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Multistage gold deposition in the Archaean Maria Lázara gold deposit (Goiás, Brazil)

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Abstract. The Maria Lázara gold deposit in the Archaean Guarinos greenstone belt, central Brazil, consists of quartz–carbonate veins formed in a ductile shear zone. Study of the sulphides and gold-bearing quartz–carbonate veins and veinlets of the potassic hydrothermal alteration zone reveals two stages of ore paragenesis. The first stage corresponds to S-rich arsenopyrite deposition and the second one to the precipitation of As-rich arsenopyrite and Bi–Te–Au–S phases. Modes of occurrence, textures and Ag contents of native gold define two types of gold. The first type is native gold with Ag contents > 5 wt % postdating the S-rich arsenopyrites. The second type has Ag contents < 3 wt % and is contemporaneous with Bi–Te–S phases.

The relevance of the association of gold with Bi-bearing phases within a genetic context centres on the origin of the gold and the timing of its deposition. This last point has long been debated in gold-vein type deposits associated with shear zones and most of the authors agree that gold is paragenetically late in the veins (Robert 1991; Robert and Brown 1986a, 1986b). In this paper, the Maria Lázara gold deposit reveals an Au–Bi–Te–S association. The gold is late introduced in the veins with a multistage deposition.

The Archaean Guarinos greenstone belt in the eastern portion of the Goiás Massif, Central Brazil, is bounded by regional transcurrent shear zones. The Maria Lázara gold deposit occurs at the contact between Archaean metabasalts of the Serra Azul formation and the Moquém tonalitic gneisses in the 2-km-wide and 60-km-long NW–SE-trending Carroça shear zone (Jost and Oliveira 1990; Pulz 1990).

The gold deposit occurs in a 600-m-wide and 5-km-long hydrothermal alteration halo which overprinted fine-grained mylonites and ultramylonites. This alteration halo comprises an outer, volumetrically extensive, propylitic zone, an intermediate 'potassic' zone and an inner sericitic zone. (Pulz et al. 1993).

The present study concerns the sulphides and gold-bearing quartz–carbonates (ankerite) veins and veinlets in

the potassic zone. The veins are a few millimeters to 50 cm thick with a length of up to 10 m. They show multiple episodes of opening and filling with the presence of bands and silvers of wallrocks. Native gold is located with sulphides, at the contacts of quartz–carbonate and wallrock (Pulz et al. 1991a).

Ore mineralogy and chemistry

Arsenopyrite constitutes more than 60% (vol.%) of the opaque minerals with minor amounts of native gold, Bi–Te–S minerals, pyrite, pyrrhotite, chalcopyrite, and rare molybdenite and galena.

Arsenopyrite

The arsenopyrite grains display variable morphologies and sizes. Some large, fractured grains, up to 5 mm in size, present two different textures (Fig. 1A): (i) a very porous core zone with abundant solid inclusions (arsenopyrite type I); (ii) a rim zone, up to 200 µm in width, without any solid inclusions and pores (arsenopyrite type II). The other arsenopyrite grains correspond to large grains of type I and to idiomorphic small grains up to 1 mm size of type (I) and type (II).

Arsenopyrite type (I) is always porous and contains solid inclusions. The pores resulted from arsenopyrite dissolution by hydrothermal leaching. SEM data reveal the presence of Ti oxides (rutile or anatase?) and monazite in these pores. The solid inclusions are composed of carbonates (calcite), silicates (sericite, chlorite, tourmaline: schörl–dravite series), sulphides (pyrrhotite, pyrite, chalcopyrite) and oxides (ilmenite). Arsenopyrite (I) grains often include volumetrically dispersed ilmenite inclusions.

