to a subtype of the MC ore, the so-called MH type. In this type of ore, millimetric bands of sphalerite intergrown with interstitial galena invariably show a strong mylonitization. They occur in a matrix of deformation-induced millimetric bands of tetrahedrite–tennantite, stannite–kësterite and chalcopyrite. Scarce centimetric concentrations of almost pure tetrahedrite–tennantite have been observed close to sphalerite-rich banded ores (Fig. 10). Replacements of sphalerite by tetrahedrite, tennantite, stannite, kësterite and chalcopyrite in this sequence are commonly observed (Figs. 11, 12, 13).

In 1991, MH ores formed 23% of the total amount of 1.3 Mt of the MC + MH + MS ores extracted (SOMINCOR, unpubl. report). For standard economic concentrates of copper obtained mostly from the jointly processed MC + MS + MH ores in 1991, SOMINCOR indicated contents of 14.9 to 22.0% Cu, 0.1 to 0.3% Pb, 0.1 to 4.0% Zn, 45 to 100 ppm Ag, ≤0.5 ppm Au, 1,000 to 3,000 ppm As, 400 to 15 ppm Sb, 0 to 300 ppm Bi, 40 to 75 ppm Hg, 5 to 100 ppm Ni, 200 to 300 ppm Co,

TABLE 1. RESERVES OF THE DIFFERENT TYPES OF ORE IN THE NEVES–CORVO DEPOSIT, ESTABLISHED ON THE BASIS OF CUT-OFF GRADES BY MINE GEOLOGISTS

	Ore types	Cut-off grade	Average grade	ore reserves
MC	massive sulfides with high copper content	Cu >2%, Sn <1%	5.71% Cu, 1.25% Zn, 0.21% Sn	15.24
FC	cupriferous stringer ore	Cu >2%, Sn <1%	3.96% Cu, 0.74% Zn, 0.14% Sn	12.48
RC	*rubané* with copper-rich ore	Cu >2%, Sn <1%	6.18% Cu, 0.39% Zn, 0.16%Sn	5.93
MS	massive sulfides with high copper and tin contents	Cu >7%, Sn 1%	12.99% Cu, 2.08% Zn, 1.65% Sn	1.63
MT	massive cassiterite ores	Sn > 5%	7.04 % Cu, 0.72 % Zn, 13..37% Sn	0.029
RT FT	cassiterite ore in the *rubané* + tin ore in stringer ore	Sn 1%	1.94% Cu, 0.38% Zn, 4.74% Sn	0.40
MZ	massive sulfides with high zinc content	Zn 3.3%, Cu <2%	0.50% Cu, 6.42% Zn, 0.08% Sn	41.68
RZ FZ	zinciferous ore in *rubané* + zinciferous stringer ore	Zn >3.3%, Cu <2%	0.40% Cu, 3.85% Zn, 0.04% Sn	8.67
ME	massive pyrite with contents both of copper and zinc	—	Cu <2%, Zn% <3%, Sn 1%	180.00
Total ore reserves				266.059

Reserves expressed in Mt. Sources: SOMINCOR and Pinto (1999).

TABLE 2. ORE MINERALOGY OF MASSIVE SULFIDES AND STRINGER ORES, NEVES–CORVO DEPOSIT

Massive sulfides rich in Cu, Cu+Sn, and Zn

Pyrite, chalcopyrite, sphalerite, tetrahedrite, tennantite, cassiterite, kësterite [$Cu_2(Zn,Fe)SnS_4$], stannite [Cu_2FeSnS_4], galena, mawsonite [$Cu_6Fe_2SnS_8$], stannoidite [$Cu_8(Fe,Zn)_3Sn_2S_{12}$], arsenopyrite, löllingite, cobaltite, betekhtinite [$Cu_{10}(Fe,Pb)S_6$], bournonite [$PbCuSbS_3$], meneghinite [$Pb_{13}CuSb_7S_{24}$], cosalite [$Pb_2Bi_2(S,Se)_5$], tiemannite [HgSe], tetradymite [Bi_2Te_2S], coloradoite [HgTe], gudmundite [FeSbS], chalcostibite [$CuSbS_2$], pyrrhotite, hematite, magnetite, rutile

Massive ores rich in Cu+Zn and bornite

Pyrite, chalcopyrite, sphalerite, bornite, enargite, mawsonite, tennantite, tetrahedrite, galena, arsenopyrite, löllingite, cobaltite, carrollite [$Cu(Co,Ni)_2S_4$], glaucodot [(Co,Fe)AsS], skutterudite [$CoAs_{2-3}$], pyrrhotite, vinciennite [$Cu_{10}Fe_4Sn(As,Sb)S_{16}$], miharaite [$(Cu,Ag)_4FePbBiS_6$], wittichenite [$Cu_3BiS_3$], aikinite [$PbCuBiS_3$], colusite [$Cu_{26}V_2(As,Sn,Sb)_6S_{32}$], betekhtinite, kobellite [$Pb_{22}Cu_4(Bi,Sb)_{30}S_{69}$], chalcostibite, galena–clausthalite solid solution, naumannite [Ag_2Se], cosalite, paraguanajuatite [$Bi_2(Se,S)$], laitakarite [$Bi_4(Se,S)_3$, tiemannite, bohdanowiczite [$AgBiSe_2$], tetradymite, coloradoite, stromeyerite [AgCuS], roquesite [$CuInS_2$], argentian gold

Cu- and Au-rich stringer ores

Pyrite, chalcopyrite, tetrahedrite, cassiterite, sphalerite, galena, arsenopyrite, löllingite, kësterite, alloclasite [(Co,Fe)AsS], glaucodot, native bismuth, aikinite, galenobismuthinite [$PbBi_2S_4$], bismuthinite [$(Bi,Pb,Cu)_2(S,Sb)_3$], "rezbanyite" [$(Cu,Ag,Co)_{4.3}Pb_{2.9}(Bi,Hg)_{9.3}S_{19}$], joséite-B [$Bi_4Te_2S$], tetradymite, laitakarite, argentian gold

Data from Garcia Miguel (1990), Gaspar (1991, 1996, 1998), Gaspar & Pinto (1991), Pinto *et al.* (1994), Marcoux *et al.* (1996a), Marcoux & Leistel (1996), and unpublished reports by O.C. Gaspar (IGM, Portugal), J.F.W. Bowles (Mineral Sciences, Ltd.), SOMINCOR, SA and P. Marion (LEM, Orléans).

TABLE 3. TRACE-ELEMENT CONCENTRATIONS IN MINERALS MAKING UP DIFFERENT TYPES OF ORE AT NEVES CORVO

Mineral	Cu	Zn	Pb	Fe	As	Sb	Sn	Cd	In	Hg	Ag	Co	Ni	Bi	Se	Te	Ta	Ga	Ti	W	Ore Type
Pyrite	4,400	2,900	403		3,900	1,800			<9			100,000			675	14	25			26	MC, MS
	7,900	2,200	7,200		15,300	1,500	800	200		400	300			1,600							MH
Chalcopyrite		800			1,960	800	5,600	200	1,800	6,800		700	230	954	456	21	84			68	MC
		178					819		434						325						MS
		11,200	800		540	2,300	3,500	400	400	1,800	380			1,200							MH
		500					3,400		900												MC3
		400	400						800	400											MT
Sphalerite	20,900			65,000		1,400	8,500	1,500	500	1,300	100			700	1,600	200					MC, MS
	10,400			12,700				17,000	1,800	1,000		4,300		8,800							MH
	7,000			19,700			2,400	2,900	12,500	1,800	100										MC3
	5,900			14,800	1,300		400	10,000	7,800	800		1,000		900	1,600	300					RC
	8,100			20,500				2,500	2,800	1,000											MT
				19,700				2,900	10,450												FZ
Tetrahedrite		28,000	824	45,600			4,784	139	2,100	3,200	14,200	4,300		400	1,201						MC
									1,500	2,660	52,500										MH
		42,000		28,400			2,400				13,600			8,800							MC3
		47,300	1,100	30,600	5,700		1,500	600			4,400	500		9,500							FC
											13,300			11,500							FZ
Tennantite		46,200		67,000		10,500	1,300	139	1,500	2,000	500			400							MC, MS
									100	600	1,500										MH
		10,900		21,700		11,100			27,000	10,000	4,100			57,300							MC3
Cassiterite	919	136	18		41	145			1,400								91		2,500		MS
									1,200												MH
				3,300					1,800												MC3
				3,000					1,900												RC
	916	136	30	25,000	6	243			3,700	2,700						261	16,000	15	4,500	16,000	MT, RT
Stannite–kësterite		43,800	325		9,700	4,000		700	2,800	2,700	340			23	1,457						MC
									16,200	1,340	300										MH
									3,830	3,900											MT
Mawsonite									40,000												MS
					400				300												MC3
Stannoidite		10,800							3,200												MS
										600	186										MH
Galena	2,400					100	700	200		700	650			1,100							MH
Arsenopyrite	1,200	3,100	800			29,300	500			200	300			600							MH

The values in ppm correspond to the highest value found for each trace element. Data compiled from Tables 5, 6, 7 and 8; J. Bowles (Mineral Science Ltd., unpubl. reports), Mostafa (1995), and P. Marion (pers. commun., 1995). ni = not indicated.

