GEOCHIMICA BRASILIENSIS

GEOCHEMICAL EXPLORATION FOR GOLD IN DEEP WEATHERED LATERITISED GOSSANS IN THE AMAZON REGION, BRAZIL: A CASE HISTORY OF THE IGARAPÉ BAHIA DEPOSIT

M.L. da Costa,
Centro de Geociências, Universidade Federal do Pará, Belém, PA

R.S. Angélica
Companhia de Pesquisa de Recursos Minerais - CPRM, Belém, PA

L. R. da Fonseca
Astrônomo, ex-geólogo da Docegeo e PSG, Belém , PA

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ABSTRACT

The Igarapé Bahia gold mine is located in the Carajás region, Pará State, northern Brazil. The area is a typical example of supergene gold mineralization related to gossans, where superimposed lateritization processes obliterated their upper horizon and gave rise to new and wider dispersion of gold and of other metals, with meaningful consequences for geological exploration in this environment. An exploration program in this area was carried out by Docegeo, a subsidiary of "Companhia Vale do Rio Doce - CVRD", which is the sponsor of the Carajás mining district and, currently, is also minig for gold at Igarapé Bahia.

The main mineralized zone at Igarapé Bahia is a ferruginous breccia-like horizon, or mixed zone, constituted by gossans, lateritised gossans, and fragments of Fe-rich metavolcano-sedimentary wall rocks. Gold contents average 5 g/t in a 12-million-tons ore reserve. Shallow to deep red clayey latosols cover invariably the gossans/laterite profiles which bear lower gold contents.

The geochemical exploration in this area was performed in two main phases, each one using different methodologies of soil sampling, what led to different results: (a) during first phase the soil materials were sieved and the coarse fraction with fragments of the gold-bearing ferruginous zone were put aside and the obtained results for the gold were around the detection limit of the method employed and did not highlight any anomalous zone; (b) during second phase, the whole soil sample was used without previous sieving, the results were noticeably enhanced and the 0.1 ppm gold isocontent line outlined the two mineralized ore bodies. The greatest contents are strictly related to the iron crust outcrops (without soil cover), while the lower contents are related to the main body (buried by a latosol cover).

The results show that gold was partly remobilized during the lateritisation of gossans, mainly within the upper part of the ferruginous zone, where latosols have been developed. A high dispersion of gold values and a weakening of the gold signal in this zone were reported. These soil covers act as a barrier to the discovery of new ore deposits. New geochemical exploration models for gold prospection and analogous geological surveys in lateritic terrains which evolved in tropical rain forest environments, as the present Amazon region, must be developed taking into account the real structuration of the supergene profiles, as well as the role of the different soil covers which overlie them.

RESUMO

A Mina de ouro Igarapé Bahia está localizada na região de Carajás, Estado do Pará, norte do Brasil. A área corresponde a um exemplo típico de mineralização supergênica de ouro relacionada com gossans, os quais foram, posteriormente, lateritizados, atingidos, principalmente, nos horizontes superiores. Como conseqüência, desenvolve-se uma nova e mais ampla dispersão do ouro e outros metais.

A principal zona mineralizada da mina Igarapé Bahia é formada por um horizonte ferruginoso que envolve gossans, e uma crosta laterítica superimposta, contendo fragmentos dos gossans. O teor médio de Au é de 5g/t para uma reserva de 12 milhões de toneladas de minério. Uma cobertura de latossolos argilosos vermelhos de espessura variável recobre o perfil laterito-gossânico, e contém baixos teores de ouro.

