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Some Observations on Gold in the Weathering Profile at Garimpo Porquinho, an Artisanal Mine in the Tapajós Region, Brazilian Amazon

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ABSTRACT

At Garimpo Porquinho (Tapajós Province, Brazilian Amazon) gold-bearing quartz veins containing sulfides occur in a narrow zone affected by hydrothermal alteration. The artisanally mined veins are exposed in a saprolite zone extending down at least 9 m to the fresh rock and are covered by a 1 m thick residual soil. Lateral gold dispersion in the saprolite is not noticeable whereas in the soil gold dispersion has been observed as far as 2 m from the vein. Trace metals associated with gold include Ag, Bi, As and Sb. Copper and lead, present in sulfides, can also indicate the presence of gold. The study of gold particles in different levels of the profile shows that gold has been affected by weathering. In the upper levels of the profile, particles are smaller, more rounded and pitted by dissolution. Grains of primary gold containing up to 20% Ag are commonly exhibit silver-poor rims which may penetrate deep into the grain. The interface between the Ag-poor rims and the interior is very sharp. Such gold-rich rims likely formed by self-electrorefining of electrum grains during weathering.

Palavras-chave: ouro supérgeno, Província Tapajós, dispersão secundária do ouro, partículas de ouro.

RESUMO

No Garimpo Porquinho (Província Tapajós, Amazônia brasileira) veios de quartzo e sulfetos portadores de ouro ocorrem em uma zona estreita afetada por alteração hidrotermal. Sobre a mineralização primária ocorre uma cobertura de saprolito de cerca de 9 m de espessura, capeada por solo de 1 m de espessura. No saprolito não há dispersão lateral do ouro. No solo, no entanto, ocorre dispersão lateral do ouro até pelo menos 2 m a partir do veio. Os principais elementos farejadores são Ag, Bi, As e Sb. Cobre e chumbo, presentes nos sulfetos, podem também indicar a presença de ouro. O estudo das partículas de ouro em diferentes níveis do perfil de alteração mostrou que o ouro foi afetado pelo intemperismo. Nos níveis superiores do perfil as partículas são menores, possuem formas arredondadas e suas superfícies apresentam minúsculos orifícios característicos de dissolução. Observa-se que grãos de ouro primário (20% Ag) exibem comumente bordas empobrecidas em prata que podem penetrar fundo no grão. A interface entre as bordas empobrecidas em prata e o interior é brusca. A formação desses grãos pode ser atribuída ao processo de auto-refinamento eletrolítico dos grãos de electrum durante o intemperismo.

INTRODUCTION

Artisanal gold mining in alluvial deposits started in the 1950s in the Tapajós region - currently known as Tapajós Mineral Province – and had its most productive days during the 1970s and 1980s. Over 100 tonnes of gold have been produced so far. Today gold production is low due to the exhaustion of alluvial productive placers, poor gold recovery from the sources sites, and to the low price of gold in the international market. During the 1990s many mining companies have been exploring the area, but up to date no important occurrences have been found.

The active artisanal mines of the Tapajós Province provide a good opportunity to study the behaviour of gold in a rain forest environment. In Brazil, similar studies have been carried out mainly in regions of savanna-type tropical climate with well-contrasted seasons (Michel, 1987; Oliveira and Campos, 1991; Porto and Hale, 1995; Oliveira and Oliveira, 2000) and in the semi-arid zone (Carvalho, 1984; Grimm and Friedrich, 1991; Vasconcelos and Kyle, 1991). In humid equatorial environments such studies are rather scarce. Some work was done in the Amazon, but in a different geomorphological context, at Serra dos Carajás (Andrade et al., 1991; Costa, 1993; Zang and Fyfe, 1993; Angélica, 1996), which is an area of elevated plateaus, in contrast to the Tapajós Province where low plains are dominant.

The aim of this paper is to present some results on morphology and composition of gold grains throughout the weathering profile at an artisanal mine in the Tapajós Province (Garimpo Porquinho), and to discuss the possible mechanisms of formation of Ag-depleted rims in the gold particles. In this site, small-scale alluvial mining activities have been known since 1970, but in recent years the production has declined, on account of the exhaustion of the placer deposit. At present gold is mined directly from the veins, and recovered through mercury amalgamation.

Garimpo Porquinho is situated in the southern part of the Amazon state (57º37’17’’W, 5º10’31’’S) (Figure 1). The access to the area is via small aircraft from the city of Itaituba (Pará state).