Arsenopyrite (II) is always free of pores and inclusions, although one native silver inclusion has been found. It forms rims on large grains of arsenopyrite (I) and, consequently, postdates the formation of the latter. In some

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Table 1. QEM arsenopyrite analyses (in wt %) of the grain from Fig. 1A. The rim is As-rich, the core is S-rich. Standard is arsenopyrite (Fe: 33.80%, As: 46.80%, S: 19.40%)

	Fe	S	As	Ni	Co	Total
S-rich core	33.44	20.64	44.75	0.14	0.17	99.15
	33.47	20.73	45.03	0.16	0.15	99.60
	33.47	20.61	45.01	0.14	0.11	99.35
	33.31	20.98	45.70	0.13	0.16	100.63
	33.02	20.36	44.62	0.11	0.16	98.32
	33.23	20.35	44.80	0.14	0.15	98.71
	33.35	20.42	44.99	0.13	0.17	99.17
	33.13	20.35	45.18	0.13	0.15	99.11
As-rich rim	33.30	19.70	46.28	0.17	0.18	99.65
	32.64	19.51	46.04	0.45	0.29	99.00
	32.56	19.28	46.32	0.24	0.23	98.70
	31.82	19.42	46.48	0.68	0.34	98.73
	32.82	19.07	46.67	0.34	0.23	99.18
	32.21	19.08	46.48	0.45	0.29	98.54
	32.29	19.11	46.67	0.48	0.33	98.91
	32.17	19.02	46.44	0.44	0.29	98.41
	32.22	19.22	46.67	0.26	0.22	98.67
	31.80	19.06	46.42	0.55	0.25	98.09
	32.40	18.97	46.63	0.34	0.28	98.63
	32.32	19.22	46.81	0.24	0.21	98.83
	32.55	19.19	47.17	0.34	0.26	99.61
	31.88	19.06	46.78	0.48	0.31	98.56

grains, ilmenite occurs at the boundary between arsenopyrite (I) and arsenopyrite (II). In other grains, arsenopyrite (II) occupies pores of arsenopyrite (I).

SEM and QEM studies reveal that the different textures of the arsenopyrites correspond to different chemical compositions (Table 1). Arsenopyrite (I) is S-rich and arsenopyrite (II) is As-rich.

Native gold

Native gold is localized: (i) along microfractures, as rare inclusions within or attached to crystal faces of S-rich arsenopyrite (gold type I); (ii) as fine intergrowths (type IIa) and relatively large grains (IIb) in Bi-Te-S multiphase grains (Fig. 1C, D).

The distinct modes of occurrence of native gold grains reveal different Ag contents (Table 2). In gold type I, they are between 5.9 to 7.6 wt % (average of 6.7) and in gold type II of the Bi-Te-S multiphase grains, they vary between 0.6 to 9.2 wt % Ag depending on the types (IIa) and (IIb). In gold type (IIa) (fine intergrowths), Ag contents never exceed 3 wt %. In some of the type (IIb) large grains, SEM studies reveal zonings with less Ag contents in external rims than in the cores. In the Fig. 1B, the average Ag contents of external rims is 2.9 wt % (Table 2, pts 3, 4) and of the core, 8.2 wt % (Table 2, pts 1, 2). They correlate, respectively, to grains of gold type (IIa) and type (I). The data clearly reveal at least two native gold generations based on distinct Ag contents, (Ag < 3 wt % and Ag > 5 wt %, respectively).

Gold as a trace element in combined state, i.e. in the crystallographic lattices, was not found in the arsenopyrite grains with ion microprobe analysis (SIMS: secondary ion mass spectrometry).

Bi-Te-S phases

Bi-Te-S grains range in size from 1 to 100 μm in greatest dimension. They appear in the interstices of quartz grains into the quartz carbonate material, in pores of S-rich arsenopyrite, and along layers of hydrothermal biotites at