A exploração geoquímica nesta área envolveu duas fases diferentes: na primeira fase, as amostras de solo foram peneiradas, sendo que a fração mais grossa, constituída de fragmentos de material ferruginoso, foi descartada. Os resultados de ouro obtidos foram quase todos abaixo do limite de detecção do método utilizado e não delinearam qualquer área anômala; durante a segunda fase, as amostras não sofreram peneiramento, e as análises foram realizadas na amostra total. Os resultados obtidos para ouro foram sensivelmente mais altos que na fase anterior, ressaltando uma curva de isoteor de 0,1 ppm de ouro, delineando perfeitamente a área atual mineralizada. Os valores mais elevados estão estritamente relacionados com os afloramentos do material ferruginoso (gossans + crosta laterítica) sem cobertura de latossolos, enquanto os teores mais baixos estão onde esta cobertura é mais espessa.

Os resultados obtidos mostram que o ouro foi parcialmente remobilizado durante a lateritização dos gossans, principalmente na parte superior da zona ferruginosa, a partir dos latossolos, com uma significativa dispersão geoquímica e diminuição do sinal do ouro. A obtenção de casos históricos como este são fundamentais para o estabelecimento de modelos de exploração geoquímica em terrenos lateríticos da Amazônia, os quais devem levar em consideração a real estruturação dos perfis supergênicos, assim como o papel dos diferentes tipos de latossolos que recobrem esses perfis.

INTRODUCTION

Systematic gold geochemical exploration programs have been carried out successfully in the lateritic terrains of West Africa and Western Australia in the last two decades and resulted in several reports and subsequent proposals of geochemical exploration models (Butt & Smith, 1980; Butt, 1987; Butt & Zeegers, 1989 and 1992). In the Amazon region, however, which is one of the greatest lateritic regions of the globe and encompasses several well-known lateritic ore deposits, few works have been done concerning this matter. In comparison with Western Australia and West Africa, this region, due to different morphoclimatic conditions, weathering and landscape evolution history since the Early Tertiary times, requires the statement of new adequate conceptual models to its reality.

In the Amazon region, the Igarapé Bahia gold mine is probably the first occurrence described, where superimposed lateritisation processes over gossans gave rise to a new and wider dispersion of gold and other metals (Costa, 1987), whose meaningful consequences must be considered during geochemical exploration in this kind of environment. This example has been used as a model in the search for new gold-bearing bodies in the Carajás region, as well as in the whole Amazon region.

EXPLORATION HISTORY

The Igarapé Bahia area is located in the western part of the Carajás Mineral District, about 450 km southwest from Belém City, capital of Pará State, Brazil (Fig. 1). The geochemical exploration for base metals began, in this region, in the middle 70's through stream sediments and heavy mineral concentrated sampling. All the exploration program was carried out by Docegeo, a subsidiary of "Companhia Vale do Rio Doce - CVRD", which is the sponsor of the Carajás Mineral District.

In the first pioneer drill hole, made in the Igarapé Bahia area, in February 1977, millimetric gold grains were recovered by gravity circuit from the weathered uppermost part of the profile, in the top soils. By then, little attention