2,000 to 7,000 ppm Sn, 100 to 500 ppm Se, 10 to 80 ppm Cd, and 200 to 400 ppm In.

Systematic studies by ore microscopy and electron-microprobe analysis were carried out on 56 samples collected from drill-core samples with the highest contents both in Hg and Ag. Analytical data provided by SOMINCOR showed that in the samples, the maximum levels of Hg and Ag found were 818 and 857 ppm, respectively. Typical bulk-compositions of the MH ore reveal, on average, 37.02% S, 14.5% Cu, 0.22% Pb, 5.65% Zn, 20.97% Fe, 2.70% Sn, 1.27% As, 2.68% Sb, 131 ppm Bi, 97 ppm Ag, 248 ppm Hg, 545 ppm In, 1,230 ppm Co, 14 ppm Ni, 293 ppm Se, 136 ppm Cd, and up to 7 ppm Te. On average, the samples studied contain about 27% chalcopyrite, 25% sphalerite, 20% tetrahedrite–tennantite, 19% pyrite, 2% (stannite–kësterite) + stannoidite + mawsonite, 1% arsenopyrite, 1% galena and 5% enargite + bournonite + gangue. Although in some samples the composition of the minerals may be consistent over 10 cm of the drill core, differences were observed in most of the samples, especially in the tetrahedrite–tennantite and stannite–kësterite series. A continuous spectrum between the end members in both series was identified, with tennantite

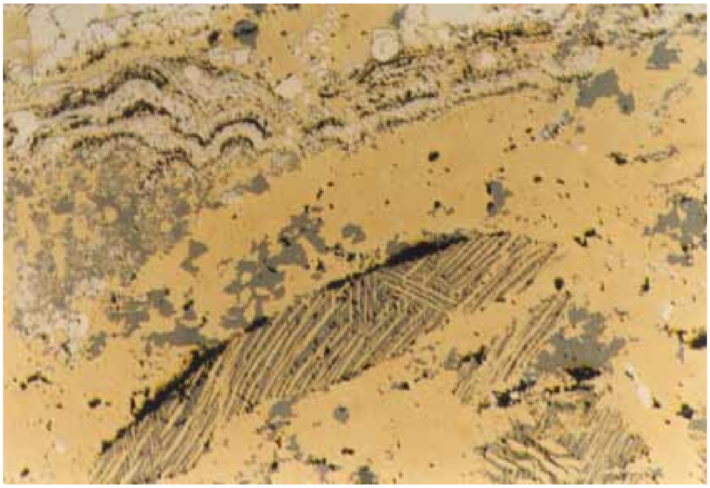

FIG. 6. The MC ore type, Corvo orebody. Chalcopyrite (yellow) replaces fine-grained pyrite. Colloform pyrite is commonly intergrown with fine-grained tetrahedrite (light grey) and sphalerite (dark grey). Coarse-grained sphalerite commonly shows the so-called *chalcopyrite disease*. In some cases, sphalerite is completely replaced by chalcopyrite. Scale: 20 mm = 360 μm.

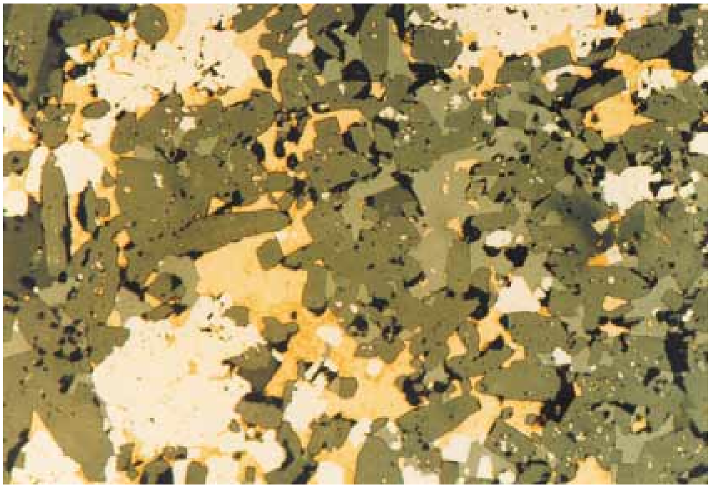

FIG. 7. The MC ore type, Corvo orebody. Fine-grained euhedral to subhedral crystals of cassiterite (mostly <150 μm) form an intergrowth with sphalerite (lighter grey) in a matrix of later chalcopyrite. Ore-microscopy studies have shown that this cassiterite – sphalerite assemblage is formed during the deposition of the polymetallic massive sulfides. Scale: 20 mm = 360 μm.

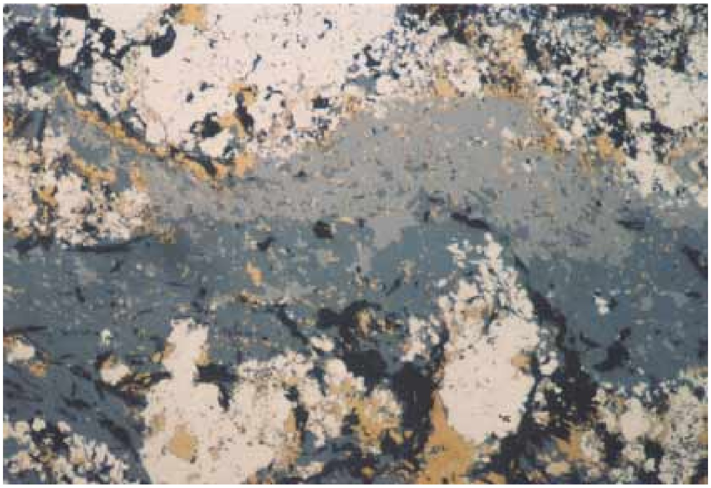

FIG. 8. Tin-bearing MC ore, Corvo orebody. Discontinuous band of sphalerite (grey) replaced by këstерite (olive grey) cuts across cataclastic intergrowths of pyrite with chalcopyrite. Scale: 20 mm = 360 μm.

preferentially associated with kësterite, whereas tetrahedrite tends to occur with stannite (Table 4). These four minerals mostly occur in close association and are commonly intergrown, in alternating layers with sphalerite and chalcopyrite. Mass balances using data obtained both by systematic ore microscopy and electron-probe micro-analysis led to the identification of the mineralogical sites of Ag and Hg. It appears that the tetrahedrite–tennantite series may be responsible for about 34% of the Hg, whereas the sphalerite contains about 26%, and the stannite + kësterite, about 5%. Sphalerite and stannite–kësterite contain insignificant amounts of silver. Tetrahedrite and tennantite are by far the most important hosts for silver (~90%). Galena, where present in appreciable quantities, also can be a significant carrier. Bournonite and Fe-rich enargite contain 580 to 990 ppm and 289 to 300 ppm Hg, respectively (Table 5). Values from 0.01 to 1.69% Cd were measured in sphalerite, with an average of 0.27%. Some Cd was found in tetrahedrite as well, but a systematic analytical study focused on this element was not carried out.

In the context of the Project Brite–EuRam II, further studies were carried out on 103 samples classified as belonging to the MC and MS types of ore. The sampling was carried out by SOMINCOR on selected drill cores and stopes at Corvo and Graça orebodies, and mostly aimed at explaining the occurrences of high As contents along some horizons of the MC and MS ores. Although the majority of the samples were indicated as belonging to the MC and MS ores, they actually resemble in many aspects the mineralogical compositions and ore textures observed in the MH ores. However, systematic ore microscopy and analytical studies indicated that most of the samples contain unusual amounts of arsenopyrite, löllingite, alloclasite and skutterudite as accessory minerals, which so far have not been identified in typical MH ore. The euhedral crystals of As and As–Co sulfides commonly occupy open spaces filled with quartz and carbonates as well. Although most of the ores are laminated and brecciated, the relict textures observed in the As–Co-rich ores are similar to the ones observed in the stringer ores found beneath of the copper-rich massive sulfides. Because the samples were systematically collected at appropriate levels in the stratigraphy, it was possible to assume that they are representative of transition zones located beneath the typical MC, MS or MH ores and that they could occur on the top of the fissural ores rich in As and Co (FC type) as well.

TABLE 4. DISTRIBUTION OF THE TETRAHEDRITE–TENNANTITE END MEMBERS IN THE GRAÇA MH ORE, IN RELATION WITH THE OCCURRENCE OF STANNITE AND KËSTERITE

Sample	Tetrahedrite	Tennantite	Stannite	Kësterite	Sp	Ccp
	As/(As+Sb)		Zn/(Zn+Fe)			
200 A		0.93		0.82	×	×
200 B	0.40		0.41			×
220 A		0.73				×
220 B	0.05				×	×
220 C	0.02		0.28			×
221 A	0.01					×
221 B	0.31				×	
221 C		0.98			×	
221 D		0.99			×	
221 E		0.99			×	×
221 F	0.03					
221 G		0.98			×	
222 A		0.93		0.82	×	×
222 B		0.93		0.80	×	
222 C	0.24				×	
236 A	0.35				×	×
236 B	0.03				×	
330		0.95			×	×
335 A		0.99		0.91	×	×
335 B	0.45				×	
320 A	0.08					
320 B	0.33					
320 C		0.90			×	×
331 A	0.08				×	
331 B	0.21					

The data were obtained by electron-probe microanalysis of 25 samples (J. Bowles, Mineral Science Ltd., unpubl. report). Sp: sphalerite, Ccp: chalcopyrite.

