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AU/AG RATIO VARIATIONS AT MINA III, MINA NOVA AND MINA INGLESA GOLD DEPOSITS, CRIXÁS GREENSTONE BELT, BRAZIL

PAULO DE TARSO FERRO DE OLIVEIRA FORTES[1], ROQUE FERNANDES COELHO[1] AND GASTON GIULIANI[2]

ABSTRACT The Mina III and Mina Nova gold deposits occur at the transition between metabasic volcanic rocks and chemical and detrital metasedimentary rocks, while Mina Inglesa occurs within metakomatiites, all in the Archean Crixás Greenstone Belt. Mina III contains three main mineralized zones: the Upper (UOZ-ms), Lower (LOZ-qv and LOZ-cs) and Garnet (GOZ) Ore Zones. The UOZ-ms is composed of massive sulfide lenses within Fe-dolomitic marbles and Fe and Al-rich rocks. A concordant quartz vein within carbonaceous schists represents the LOZ-qv, while the LOZ-cs consists of an arsenopyrite-pyrrhotite-bearing carbonaceous schist close to the quartz-vein contact. The GOZ comprises concordant quartz veins within quartz-chlorite-muscovite-garnet schist. At Mina Nova, two main ore zones occur: the Orebody 1 (OB1-cs), consisting of an arsenopyrite-pyrrhotite-bearing carbonaceous schist and the Orebody 2 (OB2-cm), represented by a carbonate-muscovite schist lenses within carbonaceous schist). Mina Inglesa has one mineralized concordant quartz vein (MOB) within talc schists. Mineralogical characterization of the orebodies indicates gold association with arsenopyrite, pyrrhotite, chalcopyrite, carbonate, quartz, micas and oxides at the UOZ; with quartz, carbonaceous matter and arsenopyrite, and less frequently with carbonate, pyrrhotite and micas at the (LOZ-qv and LOZ-cs); mainly with quartz, micas and arsenopyrite, and more rarely with chalcopyrite and oxides at the GOZ; with arsenopyrite, pyrrhotite and carbonate at the OB1; with carbonate, muscovite and arsenopyrite at the OB2; and with quartz and galena at the MOB. Microprobe analysis in individual gold grains of all ore zones indicate very low values of other elements (less than 0.5 wt. %). The identified Au/Ag ratio variations are intimately associated with host minerals or mineral associations of each ore zone. Initial Au/Ag ratios in source-rocks, transport (hydrosulfide and chloride complexes) and deposition mechanisms (fluid-rock interactions and fluid immiscibility) may have had great importance in the observed chemical variations.

Keywords: Au/Ag ratio, greenstone belt, Crixás, Brazil

INTRODUCTION The Mina III and Mina Nova are the most important underground gold mines in the Crixás region. They have, respectively, reserves of 5.2 million tons of ore with an average grade of 12.7 g Au/ton (Yamaoka and Araújo 1988), and of 3.0 million tons of ore with an average grade of 6.0 g Au/ton (W.N. Yamaoka, personal communication, 1994). Mina Inglesa has unknown reserves and a poorly estimated average grade of 4.5 g Au/ton and is exploited by underground semi-mechanized methods (*garimpo*). The Au/Ag ratio, usually expressed as fineness, has been used as criteria to identify the geological and geochemical context of gold deposits. This paper presents partial results of the orebodies mineralogical characterization studies, concerning host minerals and mineral chemistry of gold grains from different ore zones of different gold deposits in the Crixás Greenstone Belt.

GEOLOGICAL SETTING The Mina III, Mina Nova and Mina Inglesa gold deposits are situated in the Crixás greenstone belt (Saboia 1979), of Archean age (Arndt *et al.* 1989). The belt is represented by metakomatiites of the Córrego Alagadinho Formation, metabasalts of the Rio Vermelho Formations and chemical and detrital metasediments of the Ribeirão das Antas Formation (Saboia *et al.* 1981), Crixás Group (Jost and Oliveira 1991). The volcano-sedimentary sequence is bordered by the Archean to Palaeoproterozoic granite-gneissic rocks of the Anta and Caiamar Complexes, and covered, in the north, by Neoproterozoic metasedimentary rocks (Fig. 1).