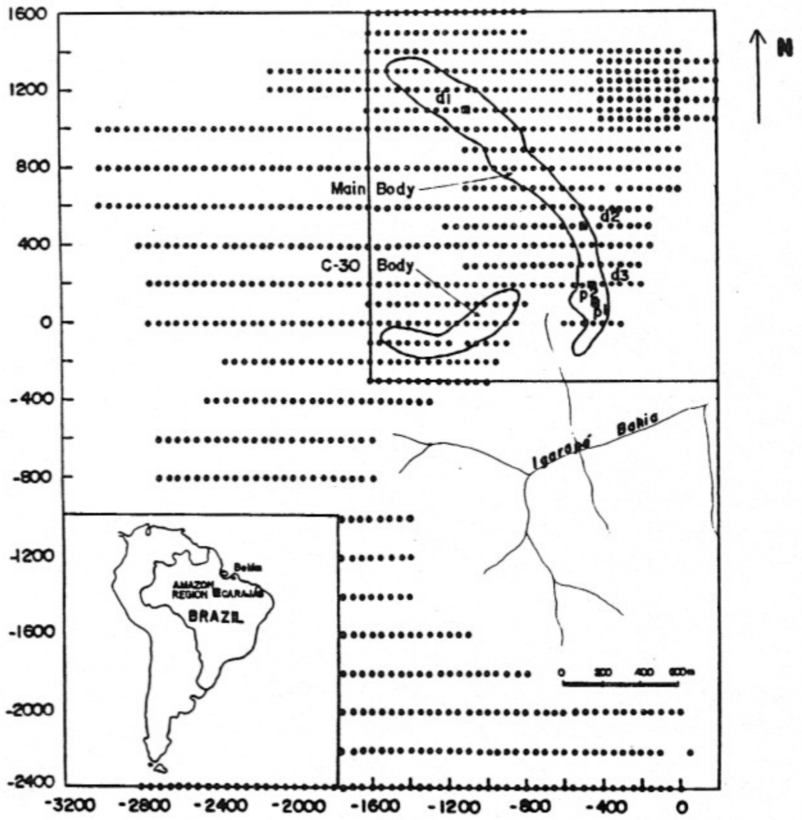

Figure 1 - The location map of the Igarapé Bahia area and the soil sampling grid used by Docegeo. Pits (p1, p2), and drill holes (d1, d2, d3) are described in Figures 7 and 9.

was given to either laterites or iron hat outcrops, which are very prominent in the area (Plate 1).

In 1981, soil sampling was performed encompassing all the plateau of the Igarapé Bahia area. The sampled surface material comprised soil and iron concretions (pisoliths), where the latter derived from the dismantling of the iron crusts. Meanwhile, this material was systematic sieved after sampling and the coarse fraction was disregarded. An isolated sample of this material exhibited gold contents which reached 0.17 ppm; most of them presented values lower than 0.1 ppm, what led to an interruption in the research.

From 1987 to 1988, the project was retaken and, following suggestions of the first author of this paper (Costa, 1987), a new geochemical prospecting program was adopted by Docegeo for the Igarapé Bahia area, consisting of a new soil sampling and a geological mapping of surface material, comprising iron crust and soils. The soil geochemical survey was performed on a 50x200-meter-spaced grid, and a closer grid with spacing of 50x100 m was also used locally (Fig. 1). The whole samples (soils plus iron concretions) were systematically crushed without previous sieving and then analyzed for gold and other trace elements (Cu, Co, Ag and Mo). The results enhanced noticeably compared with those of the first phase of the research and outlined a gold anomaly in the northern part of the plateau in agreement with a magnetic area defined by land magnetometric survey. After field work, mineralogy and texture analysis of iron crust samples, as well as observation of weathering profiles in two test pits and along some drill cores, Costa (1987) concluded that the Igarapé Bahia area is constituted by a set of gossans derived from several sulfide veins which form a large sulfide zone. The main gold-bearing supergene body has a mushroom-shaped morphology. The gossans show strong evidence of superimposed modifications driven by lateritisation processes, which must have taken place since Early Tertiary times (Costa, 1987, 1991, and 1993). All these results will be discussed further in this paper.

The exploration conducted by Docegeo was extended by means of several vertical and inclined, shallow (50 m) to deep (160 m) drill holes, as well as terrestrial magnetometric surveys, which led to the delimitation of the main body and of another one C-30 body (Fig. 2).

In 1991, CVRD began the exploitation of the supergene ore of the upper part of the supergene zone (weathered gossan and clayey zone) with mean gold content of 5.0 g/t. The pri-