In terms of both the mineral assemblages and chemical composition, the MH ore shows a great resemblance to the "tetrahedrite front" in the Kidd Creek deposit, in Ontario, as described by Hannington *et al.* (1999a, b). These authors showed that the "tetrahedrite front" is the result of the replacement of the primitive polymetallic suite of ores enriched in Zn, Ag, Pb, Cd, Sn, Sb, As, Hg ores by a later higher-temperature copper-rich suite.

The bornite-bearing MC massive sulfide ore with high contents in Cu, Sn, Bi, Co, Hg, Se, In, Ag and Au (*MC3 type*)

In 1993, drill holes at Neves Norte intersected a bornite-bearing cupriferous massive ore located at the top of mineral assemblages with unusually high contents of Cu, Sn, Bi, Co, Hg, Se, Ag and Au. The envelope of this mineralogical association is MC ore in

TABLE 5. MINERALOGY AND MINERAL CARRIERS OF Ag AND Hg IN MH ORES FROM THE GRAÇA OREBODY

Carriers	Hg	Ag
Sphalerite	170 to 1000 (630)	bdl
Tennantite	360 to 600 (490)	200 to 1040 (500)
Tetrahedrite	328 to 2660 (1140)	1020 to 52500
Stannite	660 to 1340 (1000)	bdl
Kësterite	630 to 740 (690)	bdl
Stannoidite	420 to 600 (510)	low Ag values
Mawsonite	180	bdl
Galena	420 to 700 (550)	up to 650
Bournonite	580 to 990 (790)	up to 1600
Enargite	280 to 300 (790)	up to 2300

Concentrations in ppm established by electron-probe microanalysis by John Bowles (Mineral Science Ltd., unpubl. report). The average is shown in parentheses; n = 56. Below the detection limit: bdl.

FIG. 9. The MH ore type, Graça orebody. Centimeter-size concentrations of almost pure tetrahedrite–tennantite (bluish grey) are intercalated in banded ores rich in sphalerite (dark grey) + chalcopyrite. Length of the sample: 35 cm.

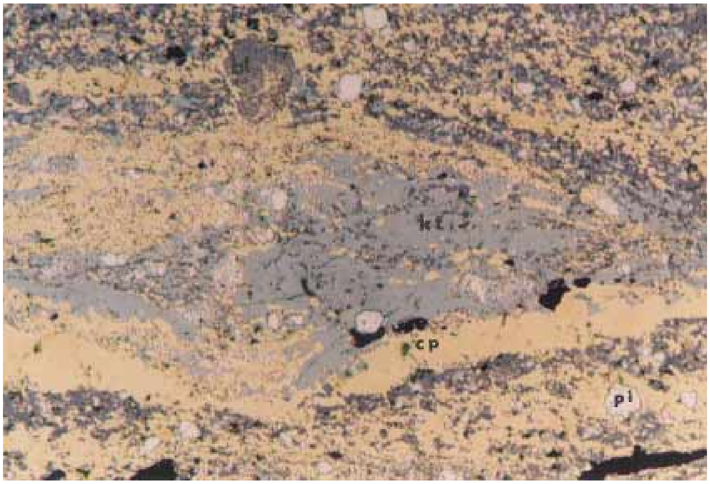

FIG. 10. The MH ore type, Graça orebody. Cataclastic sphalerite (bl) is replaced by chalcopyrite (cp). The later Cu-rich fluids also led to the replacement of sphalerite by kësterite (kt). Other symbol: pi: pyrite. Scale: 20 mm = 720 μm.

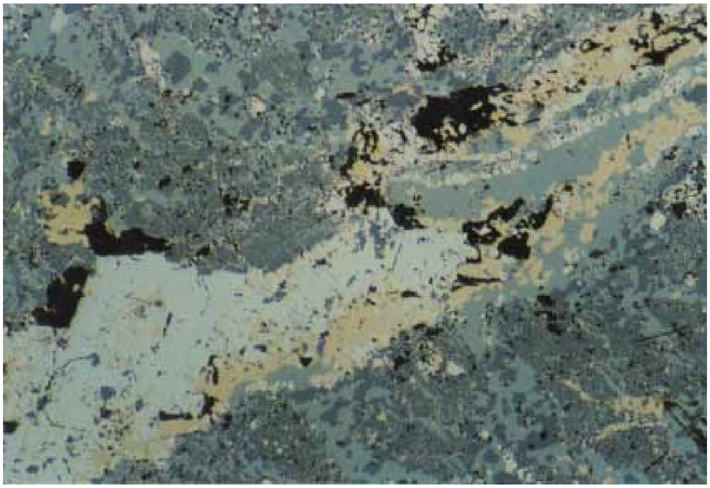

FIG. 11. MH ore type, Graça orebody. Cataclastic sphalerite (dark grey) is mostly replaced by tetrahedrite (bluish grey). In the middle of the photo, a veinlet contains arsenopyrite crystals (white) and chalcopyrite + tetrahedrite intergrowths. Scale: 20 mm = 360 μm.

contact with jasper at the roof and with copper-rich stringer ores (FC type) at the bottom. The geologists at the mine classified the bornite-rich as a MC3 type. Similar complex associations of minerals have been found associated with the tin-bearing cupriferous massive ores (MS type) at Neves Norte and at the top of stringer ores (RC type) in the Corvo and Graça orebodies (Pinto 1999). Since the MC3 ore has been observed as discrete zones, no figure has so far been presented by SOMINCOR for the tonnage of this type of ore.

The MC3 ore is mainly formed of centimetric pieces of bornite that occur along with tennantite, mawsonite and stannoidite in a matrix mainly formed by massive chalcopyrite. Associated with these minerals, a rather unusual suite of ore minerals including miharaite, carrollite, vinciennite, galena, colusite, stromeyerite, arsenopyrite, sphalerite, tetrahedrite, and naumannite (occurring as exsolution-induced blebs in galena) have been observed at a microscopic scale. Native gold was observed in naumannite, which is associated with wittichenite, but the gold grains are too small for analysis by electron microprobe (Pinto *et al.* 1994, 1997, SOMINCOR, unpubl. reports). The main gangue mineral is subhedral to euhedral quartz. Dolomite and siderite veins cut across the stringer zone. Geological evidence at the mine stopes, as links to old faults, and the ore microscopy studies of all the four bornite-rich mineralogical associations so far observed, have shown that they are later than the MC and the MS ores in which they occur.

The MC3 ore (n = 64) contains, on average, 28.0% Cu, 0.2% Pb, 0.1% Zn, 27.5% Fe, 0.4% Sn, 8,427 ppm As, 6,214 ppm Sb, 1,397 ppm Bi, 612 ppm Ag, 177 ppm Hg, and gold between 0.1 and 10 ppm. The In content is high as well. Both ore microscopy and electron-probe micro-analyses systematically carried out on 36 polished sections of drill core show that the main carrier of indium is mawsonite (up to 4.0% In), followed by tennantite (up to 2.7% In). Chalcopyrite contains significant In contents (up to 900 ppm) at the rim of crystals where in contact with mawsonite. Tennantite also contains up to 8.0% Bi and up to 1.0% Hg. Pyrite could contain up to 7.5% Co; wittichenite and miharaite contain 1.8 and 1.2% Ag, respectively; galena contains about 14% Bi and an average of about 14% of the clausthalite (PbSe) component (Table 6). A 1-m drill-core intersection of the Neves Norte MC3 ore, located at the top of stringer zones, assayed up to 10 g/t Au, and as much as 33 g/t over 0.2 m of core.