The Mina III gold deposit comprises a strongly deformed, metamorphosed and hydrothermally altered sequence of rocks. Amphibole schists and quartz-chlorite-carbonate-muscovite schists are interpreted as metabasic rocks, while Fe-dolomitic marbles, carbonaceous schists, quartz-chlorite-muscovite-garnet schists and feldspathic schists are considered as metasedimentary rocks (Fig. 2). Three main mineralized zones occur: the Upper, Lower and Garnet Ore Zones (Yamaoka and Araújo 1988). Intense hydrothermal alteration, including carbonatization, sericitization, sulfidization and silicification, is associated with and post-dates the metamorphic peak of epidote-amphibolite facies (Thomson 1986, Thomson and Fyfe 1990). The Upper Ore Zone (UOZ-ms) consists of irregular massive sulfide bodies, 0.5 to 2.5 m thick, composed mainly of arsenopyrite and/or pyrrhotite with variable proportions of both sulfides so that in parts of the orebody either arsenopyrite or pyrrhotite predominates. The massive sulfide is associated with muscovite schists, chlorite-garnet schists, magnetite schists and biotite marbles within a sequence of Fe-dolomitic marbles and quartz-chlorite-carbonate-muscovite schists. The Lower Ore Zone is a 0.5 to 3.0-m thick concordant quartz vein within carbonaceous schists (LOZ-qv) or by arsenopyrite-pyrrhotite-bearing carbonaceous schist (LOZ-cs) close to the contact with the vein. The Garnet Ore Zone (GOZ-cg) comprises centimetric, concordant quartz veins within quartz-chlorite-muscovite-garnet schists (Fortes 1996, Coelho 1999).

The geology of the Mina Nova deposit is quite similar to that of Mina III, but they differ in the absence of the UOZ since the Fe-dolomitic marbles have no complex lithological association, and the

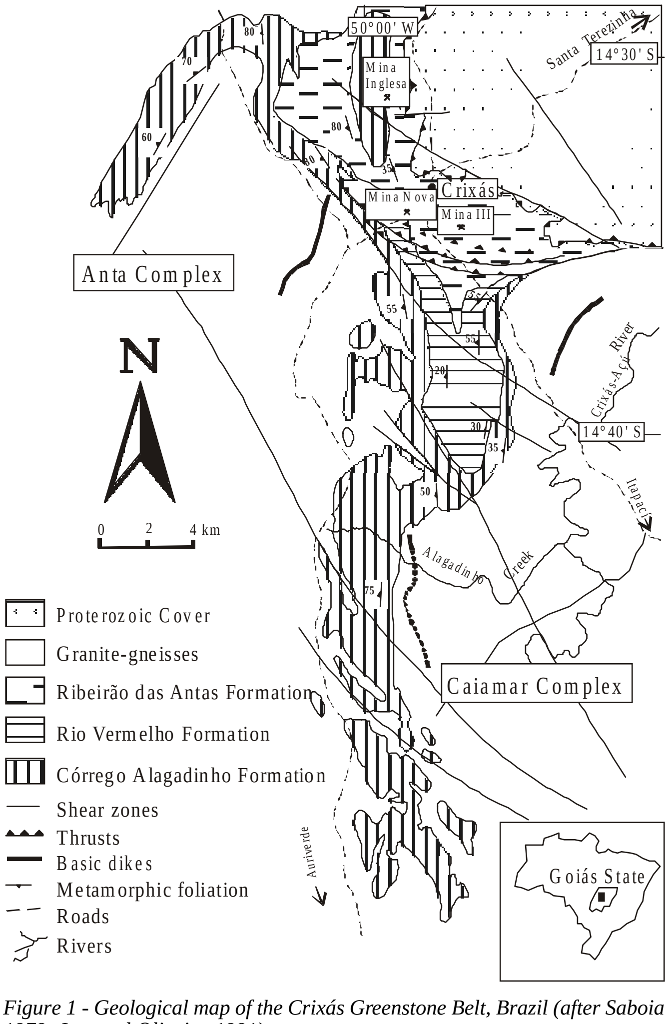

Figure 1 - Geological map of the Crixás Greenstone Belt, Brazil (after Saboia 1979, Jost and Oliveira 1991)