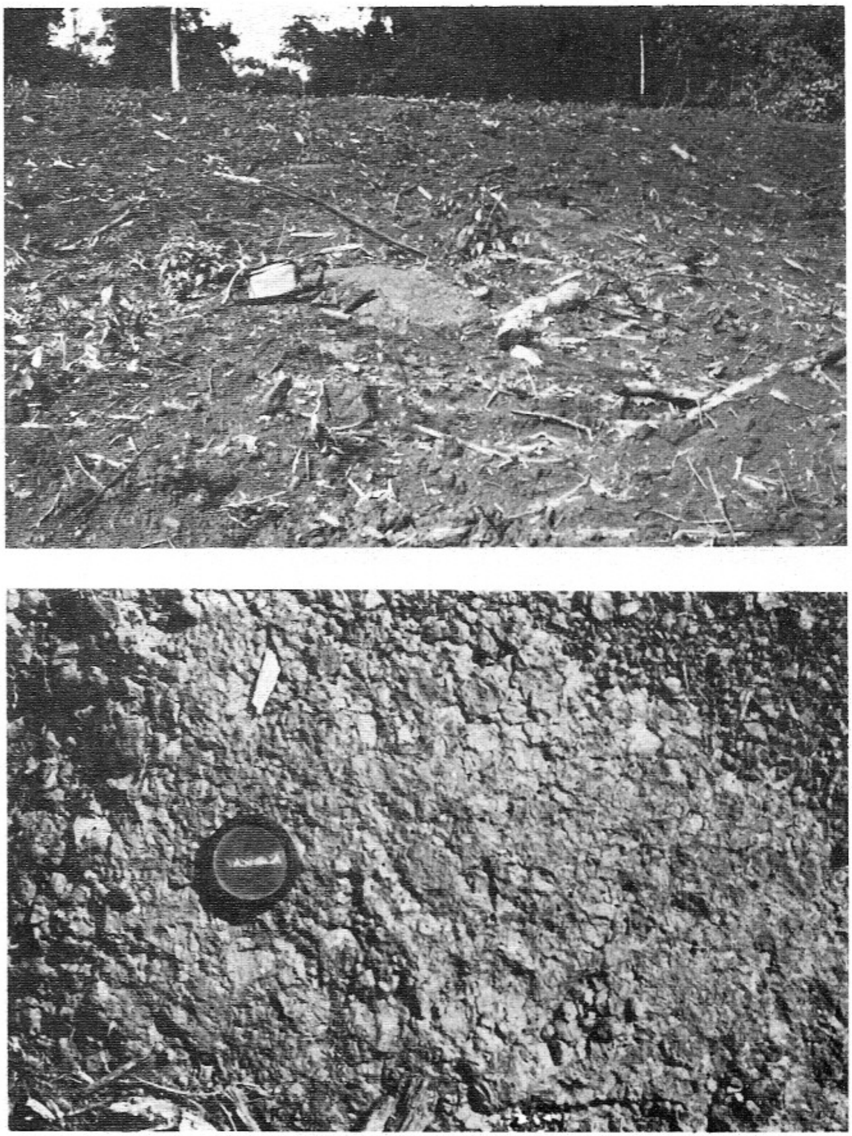

Plate 1 - Photo 1: Windows of lateritic iron crust with fragments of grossan formation; Photo 2: Detail of Photo1.