REGIONAL SETTING

The Tapajós Province covers an area of about 1,670,000 km^2 and corresponds to that part of the Amazon Craton known as the Guaporé Craton (Almeida et al., 1981). In the Garimpo Porquinho area, according to CPRM (1999), the main geological units constitute the Parauari Intrusive

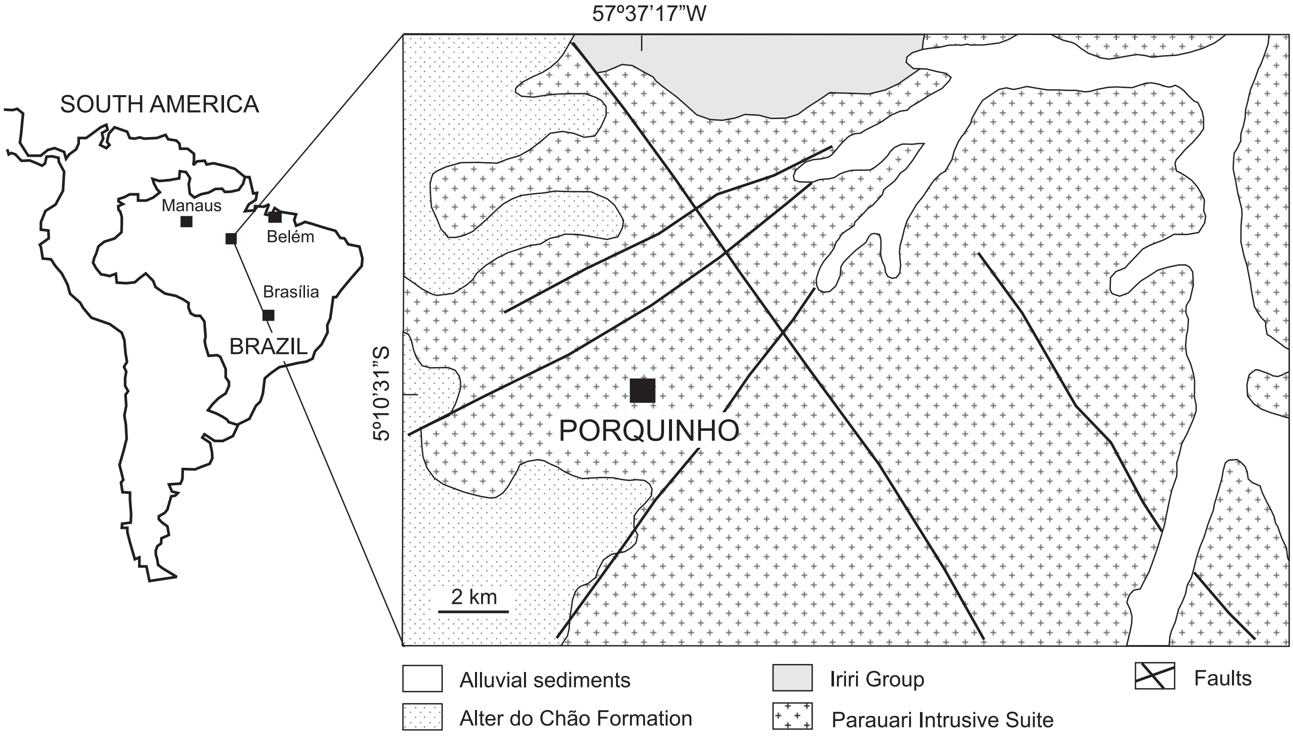

Figure 1. Location and general geology of the study area (based on CPRM, 1999).

Suite (1970 to 1870 Ma) composed of titanite-bearing granites, monzogranites and granodiorites; the Iriri Group (1850 Ma) composed of rhyolite, dacite, tuffs and ignimbrite; the Alter do Chão Formation (100 to 50 Ma) composed of silicified and iron stained quartzitic sandstones; and Alluvial sediments composed of recent unconsolidated sands and conglomerates.

The geological evolution of the Province and the nature of the associated gold deposits have been recently defined by Santos et al. (2001). According to these authors, the gold deposits of the Tapajós region belong to four main types:

1. orogenic turbidite-hosted deposits;
2. orogenic magmatic arc-hosted deposits;
3. intrusion-related, epizonal quartz vein deposits;
4. intrusion-related, epizonal disseminated/stockwork deposits.

Garimpo Porquinho is classified as an intrusion-related, epizonal quartz vein deposit.

Garimpo Porquinho lies at the margins of the Amana river in a region of flat valleys with wide flood plains limited by erosive slopes and covered with evergreen forest. The topography is gently undulating with altitudes below 200 m. The climate is hot and humid (Am, according to Köppen) with an annual average precipitation above 2500 mm/year and a mean annual temperature around 26°C. The driest months are June, July and August.