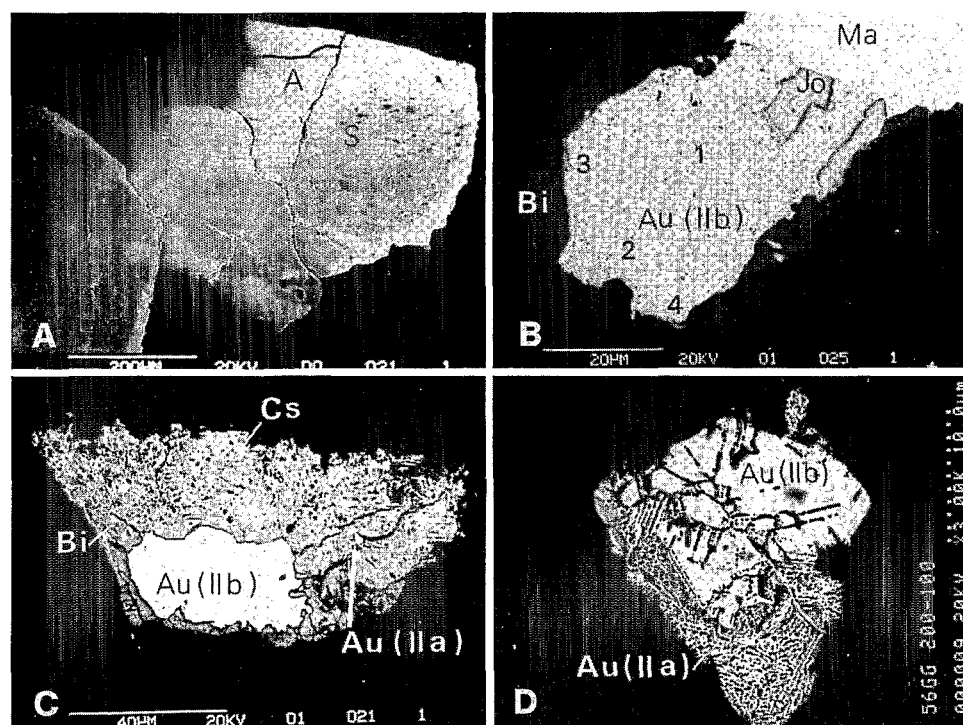


Fig. 1A-D. SEM photographs: **A** Zoned arsenopyrite grain with a S-rich core (S) and a white As-rich rim (A). **B** Bi-Te-S-Au phases: joseite B (Jo), bismuthinite (Bi), maldonite (Ma) and gold type IIb (Au IIb) with the localization of the analytical points from Table 2; 1 and 2 in core; 3 and 4 in the external rim. **C** Bi-Te-S-Au phases: gold type IIb (Au IIb), gold type IIa (Au IIa), csiklovaitite (Cs) and bismuthinite (Bi). **D** Composite gold grain with Bi-Te-S mineralogical phases in the backscattered electrons mode (sample 56GG). One part is flat (gold type IIb); the other presents typical canvas forms (gold type IIa). This grain has undergone a cold chemical attack by concentrated HNO_3 that dissolved the bismuth, tellurium and sulfur and reflects regular alternating layers between the native gold type (IIa) and the Bi-Te-S minerals

Table 2. Ag contents (in wt %) in native gold type (I) and type (IIa, b). Each analysis is named by the sample number (for example 56(06)02) and the gold grain number (for example Gr. 1). Gold type (IIa, b) occurs in the Bi-Te-S multiphase grains, type (IIa) concerns fine intergrowths, type (IIb) large grains. The analytical points (1), (2) and (3), (4) localized in Fig. 1B are respectively from the core and the external rim of the gold (IIb), sample 56(03) and grain 1. Standards are pure gold and silver

Gold grains	Ag	Au	Total
Gold type (I)			
56(06)02/Gr. 1	6.73	92.76	99.48
56(06)02/Gr. 2	7.01	92.74	99.75
56(06)02/Gr. 3	6.95	91.68	98.63
56(06)02/Gr. 4	7.18	91.96	99.14
56(06)05/Gr. 1	6.90	93.69	100.59
56(06)05/Gr. 2	6.83	94.29	101.12
56(06)05/Gr. 3	6.85	92.45	99.30
89 (11)	6.21	93.23	99.44
56(03)/Gr. 8	6.34	92.94	99.28
56(03)/Gr. 9	6.50	95.84	102.34
56(03)/Gr. 10	6.32	93.11	99.43
Gold type (II)			
IIa			
56(03)/Gr. 4	2.97	96.05	99.02
56(03)/Gr. 5	0.72	100.46	101.18
56(03)/Gr. 6	1.88	99.01	100.89
56(03)/Gr. 7	0.62	100.32	100.94
56(02)/05	1.24	98.23	99.46
IIb			
56(03)/Gr. 3	4.96	93.54	98.50
56(03)/Gr. 1 (1)	9.21	89.91	99.12
56(03)/Gr. 1 (2)	7.16	93.29	100.45
56(03)/Gr. 1 (3)	3.45	97.57	101.02
56(03)/Gr. 1 (4)	2.38	96.99	99.37