TABLE 6. AVERAGE EMPIRICAL FORMULA AND TRACE-ELEMENT CONCENTRATIONS IN THE ACCESSORY MINERALS THAT OCCUR IN THE BORNITE-RICH MC3 ORE AT NEVES NORTE

Bornite	$(Cu,Ag)_{4.93}Fe_{0.97}S_{4.10}$, contains 3300 ppm Ag, 4900 ppm Se and 1400 ppm Bi
Carrollite	$Cu_{0.97}(Co,Ni,Fe)_{1.96}S_{4.07}$, contains 8600 ppm Ni and 4800 ppm Fe
Mawsonite	$Cu_{5.95}Fe_{2.01}Sn_{1.00}S_{8.05}$, contains 400 ppm As and 300 ppm In
Tennantite	$(Cu,Ag,Fe,Zn,Hg,In)_{11.76}(As,Sb,Bi)_{4.1}S_{13.24}$, contains 3200 ppm Ag, 21,700 ppm Fe, 12,900 ppm Zn, 7150 ppm Hg, 27,400 ppm In, 10,500 ppm Sb and 46,450 ppm Bi
Vinciennite	$Cu_{10.53}Fe_{3.81}Sn_{0.95}(As,Sb,Ag)_{0.99}S_{15.72}$, contains 46,600 ppm As, 1700 ppm Sb and 500 ppm Ag
Wittichenite	$(Cu,Fe,Ag)_{3.01}Bi_{1.01}S_{2.9}$, contains 46,600 ppm As, 1700 ppm Sb and 500 ppm Ag
Miharaite	$Pb_{0.96}(Cu,Ag)_{4.00}Fe_{0.96}Bi_{1.02}S_{6.06}$, contains 4400 ppm Fe and 17,100 ppm Ag
Selenian galena	$Pb_{0.95}(S,Se)_{1.00}$, contains 72,500 ppm Se, 7250 ppm Bi, 1350 ppm Fe, 4550 ppm Ag and 5250 ppm Cu
Galena	PbS, contains about 14% Bi and an average of about 14% of the clausthalite (PbSe) component
Naumannite	$Ag_{1.95}Se_{0.94}$, contains 300 ppm Bi
Stromeyerite	AgCuS (tentatively identified)
Colusite	$(Cu,Ag)_{26.83}V_{1.56}(As,Sn,Sb,Fe)_{6.57}S_{31.00}$, contains 14,800 ppm Ag, 36,800 ppm Fe, 21,000 ppm V, 59,400 ppm As and 1900 ppm Sb
Gold	Grains (<10 µm in diameter) with variable proportions of Ag

Data from: Pinto *et al.* (1994) and J. Bowles (Mineral Science Ltd., unpubl.reports). The bornite-rich zone includes in addition the following minerals: chalcopyrite, sphalerite, tetrahedrite, arsenopyrite, cobaltite, pyrite, stannoidite and stannite.

There is a clear similarity between the mineral assemblage described in the MC bornite-rich ores from Neves Norte orebody and the bornite zone at Kidd Creek. Re-equilibration textures of the ores like the ones described by Hannington *et al.* (1999b) for the Kidd Creek deposit have been systematically observed in the MC3 ores from Neves–Corvo (Figs. 14, 15). Bornite also is present in the North Lyell section of Mt. Lyell massive sulfide ores, in Australia (Markham 1968); tennantite, galena, copper sulfides, mawsonite, stromeyerite and wittichenite (?) are associated with chalcopyrite–bornite ores. At Kidd Creek, as at Mt. Lyell, Bi–Se sulfides are also common in the stringer zones (Markham 1968, Hannington *et al.* 1999b).

The copper-rich stringer ore (*FC type*)

In the Corvo orebody, a broad continuous zone of copper-rich stringer ores (FC ore) extends for some 400 m at the bottom of the MC ore. The FC zone shows, as all the other types of ore, strong evidence of deformation. It is mainly formed by pyrite, chalcopyrite, and sphalerite, along with minor galena, arsenopyrite, löllingite, alloclasite, glaucodot, stannite, tetrahedrite–tennantite, pyrrhotite, aikinite, laitakarite, native bismuth and gold. Bulk chemical analyses carried out by SOMINCOR on 25 samples of drill core indicate average contents of 3.70% Cu, 1,40% Zn, 0.48% Pb, 33% Fe, 5.14% As, 433 ppm Sn, 842 ppm Sb, 144 ppm Bi, 42 ppm Se, 58 ppm In, 97 ppm Ni, 241 ppm Co, 6 ppm Te, 37 ppm Cd, 9 ppm Ni, 7 ppm Tl, 13 ppm Ge, 71 ppm Ag, 15 ppm Hg and 4.3 ppm Au. Positive correlations among levels of Cu, In, Sn, Bi, Se, Te and Ag, and among levels of Au and Sn, As, Sb, Ni, Hg and Tl, were found. Indium contents in sphalerite may attain 1.0%.

Drilling assessment carried out in 1991 by SOMINCOR documented important concentrations of gold along with Co, Bi, Te, Sb and Ag minerals in the stringer ores of the Lombador ore body. Bulk analyses of the 16 drill-core samples revealed average concentrations of 6.61% Cu, 0.29% Pb, 0.57% Zn, 0.08 ppm Sn, 67 ppm Ag, 22 ppm Hg, 7,455 ppm As, 666 ppm Sb, 8,423 ppm

Bi, 30 ppm Ni, 623 ppm Co, 50 ppm Te, 258 ppm In, 239 ppm Se, 17 ppm Cd, and 17ppm Au.

Ore microscopy and electron-probe micro-analyses indicate a complex association of minerals that carry those elements (Table 7). Cobaltite, glaucodot, alloclasite, native bismuth, bismuthinite, "rezbanyite", galenobismutite, tetradymite, joséite-B and gold are all associated with pyrite and arsenopyrite in these ores. Tetrahedrite, galena, sphalerite, cassiterite, stannite, kësterite and pyrrhotite occur as accessory minerals (Pinto *et al.* 1997). Gold similar to that found in Lombador was later found in some stringers from Corvo and Graça as well.

The mineralogy and the mineral chemistry of the stringer ores indicate similarities with the stockworks and interaction zones of Spanish deposits in IPB; these zones, containing chalcopyrite, Cu, Bi, Te, (Se) sulfosalts and gold, were deposited from late-stage high-temperature (>300°C) copper-bearing fluids (Marcoux *et al.* 1996, Leistel *et al.* 1998b).

The rubané ore (*RC type*)

The so-called cupriferous *rubané* ore (RC type) occurs mainly at the top of the Corvo orebody and is characterized by alternating bands of slate and laminated

TABLE 7. MINERAL CARRIERS OF Co, Bi, In, Cd, Hg, Ag, Au, Te, Sn AND Sb IN THE FC STRINGER ORES FROM THE LOMBADOR OREBODY

Elements	Mineral carriers
Zn (In, Cd)	Sphalerite, (Zn,Fe)S, contains 1.44 to 1.97% Fe; 1900 to 2900 ppm Cd, 0.78 to1.04% In
Sn	Cassiterite, SnO_2, contains about 0.18% In
Co	Glaucodot, (Co,Fe)AsS, as highly zoned crystals, contains 8 to 27% Co, and 25% As Cobaltite, CoAsS, contains 30.9 to 32.6% Co, 600 ppm Te Alloclasite, (Co,Fe)AsS, contains about 19% Co Arsenopyrite contains 0.4% Co
Bi	Native bismuth, skeletal crystals containing virtually 100% Bi Bismuthinite, $(Bi,Pb,Cu)_{1.98}(S,Sb)_{3.02}$, contains 1.2 to 3.5% Sb and 69 to 79% Bi "Rezbanyite", $(Cu,Ag,Co)_{4.3}Pb_{2.9}(Bi,Hg)_{9.3}S_{19.0}$, contains 55 to 59% Bi, 0.4% Hg, 1.3% Co, 0.7 to 1.3% Sb and <100 ppm In Galenobismutite, $PbBi_2S_4$, interstitial to pyrite or cobaltite (or both) contains 0 to 0.5% Ag, 1.9 to 3% Sb, 0 to 0.25% Te and 43 to 49% Bi
Bi, Te	Tetradymite, Bi_2Te_2S, contains 35% Te and 59% Bi Joséite-B, Bi_4Te_2S, contains 23% Te and 73% Bi
Sb, Ag	Tetrahedrite, $(Cu_{9.8}Ag_{0.2})_{\Sigma 10}(Fe_{0.8}Zn_{1.1})_{\Sigma 1.9}(Sb_{3.8}As_{0.1})_{\Sigma 4.0}S_{12.9}$, contains 0.76 to 1.15% Bi and 0.42 to 1.33% Ag
Au, Ag	First generation: a) associated with galenobismutite and "rezbanyite" as inclusions in arsenopyrite: 87% Au, 12% Ag and 0.3 to 0.7% Hg; b) in cobaltite: 80% Au, 5 to18% Ag; 0.6% to 1.7% Hg Second-generation inclusions in chalcopyrite, associated with tetrahedrite and galena invading shattered pyrite: 80% Au, 5 to 18% Ag and 0.6 to 5% Hg

Source: Pinto *et al.* (1997). EMP analyses by J. Bowles, A. Pinto and P. Marion (unpubl. reports). "Rezbanyite": a mixture of sulfosalts, *e.g.*, cosalite, krupkaite and hammarite, shown in quotation marks to indicate that it is not an IMA-approved term.