LOCAL GEOLOGY

A weathered biotite-granodiorite from the Parauari Intrusive Suite is the host unit for the mineralized quartz veins. The fresh rock is a medium to coarse-grained, equigranular, granodiorite which contains quartz, microcline, plagioclase and biotite; sphene, zircon, magnetite and hornblende are accessory minerals. Primary mineralization consists of quartz lodes which follow brittle shear zones and are associated with narrow (0.2 - 0.5 m) hydrothermal alteration haloes (sericite, chlorite, epidote and sulphides). Microscopic observations showed that gold is associated with quartz as free particles or as inclusions in pyrite.

The weathering profile is poorly differentiated. It consists of a saprolite horizon (at least 9 m thick) overlain by a thin soil horizon (1 m thick). In the saprolite the original structures of the granodiorite are well preserved, and the quartz veins may be traced throughout it; in the soil layer the original structures are lost and the quartz veins become disaggregated. The contact between these two horizons is sharp.

Most of the study described here was carried out over the main lode which is 10 cm wide in average and strikes E-W deeping 88° north (Figure 2). Thicker developments of the vein up to 30 cm can be found locally. Lateral veinlets (2 - 3 cm wide) associated to the main vein are also mineralized.

SAMPLING AND ANALYTICAL TECHNIQUES

Sampling was performed in the main quartz vein pit (Figure 2). Vein samples were taken from the profile at five different depths. H0 was sampled at about 11 m down from the top of the profile, below the water level, and is not indicated in Figure 2. H1, H2, H3 and H4 were sampled at depths of 10 m, 7 m, 4 m and 3 m, respectively. Polished mountings from the vein samples were observed under the ore microscope. Gold, Ag, As, Cu, Pb, Zn, Se, Te, Bi and S were determined by NAA and ICP-MS (Actlabs, Ontario, Canada).

Bulk samples of about 2 kg of the saprolite adjacent to the veins were also collected: H1/A, H2/A and H3/A. At level H3 saprolite samples were also taken at distances of 1 m (H3/B), 2 m (H3/C), and 3 m (H3/D) away from the vein.

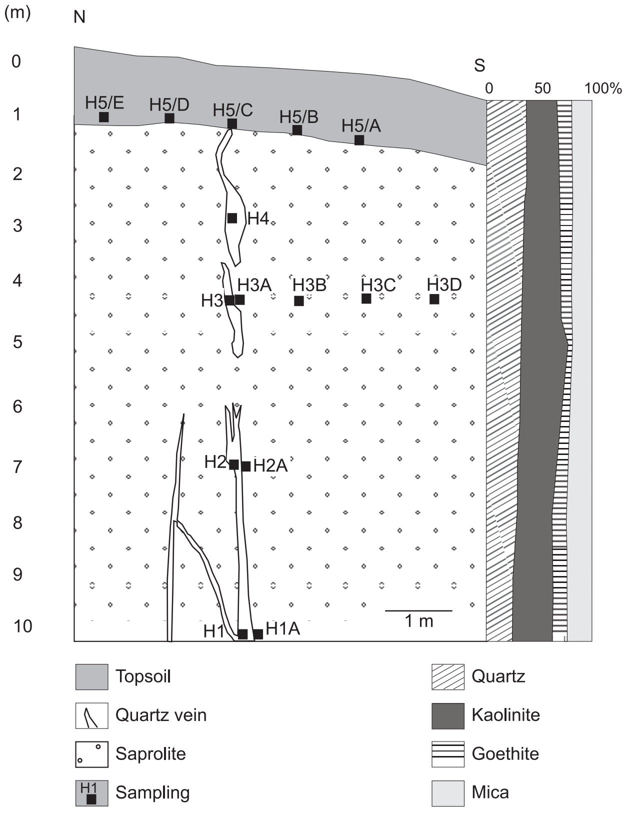

Figure 2. Garimpo Porquinho: weathering profile and sampling sites.

The topsoil was sampled just above the vein (H5/C) and 1 m (H5/B and H5/D) and 2 m (H5/C and H5/E) away from the vein. The mineralogical composition of saprolite and soil was determined by X-ray diffraction and optical microscopy of thin sections. Chemical analysis for some major and trace elements were performed by NAA and ICP-MS (Actlabs, Ontario, Canada).

Three heavy mineral concentrates were panned in the field from the saprolite at sites H1/A, H2/A and H3/A with an initial volume of 20 litres each. A considerable portion of the small gold grains (< 10 µm) was lost during panning; moderate losses may have occurred for 10 - 20 µm fraction. In the laboratory, the concentrates were dried at 60^{o} C and sieved in order to separate four size fractions: > 250 µm, 250 - 150 µm, 150 - 63 µm and < 63 µm. Heavy liquids and magnetic techniques were used to concentrate gold. Gold particles were mounted in carbon tapes and examined by means of optical microscopy and scanning electron microscopy. The chemical composition of the particles was determined by electron microprobe analyses of polished sections of the grains.