1 - Instituto de Geociências, Universidade de Brasília, Brasília, DF, Brazil, 70910-900
2 - ORSTOM/CRPG-CNRS, BP 20, Nancy, France, 54501

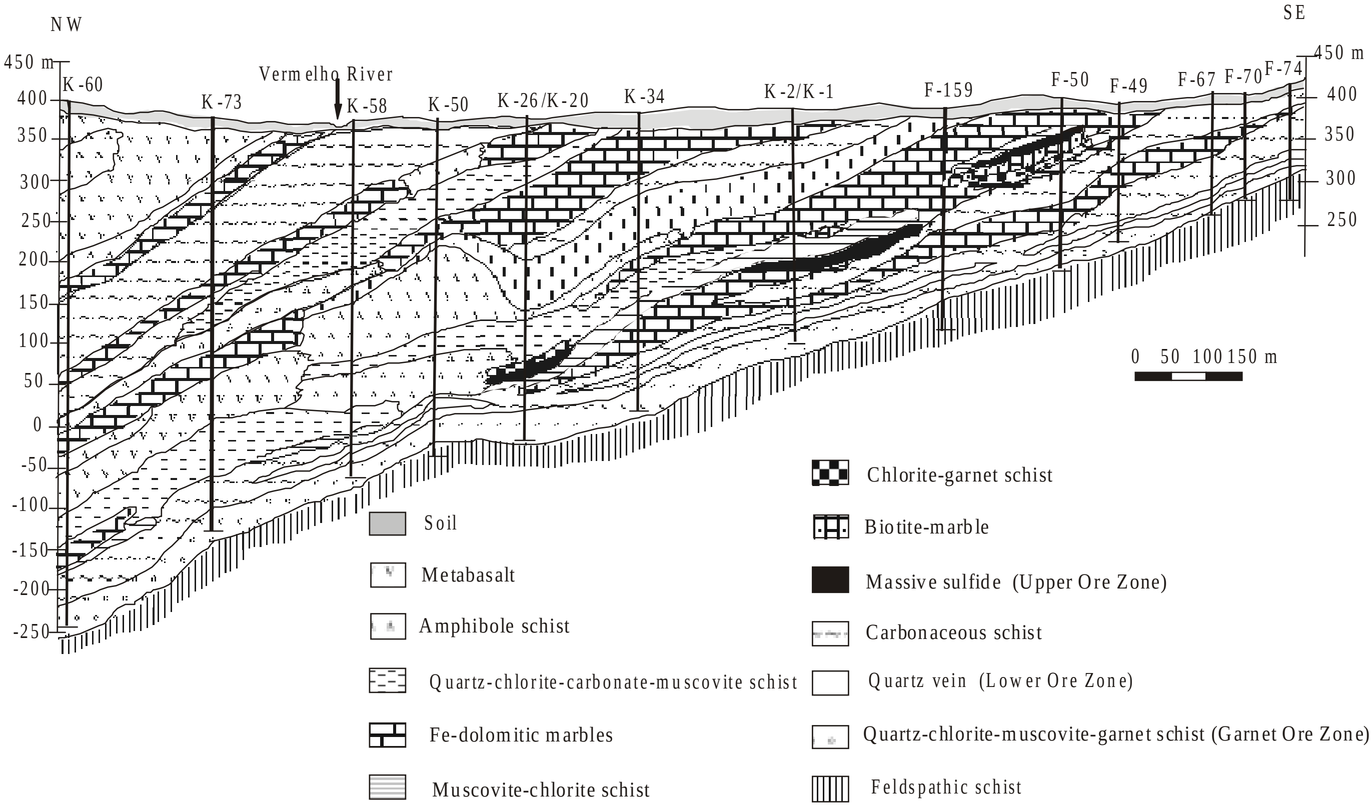

Figure 2 - Cross-section drawn by correlation of drill-holes in the Mina III region, Crixás Greenstone Belt, Brazil (after Fortes 1996)