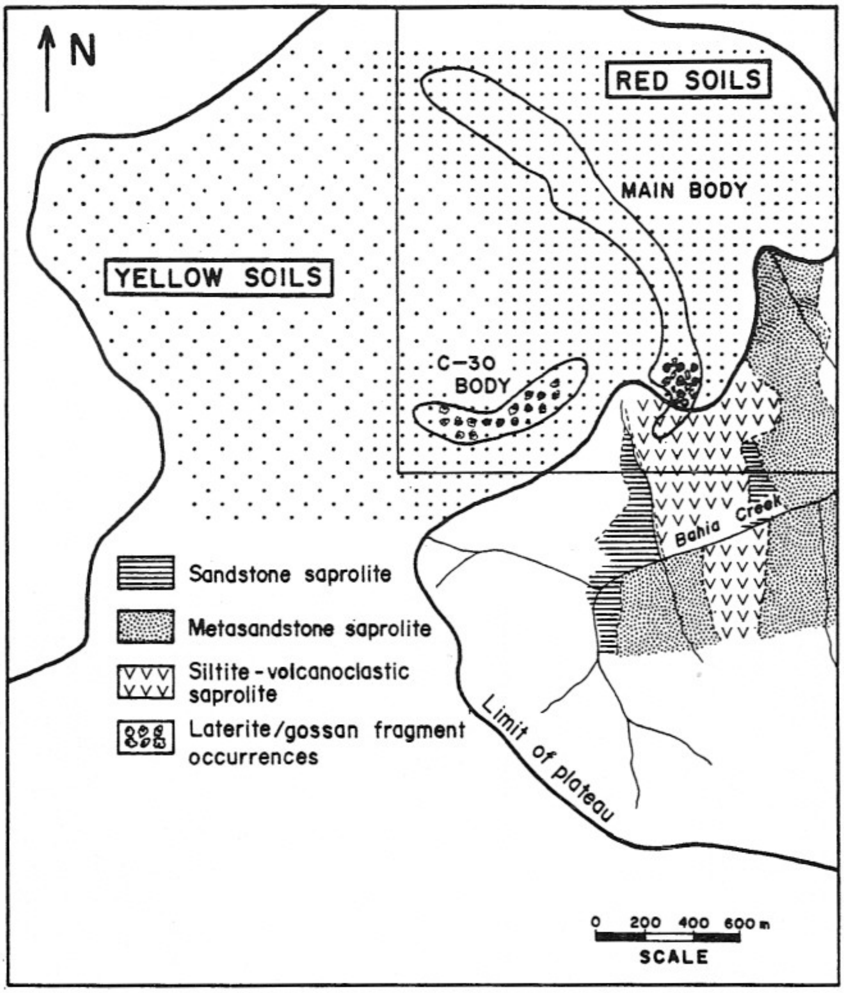

Figure 2 - Surface geological mapping of the Igarapé Bahia Plateau.

mary gold reserve was not evaluated yet.

PURPOSE OF THE PRESENT STUDY

This work presents mineralogical and geochemical data and describes the geochemical exploration methodology employed during the prospection for the supergene gold ore in the Igarapé Bahia area. The main purpose of the present paper is to evaluate this methodology, with the aim of contributing to the improvement of gold geochemical prospection in lateritic terrains under tropical rain forest conditions, using the current knowledge about gossans and lateritisation processes to enable new ore discoveries in the Amazon region and, obviously, wherever similar environment occurs all over the world.

PHYSIOGRAPHIC FEATURES

All over the Carajás region, the vegetation includes evergreen rain forest, mainly in valleys and lowlands, and Savannahs on the top of plateaus, developed directly on iron crust and, locally, called "clareiras" (clearings).

The Igarapé Bahia area is located in the homonym plateau around 700 m over sea level. The geomorphic surface is part of the complex set of plateaus which constitutes the Carajás region and contains the enormous iron ore reserve of the Carajás Ore District. The Igarapé Bahia plateau has been partially dissected in more recent times by the Bahia creek and its precursors, as well as by smaller tributary streams.

The climate is equatorial, warm and humid. The mean daily temperature is 26°C and the mean annual precipitation is 2,600 mm, being the months from July to November the driest ones.

GEOLOGY

In the Igarapé Bahia area (Fig. 2), the bedrock outcrops only in the bottom of the deep valleys and is composed mainly by sedimentary and mafic to felsic-volcanic rocks: metarenites, restricted banded iron formations, and metabasalts of Archean to Lower Proterozoic age (Ferreira Filho, 1985). Primary gold mineralization is associated with a hydrothermal sulfide zone (mainly with chalcopyrite and, locally, with molybdenite) in an almost-vertical breccia zone, up to 60 m wide (Rose et al., 1991).