TABLE 8. TRACE-ELEMENT CONCENTRATIONS IN CASSITERITE FROM MT AND RT ORE TYPES

Element	1	2	3	4	5
Fe	2,500 to 6,400 ppm (MT, RT)	2,500 to 21,900 ppm (MT, RT)	ng	5,130 to 8,783 ppm (FT)	up to 25,000 (MT)
Cu	ng	up to 919 ppm (MT, RT)	ng	ng	ng
Zn	ng	up to136 ppm (MT, RT)	ng	ng	up to 60 ppm (MT)
As	<10 ppm	up to 41 ppm (MT, RT)	5,700 ppm (RT)	ng	ng
Sb	up to 240 ppm (MT, RT)	up to 243 ppm (MT, RT)	ng	ng	ng
Ba	up to 117 ppm	ng	ng	ng	ng
Ga	ng	up to 41 ppm (MT, RT)	ng	ng	ng
Nb	<10 to 220 ppm (MT, RT)	ng	ng	70 to 210 ppm (FT)	up to 80 ppm (MT)
Te	ng	up to 261 ppm (MT, RT)	ng	ng	ng
Ta	<1 to 4 ppm (MT, RT)	16 to 98 ppm (MT, RT)	16,000 ppm (RT)	287 to 4,095 ppm (FT)	up to 100 ppm (MT)
Zr	<10 to 94 ppm (MT, RT)	ng	ng	ng	ng
Cr	up to 110 ppm (MT, RT)	ng	ng	ng	ng
Ti	<100 to 12,100 ppm (MT, RT)	ng	ng	299 to 1,438 ppm (FT)	up to 4,500 ppm (MT)
V	up to 340 ppm (MT, RT)	ng	ng	ng	up to 500 ppm (MT)
W	<120 to 3,000 ppm (MT, RT)	18 to 111,190 ppm (MT, RT)	ng	up to 2,538 ppm (FT)	up to 16,000 ppm (MT)
Sc	up to 182 ppm (MT, RT)	ng	ng	ng	ng
U	up to 37.6 ppm (MT, RT)	ng	ng	ng	ng
Au	ng	ng	130 ppb	ng	ng
In	ng	up to 394 ppm (MT, RT)	ng	ng	up to 3,000 ppm (MT)

ng: not given. Column 1: Hennig & Hutchinson (1997), data acquired by neutron activation, ICP, ICP–MS). Column 2: Serranti (1998), Serranti *et al.* (1998), data acquired by EPMA and micro-PIXE. Column 3: Cabri *et al.* (1998), dataacquired by SIMS. Column 4: Relvas (2000), data acquired by EPMA. Column 5: Jiang *et al.* (2000), data acquired by EPMA.

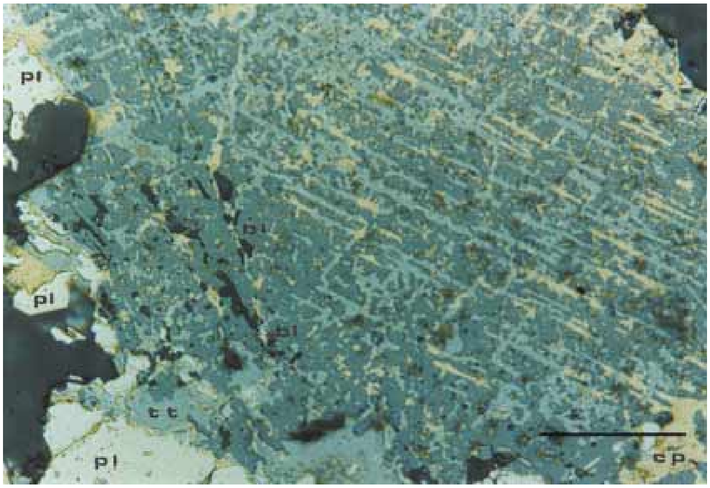

FIG. 12. MH ore type, Graça orebody. The reaction of the later Cu-rich fluids with a sphalerite crystal gives place to the formation both of *chalcopyrite disease* and *tetrahedrite disease*. bl: sphalerite, tt: tetrahedrite, cp: chalcopyrite and pi: pyrite. Scale: 20 mm = 40 μm.

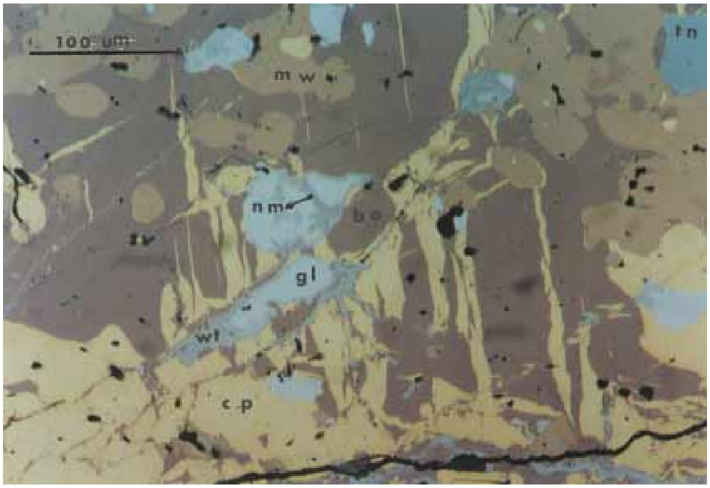

FIG. 13. The bornite-bearing MC ore type, Neves Norte orebody. Complex intergrowths and solid solutions like bornite (bo) – chalcopyrite (cp), tennantite (tt) – mawsonite (mw), and galena (gl) – naumannite (mn) and galena – wittichitinite (wt) are commonly observed. These complex mineralogical associations are very similar to the ones noted in the bornite zone of the Kidd Creek deposit, Ontario, as described by Hannington *et al.* (1999).

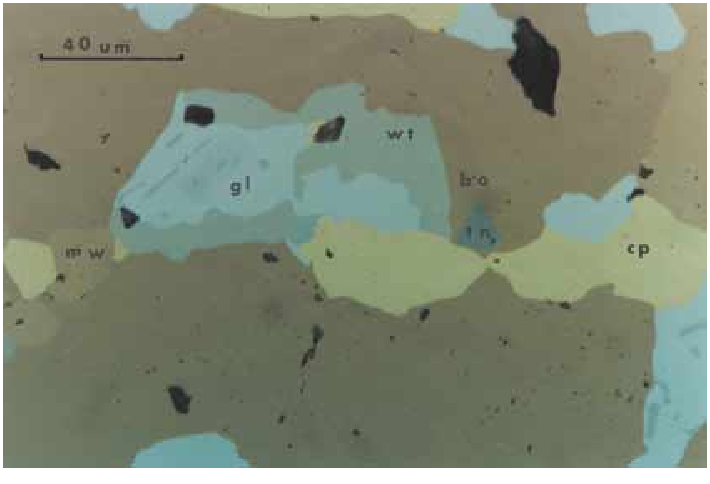

FIG. 14. The bornite-bearing MC ore type, Neves Norte orebody. See the caption for Figure 13.

chalcopyrite that under the microscope shows signs of strong deformation and recrystallization, with development of twinning in some crystals. Pyrite and sphalerite commonly occur along with accessory cassiterite, arsenopyrite, tetrahedrite–tennantite, and minor stannite–kësterite, mawsonite and galena. Small amounts of fine-grained rutile of hydrothermal origin are disseminated throughout the shale as aggregates of tiny micrometric grains elongate parallel to the foliation of the shale. Siderite may be present both as isolated grains and narrow layers developed within the shale. Hydrothermal chloritic alteration of the shale can also be observed in the immediate vicinity of mineralized fractures, commonly occur close to the sulfide veins. Geologists at the mine consider these ores as former stringer copper ores.

The polymetallic massive sulfide ores (*MZ, ME types*)

A total amount of about 47 Mt is estimated for the reserves of the polymetallic ores, which have average contents of 5.98 Zn%, 0.47% Cu, 1.21% Pb and 60 ppm Ag (Table 9). The *polymetallic massive sulfide ores* (MZ type) constitute about 38 Mt of the total reserves and occur at Neves and Lombador orebodies as duplicate thin lenses (~20 m thick) that show a continuous horizontal development. The remaining of the total reserves is mostly located at the southeastern and southwestern borders of the Corvo and Graça orebodies, respectively.

The MZ ore type mainly consists of pristine fine-grained colloform, porous or euhedral pyrite that is commonly intergrowth with chalcopyrite, sphalerite, galena and tetrahedrite. Euhedral crystals of arsenopyrite, bournonite, meneghinite, betekhtinite, pyrrhotite as small inclusions in pyrite, magnetite and rutile occur as accessory minerals. Geopetal, turbidity, slumping, reworking, banded and brecciation textures are recurrent features observed in this massive pyrite ore (Gaspar & Pinto 1991). Owing to lower-greenschist-grade metamorphism, signs of recrystallization, annealing and remobilization of the ductile sulfides abound. Recrystallized sphalerite forms ribbon-like compositional bands with interstitial galena (Fig. 16). Sphalerite generally is replaced by later chalcopyrite, giving rise to the "chalcopyrite disease" texture. Porous and almost transparent sphalerite, attributed to Fe loss as a result of "hydrothermal leaching", like that described by Eldridge *et al.* (1983) in the Kuroko ores, is commonly observed as well. The textures and mineral composition of the MZ ore are very similar to the ones observed in most of the subeconomic polymetallic massive sulfide deposits of the IPB (Gaspar & Pinto 1991).

Stringers and *rubané* ores containing more than 3.3% Zn and less than 2% Cu have been classified as FZ and RT ore types, respectively. Both ore types constitute about 18% of the total resources estimated for the zinc-rich ores from Neves–Corvo.