THE WEATHERING PROFILE AND THE DISTRIBUTION OF GOLD

Microscopically, the saprolite exhibits the original texture of the parent granodiorite. Quartz grains, slightly etched by corrosion vugs, are broken into several fragments which have a unique extinction. This is an indication that quartz grains are not displaced from their original positions; kaolinite is present as pseudomorphs after feldspars. Ferruginisation is widespread in the fractures of the quartz grains, along the cleavages of micas and feldspars and in contact zones between grains. Saprolite is, therefore, an isovolumetric product of weathering. On the other hand, in the soil - a homogeneous clayey-sandy material - the fabric of the parental material is no longer preserved.

Table 1 shows Fe, K and trace elements contents in the saprolite and soil. From Fe and K concentrations and X-ray diffraction data an estimated mineralogical composition for these two horizons was calculated (Figure 2). Both contain the same minerals: quartz, kaolinite, mica, goethite and traces of K-feldspar. Heavy mineral separates from the saprolite and soil contain, besides gold, primary minerals as mica and zircon, some preserved sulphides and neoformed phases as goethite, hematite and hollandite.

Mica is slightly more abundant in the saprolite, and iron oxyhydroxides and quartz in the soil. Together with Fe, Cr and Sc are slightly concentrated in the soil. LREE are depleted in the soil compared with the saprolite; HREE are slightly enriched. There is a close similarity between Au, Sb and As variation with depth (Figure 3).

The patterns of gold distribution in the saprolite and soil are different (Table 1). In the saprolite, high contents of gold are only found in samples collected just close to the veins (H1/A and H3/A). At a distance of 1 m from the vein (H3/B) the concentration of gold abruptly decreases. There

Table 1. Chemical contents of some major and trace elements in bulk samples of saprolite and in the soil. Fe and K in weight %; Au in ppb; other elements in ppm; **nd** = not determined.

	Saprolite						Soil				
	H1/A	**H2/A**	**H3/A**	**H3/B**	**H3/C**	**H3/D**	**H5/A**	**H5/B**	**H5/C**	**H5/D**	**H5/E**
Fe	3.2	3.8	4.7	4.0	3.1	3.8	5.3	5.3	6.0	7.5	6.4
K	nd	3.7	nd	2.4	nd	nd	2.2	nd	nd	2.2	nd
Cr	17	20	41	16	17	19	78	79	76	157	105
Sc	9	11	10	12	12	13	18	15	17	22	21
La	77	132	38	14	35	8	12	12	14	9	11
Ce	101	106	47	61	80	67	29	25	41	23	31
Nd	36	63	18	9	24	5	9	8	9	5	6
Sm	5.3	9.3	3.2	1.5	3.5	1.0	1.6	1.6	1.7	1.3	1.5
Eu	1.0	1.9	0.7	0.4	0.7	0.3	0.4	0.4	0.4	0.4	0.4
Yb	1.1	0.8	0.6	0.8	0.9	0.8	1.2	0.9	1.0	1.2	1.2
Lu	0.16	0.12	0.10	0.12	0.14	0.13	0.18	0.14	0.15	0.17	0.19
Au	2950	51	9080	12	12	23	946	1260	6690	3260	194
Sb	1.9	0.9	2.6	1.2	0.9	0.7	1.5	1.9	2.0	1.8	2.0
As	36	43	55	9	4	6	16	37	34	47	19

is, therefore, no noticeable lateral dispersion of gold in the saprolite on a metric scale. In the soil, however, a lateral dispersion of gold is more evident: gold concentrations decrease gradually to 1 m (H5/B, H5/D) and to 2 m (H5/A, H5/E) from the vein (H5/C). Antimonium and arsenic also show a greater lateral spread in the soil than in the saprolite.

Quartz veins with visible gold always show the presence of pyrite; chalcopyrite, arsenopyrite and galena may occur in minor amounts. At the bottom of the profile, sulphides are quite well preserved from weathering, but in the upper levels they become unstable and breakdown to form oxyhydroxides in typical pseudomorphic textures. Accordingly, sulphur concentrations decrease from the bottom to the top of the saprolite. In Au-bearing veins (Table 2), Ag, Cu, Pb, Se, Te and Bi concentrations correlate fairly well with gold concentrations.