The Igarapé Bahia plateau is developed on these litologies, which can be reached only by deep drilling. The peneplanation of the plateau was promoted by thick yellow (outside the mineralized area) to red (inside the mineralized area) clayey latosol cover, which may be correlated with the so-called Belterra Clay of Sombroek (1966), Truckenbrodt & Kotschoubey (1981), and Truckenbrodt et al. (1991). The iron crust outcrops at the border of the plateau as rare small windows (Plate 1).

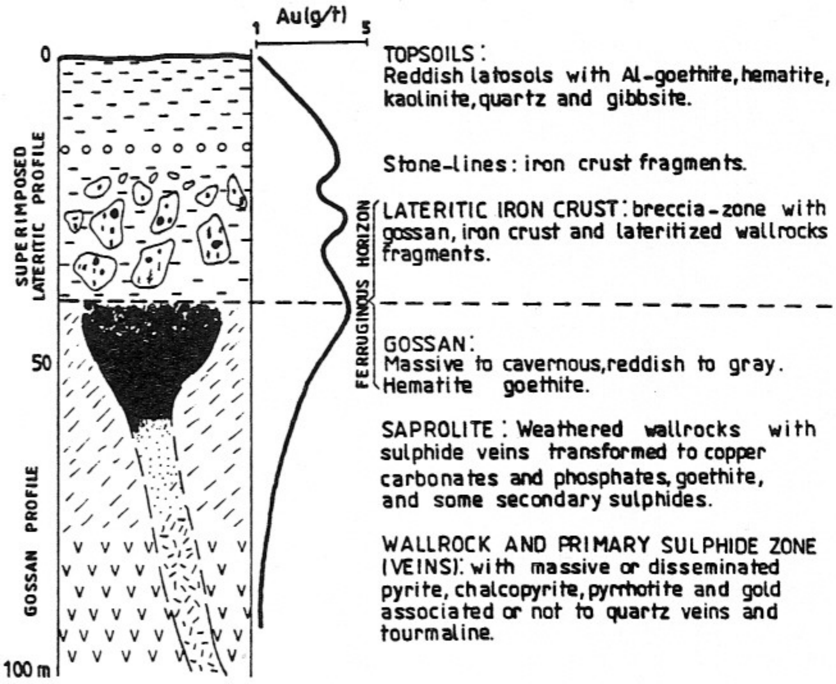

Figure 3 - Simplified geological profile of the lateritized gossan at Igarapé Bahia.

SAMPLING AND ANALYTICAL PROCEDURES

This work is based on geochemical and mineralogical data of more than 1,000 samples from topsoil, test pits, and drill cores (Fig. 1) collected by Docegeo and by the authors of this paper during several field surveys.

The samples (soils with gossan and laterite fragments) were crushed and sieved to minus 80 mesh. In the test pits, composite samples were taken at each 0.5 m and subjected to the same treatment.

The samples were analyzed for Au, Ag, Cu, Mo, and Fe through atomic absorption spectrometry (AAS) by the laboratories of Docegeo (in Belém, Pará State) and by the laboratories of Geosol (in Belo Horizonte, Minas Gerais State).

The mineralogy was determined mainly by X-ray diffraction (XRD) and, to some extent, by studies of polished and thin sections under petrographic microscope.

RESULTS AND DISCUSSIONS

The Profile

A general representation of the gossan/laterite profile at Igarapé Bahia is presented in Figure 3, where the following horizons were observed from top to base:

Topsoils (latosols) - The profile is often overlain by a loose earthy-clayey latosol (Plate 2), whose thickness ranges from few centimeters to 10 m, with predominant reddish color. Outside the mineralized area, this latosol exhibits a typical yellow color, resembling the commonest soil-like cover of the lateritic profiles of the Amazon region. The color contrast between these two types of cover is very sharp and may be used in the search for buried gossans. Around the C-30 body (Fig. 2) and in the southern part of the main body, the red soils are rich in debris derived from the gossans and lateritic iron crusts. Thus, the soils are thicker in the central and northern parts of the area, at higher altitudes (700 m), and thinner in the southern part, at lower altitudes (600 m). Several authors have already discussed the origin of these latosols and their allochtonous or autochtonous character (Sombroek, 1966; Truckenbrodt & Kotschoubey, 1981; Lecomte, 1988; Truckenbrodt et al., 1991). In this paper, these red latosols are regarded as being directly derived from centimetric to decimetric gossan-like bodies and lateritic iron crusts. At Igarapé Bahia, these soils are free from sedimentary structures, but some stone lines have been reported at the contact with the underlying iron crust (Plate 2). This lower contact is normally abrupt, irregular and without conformity with the present relief.