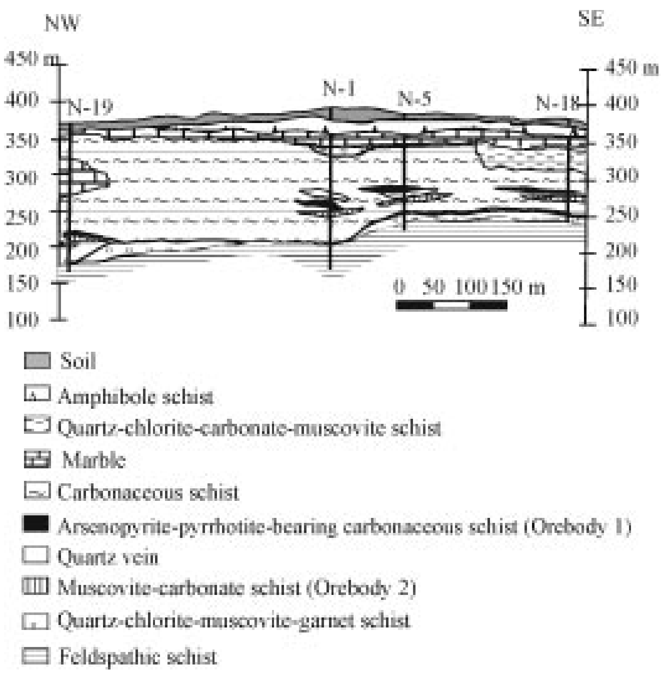

Figure 3 - Cross-section drawn by correlation of drill-holes in the Mina Nova region, Crixás Greenstone Belt, Brazil (after Fortes 1996)

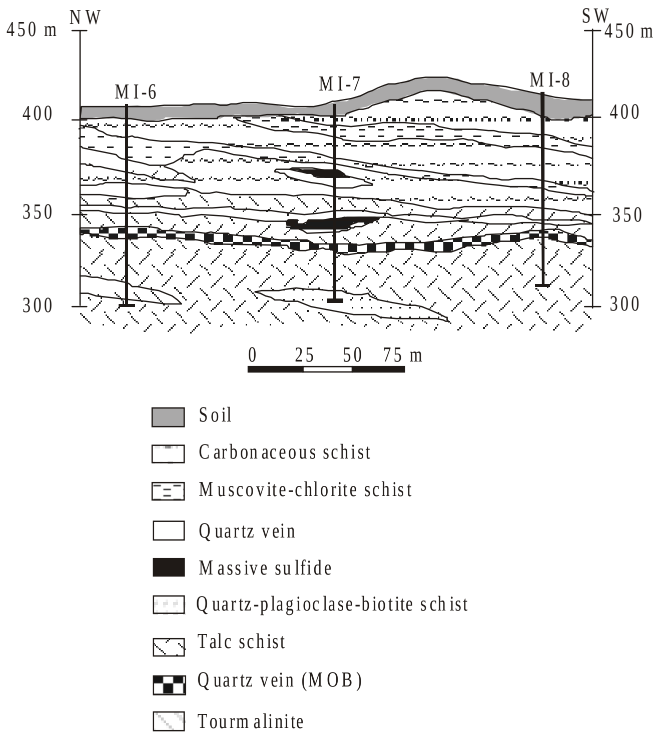

Figure 4 - Cross-section drawn by correlation of drill-holes in the Mina Inglesa region, Crixás Greenstone Belt, Brazil (after Fortes 1996)

reduced width and discontinuous nature of the concordant quartz vein within the carbonaceous schist as compared to the LOZ. Two types of ore occur: Orebody 1 (OB1-cs) and Orebody 2 (OB2-mc) (Fig. 3). The OB1 is an arsenopyrite-pyrrhotite-bearing carbonaceous schist, 1.5 to 2.8 m thick, with abundant concordant decimetric folded quartz veins. The OB2 is a discontinuous lens of muscovite-carbonate schist, 0.3 to 1.7 m thick, within carbonaceous schist (Fortes 1996, Coelho 1999).

The Mina Inglesa gold deposit contains one concordant quartz vein (MOB-qv), 3.0 to 5.0 m width, within talc schist that occurs in a sequence of carbonaceous schist, muscovite-chlorite schist, quartz-plagioclase-biotite schist, tourmalinite and massive sulfide (Fig. 4).