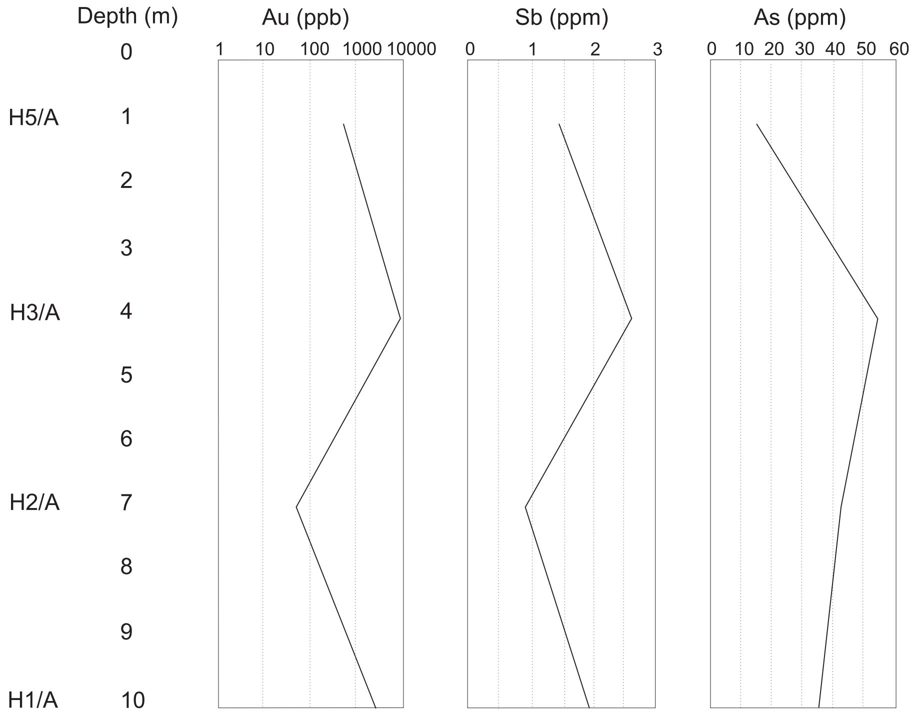

Figure 3. Au, Sb and As variation with depth.

Table 2. Gold and trace element contents in quartz veins (ppm); **nd** = not determined.

	H0	H1	H2	H3	H4
Au	362	0.3	45.2	17.5	3.3
Ag	226	5	25	5	5
As	151	4	750	107	6
Cu	24827	20	7563	94	12
Pb	9859	nd	487	200	nd
Zn	36	nd	37	9	nd
Se	5.6	< 1	2	nd	< 1
Te	7.3	< 1	0.2	nd	< 1
Bi	170	nd	12	40	nd
S(%)	3.6	3.4	3.9	0.01	0.01

SIZE, MORPHOLOGY AND COMPOSITION OF GOLD GRAINS

In the unaltered vein (H0), gold occurs mainly as free particles associated with quartz and pyrite (Figure 4A). Most grains are xenomorphic, with extremely irregular morphology and smooth outlines. Dimensions vary from less than 1 µm to over 500 µm. Larger grains can be formed by agglomeration of smaller euhedral crystals of about 5 µm each fused together, leaving void spaces between them (Figure 4B).

In the saprolite, most of gold particles from heavy mineral concentrates are in < 63 µm fraction. From the bottom (H1) to the top (H3) of this horizon, particles get smaller: in H1/A and H2/A they are present in the four analysed fractions (> 250 µm, 250 - 150 µm, 150 - 63 µm, < 63 µm), but in H2/A there are fewer particles in the > 250 µm fraction than in H1/A. In H3/A, H3/B, H3/C and H3/D there are no particles in the > 250 µm fraction. They are generally xenomorphic with jagged outlines (Figures 4E and 4F).

Gold grains from H1/A heavy mineral separate present crystal faces with blunt edges (Figure 4D); higher in the profile, in H2/A, these features are less frequent and totally absent in H3/A. In this level most of the particles are well rounded and the crystal shapes are no longer recognizable. Rugosity at the surface increases from H1/A to H3/A as well as the presence of subcircular etching pits of less than 1 µm to 2 - 3 µm. These cavities, which seem to be formed by the dissolution of gold, are more abundant and larger on the surface of particles from level H2 upwards. The surface of some particles have a characteristic lobate or bulbous texture (Figure 4C) similar to that described by Groen et al. (1990) in alluvial gold as "stromatolite-like".

Microprobe determinations of Ag, Cu, Fe, Pd and S in homogeneous gold particles from H2/A and H3/A heavy mineral separates were performed, but only Ag was found above the detection limit estimated to be 0.1%. Silver contents of most grains are between 19.0 and 31.6%, what corresponds to a fineness in the range 679 to 800 (Table 3).

Many grains show rims of high fineness (Table 3) with preferential development in and around embayments (Figure 5A), and pits on their surface (Figure 5B). Ag-depleted rims are also observed filling fractures of the grain (Figure 5E). These linear accumulations can be found locally enlarged, forming pockets (Figure 5A2). In addition to these features, irregular zones of Ag-poor gold in contact with Ag-rich gold can also be observed (Figures 5C and 5D). In any case, the boundary between Ag-rich and Ag-poor zones is sharp, not diffuse.