TABLE 9. RESOURCES AND AVERAGE CONTENTS OF Cu, Pb, Zn AND Ag IN THE POLYMETALLIC ORES (MZ, RZ AND FT ORE TYPES)

Orebody	Resources Mt	Zn %	Cu %	Pb %	Ag g/t
Corvo	5.768	6.65	0.32	1.07	62
Graça	3.090	6.90	0.68	1.11	77
Zambujal	5.270	4.80	0.40	0.90	30
Neves	21.366	5.03	0.53	1.02	56
Lombador	11.283	7.73	0.44	1.80	75
Total reserves and average grades	46.777	5.98	0.47	1.21	60

Reference: Pinto (1999).

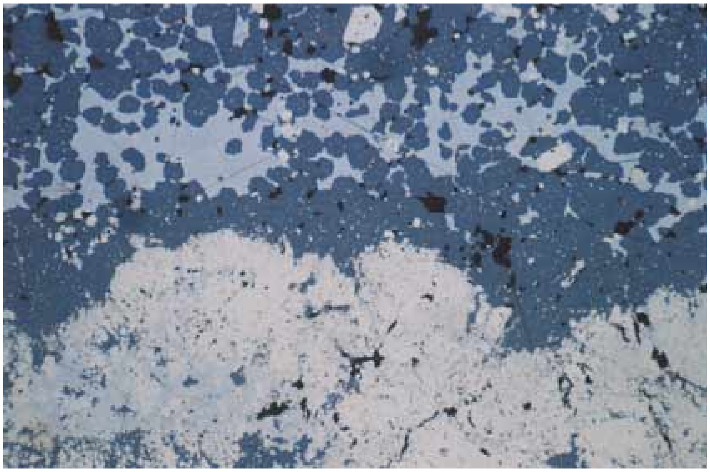

FIG. 15. MZ ore type, Corvo orebody. Owing to deformation and lower-greenschist-grade metamorphism, recrystallization, annealing and remobilization of the ductile sulfides are commonly observed. Recrystallized sphalerite (dark grey) forms ribbon-like compositional bands with interstitial galena. Partly recrystallized pyrite (pale yellow) is intergrown with interstitial tetrahedrite (light grey). Scale: 20 mm = 360 µm.

The lenses of ME ore represents about 68% of the total resources estimated for all massive sulfides occurring at Neves–Corvo (Table 1) and have average contents of <3.3 % Zn, <2% Cu, and <1% Sn. The ME ores is very similar to the MZ ores in terms both of their qualitative mineralogical composition and textural patterns. The two different designations of such similar ores results only from the fact that the ore classification established by SOMINCOR at the mine has been mostly based on the cut-off grades established both for valuable and deleterious metals. MZ ores with contents up to 3% Zn occur in every orebody (Fig. 17). The polymetallic massive ores are assumed to correspond to a pristine volcanogenic massive sulfide ore not affected by the later mineralization responsible for the high copper contents. In fact, a continuum of mineral compositions and textures of the ores that constitute Neves Norte and Neves Sul has been established between the different orebodies (Gaspar & Pinto 1991).

Although it is assumed by some authors that the deposition of the massive sulfides from Neves–Corvo is not a result from venting of hydrothermal fluids on the sea floor (Relvas 2000), mineral textures similar to the ones described in recent deposits have been commonly observed both in the MZ and ME ores (Figs. 18, 19).

At Neves Norte, the FE stringer ores mainly consist of quartz, pyrite and arsenopyrite, along with minor galena, sphalerite, chalcopyrite, stannite and tetrahedrite, and have average contents of 0.02% Cu, 0.32% Pb, 0.06% Zn, 3.58% As, 894 ppm Sb, 700 ppm Sn, 78 ppm Bi, 19 ppm Ag and 11 ppm Hg. In some samples of the FE ores, erratic high gold contents attain 4 g/t (SOMINCOR, internal report). Electron-microprobe and SIMS analyses of six samples of FE ore show that arsenopyrite is the main carrier of gold. Gold contents up to 1,000 ppm, determined in the core of one arsenopyrite crystal, decrease to 50 ppm toward the rim (A. Pinto, P. Marion and A. Ferreira, unpubl. report). Particles of free gold were not found.

The Occurrence of High Tin Contents

Neves–Corvo contains in excess of 300,000 tonnes of tin allocated to the several types of ore, with Sn grading from 400 ppm up to some 60.0%, depending on ore type. These Sn values are quite unique, considering both the range (6 ppm to 0.77%) and average contents (395 ppm) found in 78 samples from different types of mineralization collected in 25 Spanish deposits of the IPB (Leistel *et al.* 1994). At Aljustrel, as in other volcanogenic massive sulfide deposits in the Portuguese sector of IPB, bulk samples of ore seldom contain more than 500 ppm Sn, and ore microscopy studies have shown that Sn grade is essentially linked with fine-grained cassiterite (crystals mostly <10 μm) included in sphalerite. Tin can also occurs as stannite that usually forms a rim at the contact of sphalerite with chalcopyrite, or less frequently as blebs in sphalerite. Cassiterite as an inclusion in sphalerite has not yet been found in the copper-rich massive sulfides (MC and MS types) from Neves–Corvo. The unusually large contents of tin mainly observed in the Corvo and Graça orebodies reflects the occurrence of a complex suite of mineral associations formed by cassiterite and Cu–Sn sulfides.

The massive cassiterite ore lenses (*MT type*) *and the tin-bearing rubané ore* (*RT type*)

The present spatial distribution of the tin mineralization in the various orebodies, according to Richards & Ferreira (1992), is controlled by the major tectonic discontinuities that follow the same N–NE trend. Massive cassiterite cross-cut by chalcopyrite veins occurs as meter-sized discrete lenses (MT ore) and has been mostly found in discordant contact both at the base and top of the cupriferous massive sulfide ores at Corvo. Most of the Corvo orebody is overlain by the so-called *rubané* ore that is made up of veins, consisting either of banded chalcopyrite (RC ore) or cassiterite (RT ore), both developed within a deformed shale horizon that was extensively altered to a fine-grained quartz–chlorite assemblage. The cassiterite-bearing veins encompass a number of types, both in increasing degree of complexity of their constituent minerals and textural relationships. The veins show evidence of repeated opening and limited movement that resulted in extensive fracturing of their constituent minerals. Local shearing and the introduction of later styles of mineralization superimposed upon the earlier cassiterite-rich assemblages were observed. In the *rubané* ore (RT), cassiterite is an early phase, generally intergrown with quartz and siderite or dolomite. A significant amount of pyrite was introduced toward the waning stages of cassiterite precipitation (Fig. 20). Later veins of pyrite along with chalcopyrite cut across and partly replace cassiterite (Fig. 21). The cassiterite crystals from the massive lenses are euhedral to subhedral and are commonly markedly elongate or prismatic. Individual crystals range between 150 μm and 2 mm in size, generally showing growth banding and fracturing. In the massive cassiterite ores (MT type), a later period of mineralization, linked to extensive fracturing, resulted in complex chalcopyrite – stannite – sphalerite – pyrite assemblages (Fig. 22). Minor amounts of arsenopyrite, chalcopyrite, sphalerite, galena and löllingite have been observed sporadically within the ores. Signs of a reaction between cassiterite crystals and later fluids carrying sulfides are also observed, in some cases producing a halo of stannite.

The FT ores occur as tin-rich stringers at the base of massive sulfides and in the middle both of the tin-bearing copper-rich massive sulfide ore (MS) and tin-poor (<1.0% Sn) copper-rich massive ores (MC ore). A direct spatial relationship either with the MT ore or with the RT ore was not found at the mine, although the trace-element signatures indicate some resemblance of the three types of ore. The cassiterite in both the MT and RT ores is different from that observed in the tin-poor cupriferous massive ore (MC), in terms of grain size, growth habit and mineralogical association. Either in MT or in RT ores, cassiterite has not, so far, been found in association with sphalerite. The color of cassiterite from MT, RT and FT ores in transmitted light under the microscope varies between light reddish brown and pale yellow, and both compositional zoning and evidence of strong deformation have been observed. Strong zoning of minor and trace elements in cassiterite was confirmed by Serranti (1998), who reported on 11 cassiterite grains ranging in Fe content from 0.25 to 2.19 wt% FeO, as determined by electron-probe micro-analysis. Two cassiterite crystals from RT samples that show no growth zoning were analyzed by Neiva (1996); 0.18 wt% FeO was found in a pale yellow crystal, and 1.93 wt% FeO in a brown crystal. Hennigh & Hutchinson (1997) found that 90% of all cassiterite samples contain between 0.25% and 0.60% Fe, and that unlike the contents of Sc, Ti, V and Cr, which decrease from stockwork varieties of ore to massive ore, there is no consistent trend in Fe content from one ore type to another. Serranti *et al.* (1997), Hennigh (1996) and Hennigh & Hutchinson (1997), Cabri *et al.* (1998), Relvas (2000), Jiang *et al*. (2000) also reported trace-element data for several ore minerals from the massive sulfide lenses at Corvo. All the cassiterite shows low concentrations of Ti, Nb, Ta, As and V. In most cases, the cassiterite from massive tin lenses exhibits high contents of W (up to 1.6%) and Fe (up to 2.5% FeO), with both elements decreasing in content from the center to the rim of crystals, following the pattern of zonal growth (Table 7). Analytical data published by Cabri *et al.* (1998) for a Sn-rich (31% Sn) *rubané* sample from Neves–Corvo gave 130 ppb Au and 5,700 ppb As, in addition to 1.6% Ta.