Table 1 - Modal mineralogical composition (%) of the Upper Ore Zone (UOZ-ms, massive sulfide), Lower Ore Zone (LOZ-qv, quartz vein LOZ-cs, carbonaceous schist) and Garnet Ore Zone (GOZ-cg, quartz-chlorite-muscovite-garnet schist) from Mina III, Ore Body 1 (OB1-cs, carbonaceous schist) and Ore Body 2 (OB2-mc, muscovite-carbonate schist) from Mina Nova and Main Ore Body (MOB-qv, quartz vein) from Mina Inglesa gold deposits, Crixás Greenstone Belt, Brazil (after Fortes 1996, Coelho 1999)

	UOZ ms	LOZ qv	LOZ cs	GOZ cg	OB1 cs	OB2 mc	MOB qv
arsenopyrite	40 %	1 %	5 %	5 %	5 %	5 %	1 %
pyrrhotite	40 %	1 %	5 %	5 %	5 %	5 %	1 %
chalcopyrite	2 %	trace	trace	trace	trace	trace	-
galena	-	-	-	-	-	-	3 %
ilmenite	2 %	trace	trace	trace	trace	trace	-
magnetite	1 %	-	trace	trace	trace	trace	-
quartz	3 %	90 %	25 %	20 %	20 %	15 %	95 %
carbonate	3 %	3 %	15 %	5 %	20 %	20 %	-
plagioclase	2 %	trace	trace	trace	trace	trace	-
muscovite	1 %	trace	7 %	15 %	15 %	45 %	-
biotite	4 %	trace	8 %	10 %	trace	3 %	-
chlorite	2 %	trace	5 %	15 %	trace	2 %	-
carbonaceous matter	-	5 %	30 %	10 %	35 %	5 %	-
garnet	-	-	-	15 %	-	-	-
tourmaline	-	-	trace	trace	-	-	-

All ore zones show a strong structural control, related to intersection and/or elongation lineations parallel or sub-parallel to the axis of semi-recumbent and asymmetric folds. These secondary structures formed by ductile progressive simple shear that also developed a penetrative axial-plane foliation. The genesis of the deposit favors a hydrothermal-mesothermal model associated with the development of a regional shear zone (Fortes and Giuliani 1995), probably related to the Brasiliano Cycle (± 500 My) (Fortes *et al.* 1997).

Table 1 presents the modal mineralogical composition for each ore zone.

GOLD OCCURRENCE About 100 thin polished sections were investigated, being representative of ore samples. The microscopic study was held by using 10, 20, 40 and 100 X objectives under transmitted and reflected light. Gold grains have regular or irregular forms, the former including quadratic, circular, rectangular, elliptical or triangular forms. About 1,700 gold grains were observed, of which 65 % are more than 2,500 μm^2, 21 % varies from 500 to 2,500 μm^2, 11 % from 70 to 500 μm^2, 2.5 % from 10 to 70 μm^2 and 0.5 % from 0.01 to 10 μm^2. The occurrence of the gold grains is described in terms of host minerals and mineral associations. Gold grains are completely enclosed in the host minerals, such as arsenopyrite, quartz, carbonate and oxides; occur at the border between grains of pyrrhotite, chalcopyrite, galena, oxides, quartz, carbonate, muscovite, chlorite; or are associated with carbonaceous matter.

Table 2 - Gold grains occurrence (%) according to the host minerals and mineral association for each ore zone of Mina III, Mina Nova and Mina Inglesa gold deposits, Crixás Greenstone Belt, Brazil (same abbreviations used in Table 1) (after Fortes 1996, Coelho 1999)