Table 3. Chemical composition (weight %) of gold particles from H2/A and H3/A heavy mineral separates (**i** = interior of the grain; **r** = rim; **n** = number of points analysed in the grain).

Au particles		Au	Ag	Fineness	n
H2/A	i	76.9 - 77.3	19.7 - 20.1	795	4
H2/A	i	76.2 - 80.7	19.4 - 19.8	799	7
H2/A	i	75.7 - 79.0	19.8 - 20.4	794	10
H2/A	i	83.0 - 83.2	15.6	842	2
H2/A	r	100.0	0.0	1000	1
H2/A	i	87.0 - 87.4	11.4	886	4
H2/A	r	96.6 - 96.9	2.7	973	3
H3/A	i	64.4 - 69.6	30.9 - 31.6	679	3
H3/A	i	77.0 - 79.6	19.0 - 20.9	800	9
H3/A	i	75.8 - 77.7	19.3 - 20.1	797	13
H3/A	i	84.5	14.3	846	1
H3/A	r	98.8 - 98.9	0.8	992	3
H3/A	i	81.5 - 81.6	16.8	829	3
H3/A	r	98.7	0.8	991	1

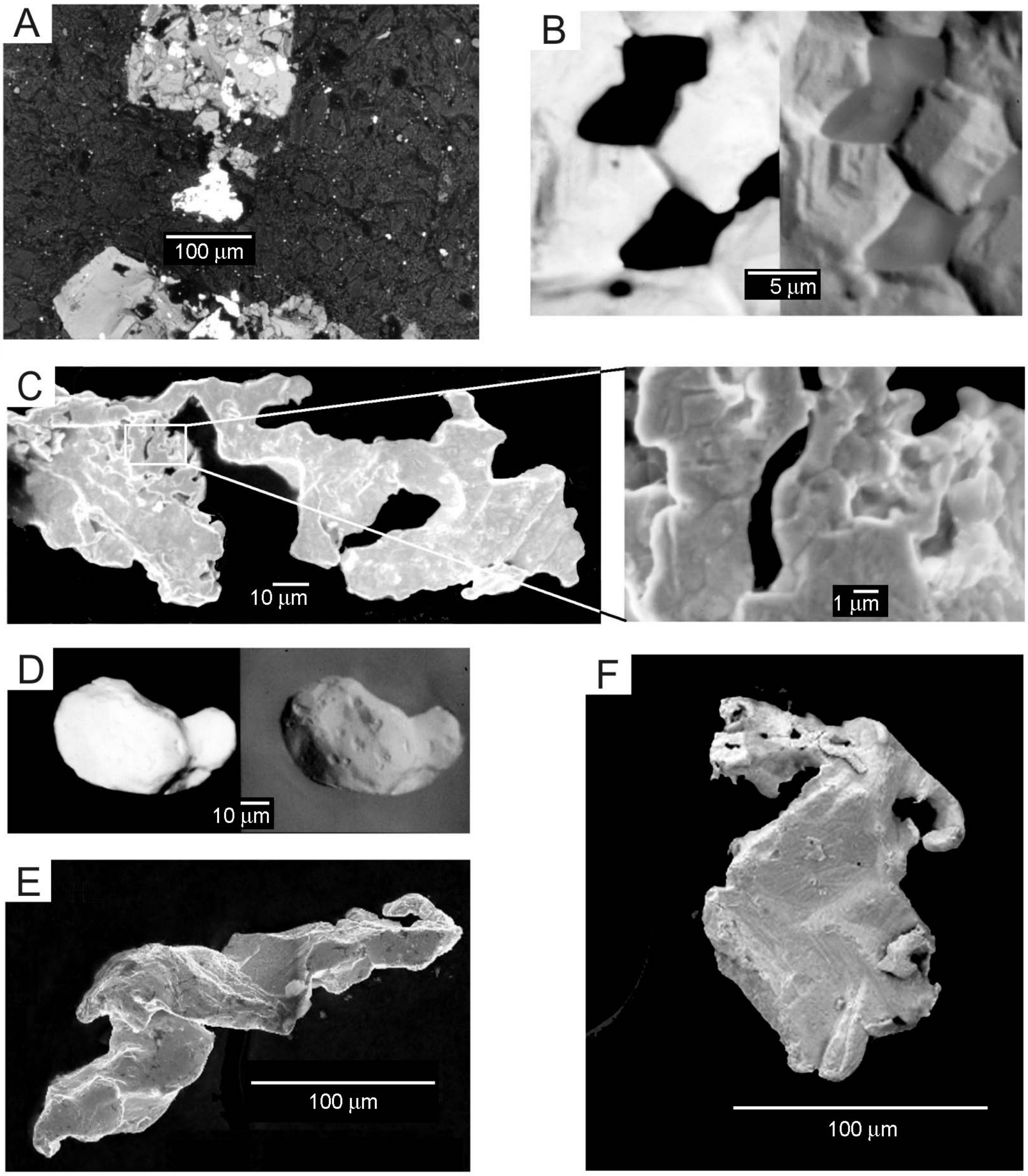

Figure 4. Backscattered SEM images of gold grains from H0 vein and from heavy mineral separates: **A.** polished section of H0 quartz vein. Gold is included in quartz (dark gray) and in pyrite (medium gray); **B.** gold grain from H0 vein. Euhedral juxtaposed gold crystals leaving voids between them; **C.