The paragenesis, grain size and composition of the cassiterite found in the MC ores, which in fact are relics of the pristine polymetallic ores (MZ type), are very similar to those of cassiterite found both in the massive sulfides from the Aljustrel deposit (Gaspar 1984, 1996) and the cassiterite found in the Kidd Creek deposit which, as proposed by Hannington *et al.* (1999a, b), belongs to a low-temperature, polymetallic suite enriched in Zn and Sn.

Electron-probe micro-analyses of cassiterite from MC ores carried out by J. Bowles (Mineral Science Ltd., unpubl. reports) have shown that they contain between 200 and 1,400 ppm In, whereas indium contents up to 3,000 ppm were found both by J. Bowles and Jiang *et al.* (2000) in cassiterite both from the MT and RT ores.

THE OCCURRENCE OF GOLD

The gold potential of the IPB deposits is significant, with geological resources of gold estimated at 920 t from about 1,700 Mt of massive sulfides. Marcoux *et al.* (1996) and Leistel *et al.* (1998a, b) reviewed the mineralogy and geochemistry of many Spanish VMS of the IPB and made some observations on three Portuguese ore deposits. They reported that these deposits generally contain from 1 to 1.5 g/t Au (exceptionally up to 50 g/t), but with lower Au grades in the massive sulfides of the Portuguese deposits. Marcoux *et al.* (1996) indicated that stockworks and interaction zones at the base of the massive sulfides in the IPB contain both an early Co stage with cobalt sulfarsenides, and a later high-temperature (>300°C) Cu–Bi–(Te–Se) stage with chalcopyrite and Pb–Cu–Bi sulfosalts. Detailed mineralogical and geochemical studies of IPB deposits in Spain led Leistel *et al.* (1998b) to define two types of gold association: (a) an early higher-temperature (>300°C) association of Au (with Co ± Bi) enriched in stockworks and zones of interaction at the base of the sulfide mounds, and (b) a later, lower-temperature (<280°C) generation of Au enriched in polymetallic sulfides (Zn + Ag ± As ± Tl ± Hg) in a distal position or beneath massive sulfides. In the first association, gold mostly occurs as small (<10 μm) grains of Au–Ag alloy associated with Bi minerals, as inclusions within cobaltite or alloclasite, or attached to cobalt minerals in chalcopyrite. The Au in the second association occurs as Au–Ag alloy and gold-bearing needle-shaped arsenopyrite and pyrite within a polymetallic association (predominantly Pb–Zn). Leistel *et al.* (1998) reported results of laser-ablation microprobe – inductively coupled plasma – mass spectrometry (LAM–ICP–MS); gold contents range between 15 and 3,150 ppm (average 280 ppm) in arsenopyrite, and between 200 and 500 ppb in pyrite (analyses done by R.W. Nesbitt, *in* Cabri *et al.* 1998).

Grades of gold seldom exceed 1 g/t in the Zn – Pb ± Ag massive sulfides at Aljustrel (Pirites Alentejanas, SA, unpubl. report), and most are 0.5 g/t in the cupriferous massive sulfide MC ores from Corvo, Graça and Neves Norte orebodies (SOMINCOR). There is some information published about the occurrence or distribution of gold in the Neves Norte and Lombador orebodies (Ferreira *et al.* 1997). The gold content in the Neves–Corvo zinc-rich massive ore (MZ type) has not, to date, been systematically estimated, but from fire-assay data, it is assumed by the mine geologists to be predominantly lower than 1 g/t. Fire assays of drill-core intersections of stringer FC ores from the Lombador orebody reveal contents of 15 g/t Au over 3 meters with a value of 22.6 g/t for the central one-meter of core, and 94.5 g/t for the richest part. A one-meter drill-core intersection of the Neves Norte bornite-rich MC3 ore, located at the top of stringer zones, gives assays of up to 10 g/t Au, and as much as 33 g/t over 0.2 m of core (Ferreira *et al.* 1997, Pinto *et al.* 1994, 1995, 1997). The gold in MC3 and FC ores from Neves Norte and Lombador, respectively, occurs along with unusual assemblages of minerals (Tables 6, 7). Remarkable contents of gold, up to 4 g/t, have been found in FE stringer ore from Neves–Corvo that mainly consist of quartz, arsenopyrite and pyrite;

FIG. 16. ME ore type, Corvo orebody. The ore is mostly formed by bands of fine-grained sphalerite in a matrix of porous pyrite that in some places carry small grains of galena (at bottom of the figure). Scale: 20 mm = 720 μm.

FIG. 17. Mineral textures similar to the ones described for the recent submarine (seafloor) deposits have been commonly observed both in the MZ and ME ores from Neves–Corvo. Banded intergrowths of chalcopyrite (yellow) and tetrahedrite (bluish grey) in a matrix of colloform pyrite, similar to the ones observed in modern submarine sulfide deposits at the East Pacific Rise (21°N) by Oudin (1981).

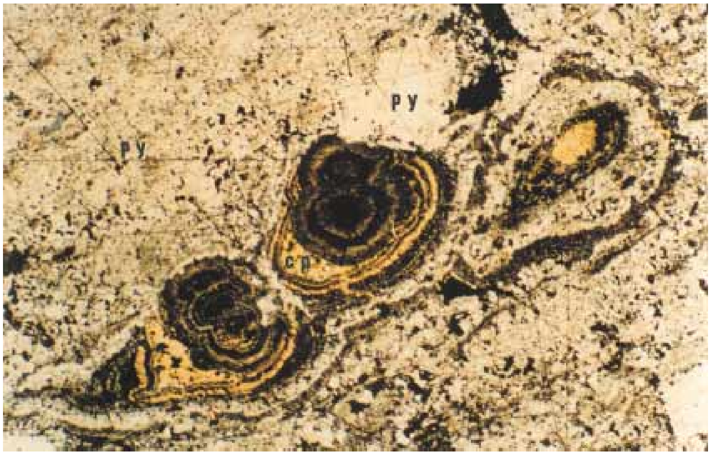

FIG. 18. Mineral textures similar to the ones described for the recent submarine (seafloor) deposits have been commonly observed both in the MZ and ME ores from Neves–Corvo. Concentric zonation of melnikovite – pyrite and chalcopyrite in a matrix of porous colloform pyrite very similar to that observed in sulfide deposits in Cyprus (Oudin & Constantinou 1994). Scale: 20 mm = 360 μm.

FIG. 19. MT ore type, Corvo orebody. A large meter-sized lens of massive cassiterite located at the top of a lens of massive MC cupriferous ore. At the top of the MT lens, the chloritic schist (xcl) and the tin ore (RT) both form the *rubané* unit.

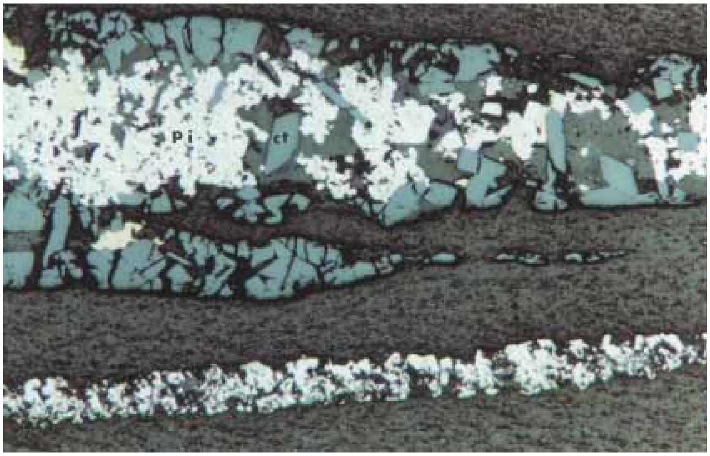

FIG. 20. RT ore type, Corvo orebody. In the rubané tin ore, the cassiterite as an early phase forms bands in the chloritic schist and generally occurs intergrown with pyrite, quartz and siderite or dolomite. Scale: 20 mm = 720 µm.

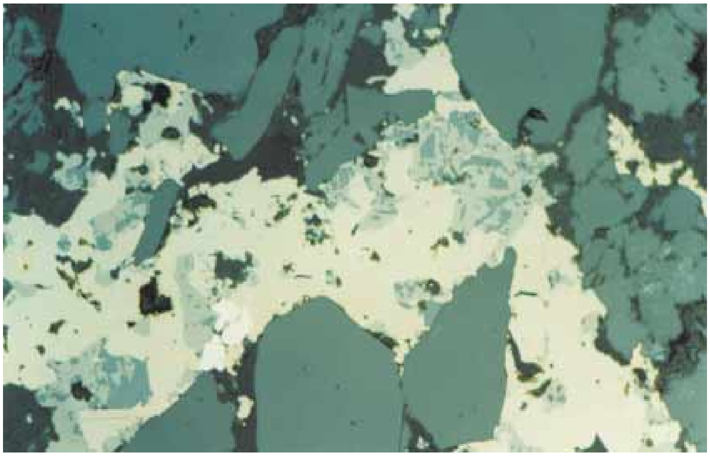

FIG. 21. MT ore type. As a result of a later period of mineralization, related to extensive fracturing, cassiterite is replaced by complex chalcopyrite – stannite – sphalerite – pyrite assemblages. Scale: 20 mm = 180 µm.

the "invisible gold" is mainly carried by arsenopyrite, although pyrite could carry some gold as well (up to 1,000 ppm). Free gold has not been observed.