	UOZ ms	LOZ qv	LOZ cs	GOZ cg	OB1 cs	OB2 mc	MOB qv
arsenopyrite (enclosed)	38 %	11 %	26 %	11 %	68 %	-	-
pyrrhotite (at the border)	26 %	13 %	3 %	4 %	6 %	-	-
chalcopyrite (at the border)	7 %	-	-	4 %	-	-	-
galena (enclosed or at the border)	-	-	-	-	-	-	20 %
oxides (enclosed or at the border)	6 %	-	-	2 %	-	7 %	-
quartz (enclosed or at the border)	10 %	46 %	26 %	44 %	10 %	8 %	80 %
carbonate (at the border)	9 %	15 %	8 %	-	3 %	40 %	-
muscovite (at the border)	4 %	-	7 %	12 %	5 %	45 %	-
chlorite (at the border)	-	-	-	23 %	trace	-	-
carbonaceous matter (associated)	-	15 %	30 %	-	8 %	-	-

Table 2 summarizes the occurrence of gold grains (%) in relation to host minerals and mineral associations for each ore zone.

Au/Ag RATIO About 350 gold grains were analyzed by a Cameca SX-50 microprobe under 10 s counting time, 1 µm beam size, 15 kV and 25 nA operation conditions, at the Geosciences Institute, Brasília University. Elements, such as Sb, Te, Se, Fe, Cu and Pd, were also detected in all analyzes, adding less than 0.5 weight %. Au content (wt. %) of gold grains ranges between 82 and 95, except for gold associated with oxides, indicating that they may be classified as native gold, according to Boyle (1979) and Gasparrini (1993). The microprobe analyses of gold grains (Fig. 5) indicate a clear relationship between the Au/Ag ratio and the host mineral or mineral association for each ore zone. Despite there is some overlapping of analysis results, gold associated with arsenopyrite, pyrrhotite and chalcopyrite at Mina III and Mina Nova has higher Ag content than gold associated with carbonate, quartz and carbonaceous matter, except for gold associated with quartz veins at the GOZ-cg. Also, gold associated with oxides presents much higher Ag content than other gold grains. At Mina Inglesa, gold associated with quartz has higher Ag content than gold associated with galena.

DISCUSSION Gold fineness was defined by Fisher (1945) as (Au/Au+Ag).1,000, in weight %, and has been used to determine secondary Au enrichment in lateritic and (paleo) placer Au-Ag alloys (Mackay 1943, Hirdes 1984, Santosh *et al.* 1992), as well as geological and geochemical controls of different gold mineralization types at the regional (Titley 1989) or global scales (Morrison *et al.* 1991).

UOZ-ms Mina III, Mina Nova and Mina Inglesa ore zones have a gold fineness medium value around 942, with a minimum and maximum values of 866 and 980, respectively. These are compatible with the typical Archean gold mineralizations values of 940, 780 and 1,000, respectively, medium, minimum and maximum values of Morrison *et al.* (1991).

Table 3 details gold fineness values for each ore zone.

Table 3 - Medium, minimum and maximum gold fineness values for each ore zone from Mina III, Mina Nova and Mina Inglesa gold deposits, Crixás Greenstone Belt, Brazil (same abbreviations used in Table 1) (after Fortes 1996, Coelho 1999)

	UOZ	LOZ	LOZ	GOZ	OB1	OB2	MOB
average	947	949	942	938	942	928	932
minimum	925	929	866	923	892	968	907
maximum	980	962	961	955	972	943	949

The ore zones at Mina III, Mina Nova and Mina Inglesa show different lithological compositions, except for LOZ-cs and OB1-cs. The medium values of gold fineness (Table 3) may reflect such differences among ore zones, which may be related to different sources and initial Au/Ag ratios, as well as different deposition mechanisms depending on fluid-rock interaction.

The presence of very high salinity aqueous-carbonic fluids coexisting with medium salinity aqueous-carbonic fluids that show evidences of immiscibility (Fortes and Giuliani 1995), may have influenced the gold transport (as hydrosulfide and/or chloride complexes) and deposition (pH, Eh, aCl, aS and fO_2), causing variations of the Au/Ag ratio.

Some minerals associated with gold do not have the same value range of Au/Ag ratio in all ore zones. However, it is possible to recognize that for each ore zone the host mineral and mineral association have a clear relationship with the Au/Ag ratio, suggesting that the paragenetic sequence (sulfides tend to be later) has also influenced the Au/Ag ratio.