** dendritical gold particle from H0 vein formed by juxtaposed pseudohexagonal crystals. The surface of the particle presents a characteristic lobate texture; **D.** gold grain from H1/A. The grain is rounded and displays visible corrosion features at the surface. Edges of some faces are still discernible; **E, F.** xenomorphic gold grains from H2/A with jagged outlines.

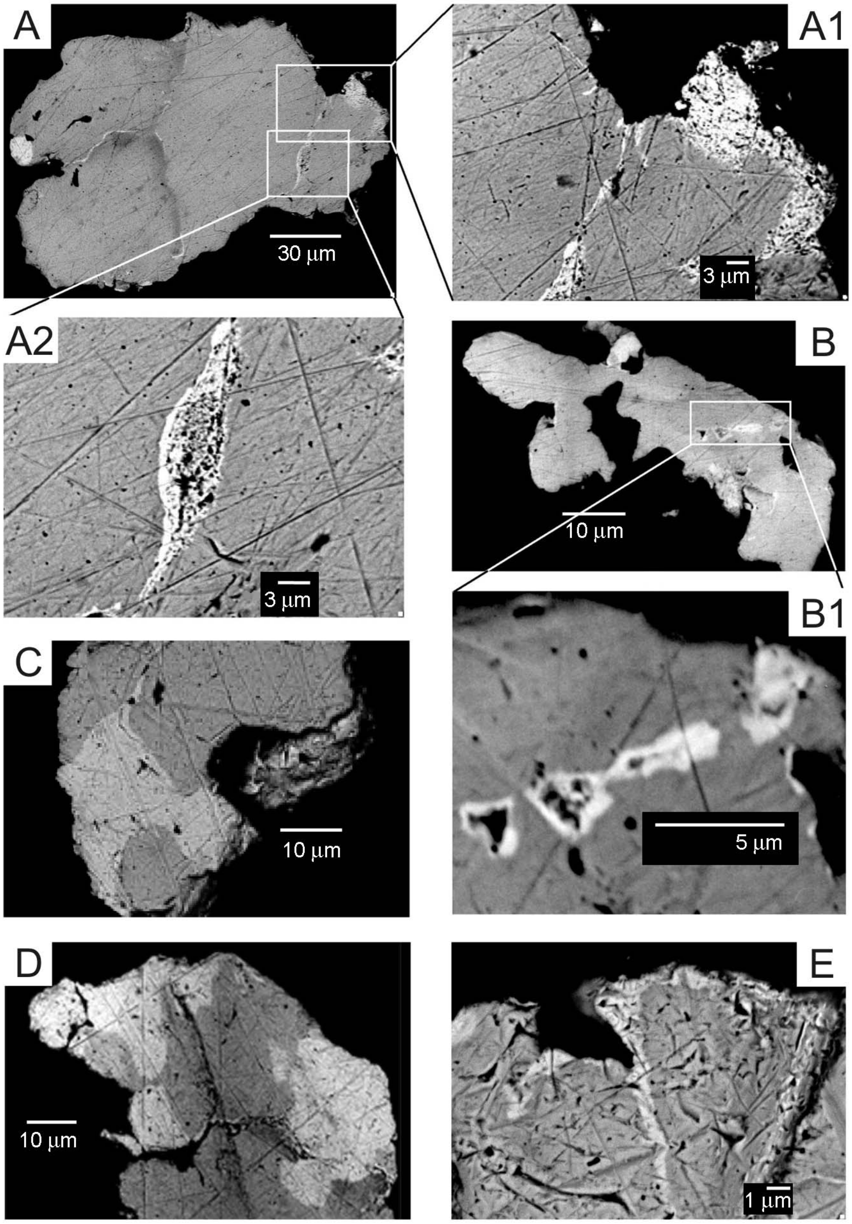

Figure 5. Backscattered SEM images of polished sections of gold grains from heavy mineral separates: **A, A1.** gold grain from H2/A showing Ag-depleted zones as rims and filling fractures (paler gray); **A2.** pocket of Ag-depleted gold in the same gold grain; **B, B1.** gold particle from H2/A showing corrosion pits surrounded by Ag-depleted gold rims; **C, D.** gold grains from H3/A containing irregular zones of Ag-depleted gold; **E.** etched pits on a particle from H2/A. Rims of Ag-depleted gold are very narrow.