No direct quantitative correlation between cassiterite and sulfides occurrences has so far been established. The first results obtained on gold occurrence in the *rubané* and massive tin ores (MT and MR) were presented and discussed by Cabri *et al.* (1998) on the basis of bulk assays, ore microscopy, image analysis, LAM–ICP–MS and ion-microprobe analyses (SIMS) of minerals in hand samples from massive and *rubané* tin ores (MT and RT), as well as from a sample of high-grade tin concentrate. Because cassiterite from two different types of ore (MS and RT) is used to prepare the tin concentrate, that sample (collected in September 1997) probably represents a mixture of two different generations of cassiterite.

For all samples, arsenopyrite that occurs as isolated grains shows concentrations in the range from 0.036 to 2.719 g/t Au, and recrystallized pyrite, from 0.048 to 0.737 g/t Au, whereas syngenetic colloform pyrite had either no gold detected or lower contents than the recrystallized crystals of pyrite. Average concentrations of gold for samples from massive lenses (MT ore) are 1.117 g/t in arsenopyrite and 0.070 to 0.504 g/t in pyrite in tin concentrates from MS and RT. No grains of gold were found by optical microscopy. A few small inclusions of an unidentified Bi–Te–Se mineral (containing trace amounts of As and Pd) were found included in cassiterite. A SIMS analysis of chalcopyrite and stannite that cut across cassiterite in the samples of RT ore shows that they do not carry gold. In the high-grade Sn concentrates, mineralogical balances for gold show that arsenopyrite and pyrite account for only 12% of the gold and that the unaccounted portion is significant (88%). In MT ores, which are richer in As, "invisible gold" accounts for about 42% of the sample, distributed between arsenopyrite (18.0%), colloform pyrite (21.3%), and recrystallized pyrite (3.0%), leaving 57.7% unaccounted for.

No native gold or Au–Ag alloy is present in the samples studied. Because cassiterite is the dominant mineral, Cabri *et al.* (1998) considered cassiterite as a possible host for gold and suggested that up to 14 ppm Au occurs in Neves–Corvo cassiterite. Mineralogical balances, admittedly carried out with limited data, suggest that up to about 42% of the gold may be accounted for by arsenopyrite and pyrite for RT and MT ores in the Corvo deposit. Cabri *et al.* (1998) also assumed that the missing gold occurs in the cassiterite structure, so that the cassiterite from massive lenses could contain about 133 ppb Au (57% of the total Au) and a similar content of about 149 ppb Au in cassiterite of the high-grade Sn concentrate (88% of the total Au). These analytical results are the first to suggest the possibility that cassiterite may be a gold carrier in the VMS deposits of the Iberian Pyrite Belt.

At Neves–Corvo, gold occurs both in a distal position in MZ ore from all orebodies (≤1 g/t according to SOMINCOR) and in FC stringer ore from Corvo (≤4 g/t, according to A. Ferreira, P. Marion and A. Pinto, unpubl. report). Significant gold contents have so far only been observed in FC ores from Lombador and in bornite-rich cupriferous massive MC3 ores from Neves Norte. The geochemical, mineralogical and spatial associations of gold observed in MZ and Fe ore are similar to those in the low-temperature facies with a polymetallic (Zn + Ag ± Tl ± Hg) signature, as proposed by Leistel *et al.* (1998a, b) for the Spanish deposits in the IPB. The paragenesis, mineral chemistry and spatial distribution of the gold-rich mineral associations observed in the stringer FC ore from Lombador (Table 6) and in the bornite-rich cupriferous massive ores (MC3 type) from Neves Norte (Table 7) are similar, respectively, to the early Co stage with cobalt sulfarsenides and Bi sulfides, and to the later-stage assemblages at the base of the massive sulfides, deposited from high-temperature (>300°C) fluids rich in Cu, Bi, Te and Se, along with large amounts of chalcopyrite with Pb–Cu–Bi sulfosalts, as proposed by Marcoux *et al.* (1996).

Discussion and Conclusions

The geotectonic complexity and scarcity of geological data on the Neves–Corvo deposit and its surroundings have not so far allowed a complete understanding of the structure of the deposit, nor the paleogeographic environment in which it formed. Hence the establishment a consistent metallogenetic model embracing all Neves–Corvo ores remains a difficult task. There is some controversy concerning both the genesis and the geological structure of the tin- and copper-rich ores in the Neves–Corvo deposit, particularly those at the Neves Norte, Corvo and Graça orebodies. The thin-skinned style of late Hercynian deformation played a major part in determining the present geological structure of the deposit, and the location and metamorphism of the tin-rich and copper-rich ore. In addition, tectonism during ore deposition was important. Textures due to brittle tectonic deformation are commonly developed in all ore types and are syngenetic, and also arose during later events. Synsedimentary folds (mainly involving sphalerite in fine-grained porous pyrite), geopetal, reworking and clastic textures have been widely observed in the massive sulfide ores. Banded and remobilization textures mainly involving chalcopyrite + tetrahedrite–tennantite, tin sulfides and sphalerite + galena are common in the cupriferous massive ores.

Mainly on the basis of trace elements found in cassiterite from different varieties of tin ores (Table 8), Hennigh (1996), Hennigh & Hutchinson (1997), Relvas (2000) and Jiang *et al.* (2000) suggested that the cassiterite from MT and RT ores formed from magmatic fluids related to a high-level intrusive body of tin-rich granite. Recently, data on oxygen and hydrogen isotope data were published by Relvas (2000), Relvas *et al.* (2000), and Munhá *et al.* (2000) in support of this inference. On the basis of both ore petrology studies of the different types of ore and the information provided by SOMINCOR geologists, Gaspar (1991) concluded that the cassiterite from MT and RT ores predates all other occurrences of cassiterite at Neves–Corvo.

The highest Cu contents have been observed in the bornite-rich MC ores, along with high contents in Sn, Bi, Co, Hg, Se, In, Ag (MC3 subtype ore), with an average content of 28% Cu, in the MC tin-bearing cupriferous massive ores (MS subtype ore with an average content of 15.2% Cu), and in MC massive cupriferous ores with high contents in Zn, Hg, Ag, Sb, As and Sn (MH subtype ore with an average content of 14.5% Cu). The MC3 and MH ores are located at the top or not far from stringer-type ores that are structurally linked to NNE faults.The large variety of Cu, As, Sn Co, Bi, Te (Se) and Ag sulfosalts at Neves–Corvo is similar to that encountered in stringer ores of the Spanish sector reported by Marcoux & Moëlo (1993), Marcoux & Leistel (1996), Marcoux *et al.* (1996) and Leistel *et al.* (1998a).

Ore petrology and mineral chemistry studies indicate that: 1) The cassiterite occurring in MT and RT ores and, to some extent, in MS ores, is similar, whereas the cassiterite from MC ore shows a different mineral association, texture and trace-element composition. Cassiterite in MT and RT ores is relatively enriched in Fe, W, Ti, Sc and In, and contains erratic but substantial concentrations of Ta, Nb and Zr. 2) The bornite-rich MC3 ores from Neves Norte (Table 6) are remarkably similar to those of the bornite zone at Kidd Creek, and the mineralogical associations and geochemistry of the MH ores (Tables 2, 4, 5) are similar to the tetrahedrite front at that deposit, as described by Hannington *et al.* (1999b). 3) The geochemical and mineralogical characteristics and gold associations observed both in the stringers (FC type) and in the MC3 ore type from Neves Norte are similar to those observed in the gold-bearing stringers and transition zones in some deposits in the Spanish sector of the IPB (Marcoux & Leistel 1996, Marcoux *et al.* 1996), which are attributed to a late high-temperature (>300°C) Cu–Bi–(Te–Se) stage. Gold (content ≤1 g/t) also occurs in FE and MZ ores, which are similar to the typical polymetallic ores from the low-temperature facies with (Zn + Ag ± Tl ± Hg) signatures proposed Leistel *et al.* (1998b).

Macro- and micro-scale research so far suggests the following sequence of events: a) deposition of the tin-rich ores (MT, RT and FT types); b) protracted formation of the polymetallic massive sulfide ores, mainly the MZ and ME type, responsible for about 86% of the total Neves–Corvo resources, as in most of the deposits in the Iberian Pyrite Belt, and c) a later anomalous Cu-enrichment confined to discrete zones of the polymetallic massive sulfides (MC and MS type), that also gave rise to interaction zones like the bornite-rich ores (MC3 type) and ores rich in chalcopyrite – sphalerite – tetrahedrite–tennantite, and enriched in Zn, Hg, Ag, Sb and As (MH type).

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