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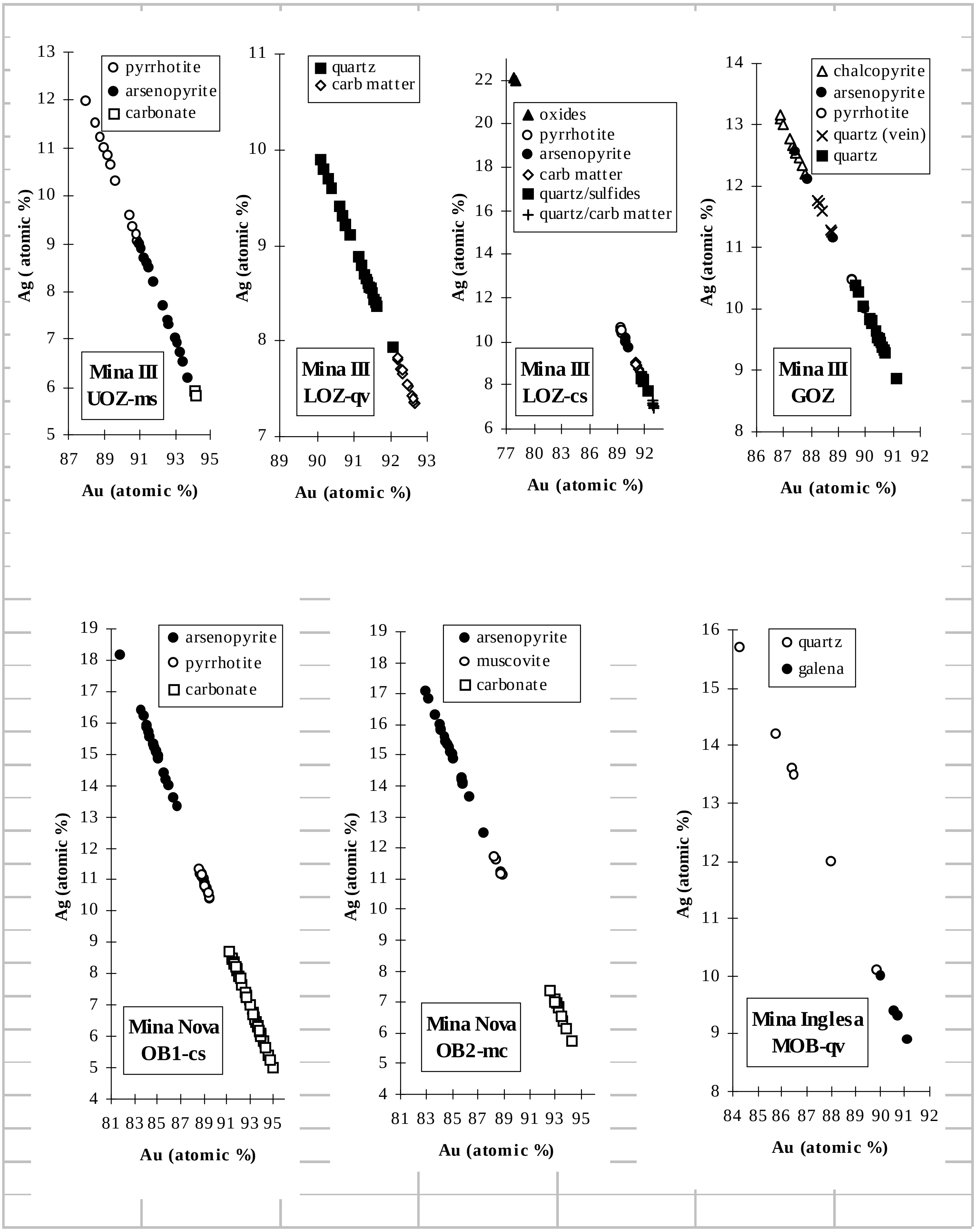

Figure 5 - Au (atomic %) versus Ag (atomic %) diagrams for each ore zone from Mina III, Mina Nova and Mina Inglesa gold deposits, Crixás Greenstone Belt, Brazil (same abbreviations used in Table 1; carb matter = carbonaceous matter) (after Fortes 1996, Coelho 1999)

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