DISCUSSION AND CONCLUSIONS

The weathering profile here described is of the type B 2 0 [0] according to the classification of Lecomte and Zeegers (1992) for geochemical exploration in humid tropical terrains with moderate recent alteration (pre-existing profiles partly truncated). The present topographic surface intersects a pre-existing lateritic profile at the saprolitic level which thickeness is probably greater than 10 m. The pedological differentiation in the upper portion of the saprolite results in a soil layer of small thickness. From a prospective point of view, significant dispersion halos can be expected only in the soil. Trace metals accompaning gold anomalies include Ag, As, Cu, Pb, Sb, Se, Te and Bi.

The gold particles found in the weathering profile are clearly related to the primary deposit underneath. They are residual throughout the entire profile and progressively affected by weathering. This is indicated by their decreasing size and the increasing evidences of chemical attack at their surfaces from the bottom to the top of the profile. Similar behaviour of gold has been described in lateritic profiles in Africa and in Brazil (for instance, Colin et al., 1989a, 1989b; Colin and Vieillard, 1991; Porto and Hale, 1995 etc.).

Gold grains showing Ag-depleted rims with respect to their cores such as those found at Garimpo Porquinho are very common in lateritic profiles and generally interpreted as a result of loss of Ag during weathering (Mann, 1984; Freyssinet et al., 1989; Grimm and Friedrich, 1990; Colin and Vieillard, 1991; Oliveira and Campos, 1991; Bowell, 1992; Gray et al., 1992; Lawrance and Griffin, 1994 etc.). However, particles including irregular zones of Ag-poor gold in sharp contact with zones of Ag-rich gold such as those described here (Figures 4C and 4D) are not so often reported. In Brazil there is another example described by Grimm and Friedrich (1990) for gold particles from colluvial lateritic soils in the semi-arid Gentio do Ouro area in the state of Bahia.

Three mechanisms to explain the formation of Ag-depleted rims have been proposed (Groen et al.,1990; Bowell, 1992):

1. preferential dissolution of Ag;

2. precipitation of pure gold as a rim surrounding the primary particle (cementation);

3. self-electrorefining process, where the electrum dissolves and gold immediatly precipitates onto the surface of the grain.

As to model (1), it requires that the atoms of Ag from the inner part of the grain come into contact with the solution. Diffusion could be a mechanism, but it would take 10^{17} to 10^{18} years, according to Groen et al. (1990) calculations. Model (2) is based on the solubility of gold in surficial environment through, for instance, Cl-ligands (Krauskopf, 1951; Cloke and Kelly, 1964; Mann, 1984), sulphur complexes (Goleva, 1970; Plyusnin et al., 1981; Webster, 1986), organic complexes (Baker, 1978; Bowell et al., 1993) and hydroxy complexes (Rosylyakov, 1971; Vassopoulos and Wood, 1990). Precipitation of gold from solution takes place by the reduction of Au^{1+} or Au^{3+} ions associated with the oxidation of Fe^{2+} to Fe^{3+} (Mann, 1984; Stoffregen, 1986). The common occurrence of secondary gold intergrown with iron oxy-hydroxides in gold nuggets (Wilson, 1984; Vasconcelos and Kyle, 1991; Santosh and Omana, 1991; Oliveira and Campos, 1991; Santosh et al., 1992; Zang and Fyfe, 1993) is an evidence of such a process. At last, model (3) is based on the hydrometallurgical process in which a multi-component alloy is electrochemically dissolved and a pure phase of the most inert metal is precipitated. Mann (1984) performed electrochemical experiments with synthetic Au-Ag alloys and his results indicated that this process produces rims of pure gold similar to those found in natural environments. This process does not require a sharp Eh gradient and would be accelerated by the presence of ligands such as CN^-, HS^-, NH_3 and fulvates. Gray et al. (1992), based on kinetic considerations, showed that this model could well account for the observed phenomenon.

At Garimpo Porquinho, the absence of noticeable gold dispersion in the saprolite suggests a limited migration of complexing solutions and therefore an essentially *in situ* gold reprecipitation. Thus, self-electrorefining could have been a process of forming gold-rich rims and pockets in the primary grains. Through this process, silver was evacuated in solutions that percolated the fractures of the grains. This mechanism produces surfaces bearing lobate protusions of the deposited gold (Groen et al., 1990) which are similar to those observed in Figure 4C. More difficult to explain are the irregular zones of Ag-rich gold in contact with zones of Ag-poor gold in the interior of gold grains. The mechanisms above described would require extensive dissolution and reprecipitation of gold which are not likely to occur.

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