Table 3. QEM analyses (in wt %) of the Bi-Te-S-Au phases. Bismuthinite: Bi_2S_3 , csiklovaite: Bi_2TeS_2 , maldonite: Au_2Bi , joseite (B): $\text{Bi}_4\text{Te}_2\text{S}$ and native bismuth: Bi. Standards are for: Bi and Au, pure standards-Te, ZnTe (Te: 66.12%, Zn: 33.88%)-S, FeS_2 (S: 53.45%, Fe: 46.55%)

	Bi	S	Te	Au	Total
Bi_2S_3	79.53	18.39	—	0.70	98.63
Bi_2S_3	78.22	16.84	3.56	0.08	98.70
Bi_2S_3	79.78	18.19	—	1.25	99.22
Bi_2S_3	81.24	18.33	—	0.19	99.76
Bi_2S_3	80.67	18.87	0.04	0.10	99.68
Bi_2S_3	82.08	18.81	—	—	100.89
Bi_2TeS_2	65.49	9.94	21.07	—	96.50
Bi_2TeS_2	66.29	10.69	20.48	—	97.46
Au_2Bi	34.39	0.04	—	65.37	99.81
Au_2Bi	34.72	0.05	—	65.92	100.68
$\text{Bi}_4\text{Te}_2\text{S}$	74.24	2.87	21.39	0.07	98.58
$\text{Bi}_4\text{Te}_2\text{S}$	71.13	3.71	23.72	0.13	98.69
$\text{Bi}_4\text{Te}_2\text{S}$	76.23	3.39	19.23	—	98.85
$\text{Bi}_4\text{Te}_2\text{S}$	74.32	2.69	21.74	0.21	98.96
$\text{Bi}_4\text{Te}_2\text{S}$	74.02	2.94	22.42	—	99.38
$\text{Bi}_4\text{Te}_2\text{S}$	75.04	2.94	21.62	0.07	99.67
Bi natif	98.99	0.02	—	—	99.00
Bi natif	99.08	—	—	—	99.08
Bi natif	99.13	0.03	0.02	—	99.18

the contact between wallrocks and quartz carbonate veins. They only occur in samples where As-rich arsenopyrites are observed.

In each composite grain, the different minerals appear as sheets and layered intergrowths closely associated with native gold type IIa or juxtaposed with gold type IIb grains (Fig. 1B–D). Mineralogical identification was carried out by electron microprobe analyses (Table 3) based upon the cation/anion ratio. Selenium was not detected.

The most volumetrically abundant phase is bismuthinite (Bi_2S_3), frequently associated with joseite B ($\text{Bi}_4\text{Te}_2\text{S}$) or csiklovaite (Bi_2TeS_2). Maldonite (Au_2Bi) shows rectilinear boundaries with native gold, type IIa; both are interstratified with bismuthinite and joseite (Fig. 1B). Native bismuth occurs as isolated grains.

Ore paragenesis

The above data about the ore minerals of the quartz carbonate veins from the potassic zone carry some implications for the ore paragenesis.

Multistage deposition of sulfides

The first sulfides to form in the vein fillings are the S-rich arsenopyrites. They correspond to the largest arsenopyrite deposition. The conspicuous presence of pores indicates that they subsequently underwent a dissolution event which occurred preferentially along discontinuity zones such as the boundary between micro-inclusions and S-rich arsenopyrites. These data indicate that the S-rich arsenopyrites have undergone lower $f\text{S}_2/f\text{O}_2$ conditions prior to the deposition of the As-rich arsenopyrites and Bi-Te-S minerals that have never shown evidence of such a dissolution.

The problem of gold deposition

The association of the gold with arsenopyrite grains of distinct modes of occurrence and chemical composition (S and As-rich arsenopyrite), and with Bi-Te-S minerals indicates that the precipitation of the gold took place in a multistage process. The Ag contents of the gold type (I) and type (IIa, b) characterize at least two generations of native gold.

The first one is represented by the gold with Ag contents > 5 wt %. This gold generation is prior to the Bi-Au-Te-S multiphase grains because gold with Ag contents < 3 wt % forms external rims on it, but is later than S-rich arsenopyrite deposition.

The second one corresponds to the gold with Ag contents < 3 wt %. It is closely associated with the Bi-Te-S multiphase grains and never appears without these grains. This gold deposition is contemporaneous with that of the As-rich arsenopyrite and Bi-Te-S minerals.

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