Ferruginous horizon - This horizon is typically rich in iron oxy-hydroxides with dark brown to reddish color, reaching depths down to 50 m and comprising:

a) A pisolitic-nodular to pseudobrecciated lateritic iron crust: it is constituted by millimetric to centimetric subrounded concretions and fragments derived from gossans and wall rocks, which are partly involved by red to yellow loose clayey matrix. The upper part

Plate 2 - Photo 1: Deep red soil going to saprolitized gossan at Igarapé Bahia gold mine; Photo 2: Red soil cover in an abrupt contact (stone lines) over less disturbed gossan formation.

of this horizon is normally dismantled and gives rise to stone-lines.

b) Massive to terrous hematite (gossan, sensu strictu): they are generally massive, magnetic, with predominant black to brownish color. This material builds up an enormous volume of a compact ferruginous crust (Plate 3), in which different cavernous and boxwork textures are observed on a centimetric to millimetric scale. This crust occurs normally below the earth surface and rarely outcrops, where the best exposures were obtained into the open pit.

Saprolite - This horizon represents the saprolite of the metavolcano-sedimentary wall rocks that encompass the mineralized bodies. It is a thick reddish clayey zone reaching up to 60 m depth and extending downward into the primary wall rocks. Primary subvertical foliation is still preserved. Centimetric brittle-quartz veins occur dispersed in this horizon where millimetric to centime-tric gold grains were described.

Supergene and primary sulfide zones - These zones were reached only through drill cores at about 120 to 160 m depth and comprise massive to disseminated copper-sulfides ore bodies (mainly chalcopyrite and pyrite), which crosscut brecciated metavolcano-sedimentary wall rocks.

General Mineralogical and Chemical Aspects of the Profile

The topsoils are composed primarily by kaolinite, goethite, Al-goethite, some maghemite, quartz, and rare gibbsite. The ferruginous horizon is constituted mainly by hematite and maghemite, besides goethite and gibbsite, in smaller amounts. Hematite is progressively substituted by goethite from the gossans toward the lateritic iron crust. This is the main mineralized zone, whose thickness ranges down to 50 m of depth, with mean gold contents of 5.0 g/t. Gold values decrease gradually toward the lateritic iron crust (laterally) and abruptly going into the underlying saprolite and into the upper topsoils. The knowledge about the mineralogical composition of the saprolite is restricted to its upper part, consisting of goethite, kaolinite, and hematite. In the secondary sulfide enrichment zone and at the base of the oxidation zone, malachite, pseudomalachite, azurite, chrysocola, cuprite, and native copper were identified. The main sulfide minerals are chalcopyrite and pyrite.

The supergene gold-mineralized zone, related to the weathering profile of the Igarapé Bahia area, presents a high concentration of Fe_2O_3 (40-60%), SiO_2 (10-30%), and Al_2O_3 (15-25%), mainly at the ferruginous zone. Its relatively high SiO_2 and Fe_2O_3 concentrations allow to distinguish the gossan profiles from the lateritic ones only around the Igarapé Bahia mine. The lateritic alterations at the top of the ferruginous zone is indicated by the decrease of SiO_2 and Al_2O_3 contents and the increase of Fe_2O_3 contents, along with supergene morphological features, and by the gradual change toward the neighboring widespread laterite profiles.

Gold Geochemistry

In the Soils

From the 1,142 soil samples collected and analyzed

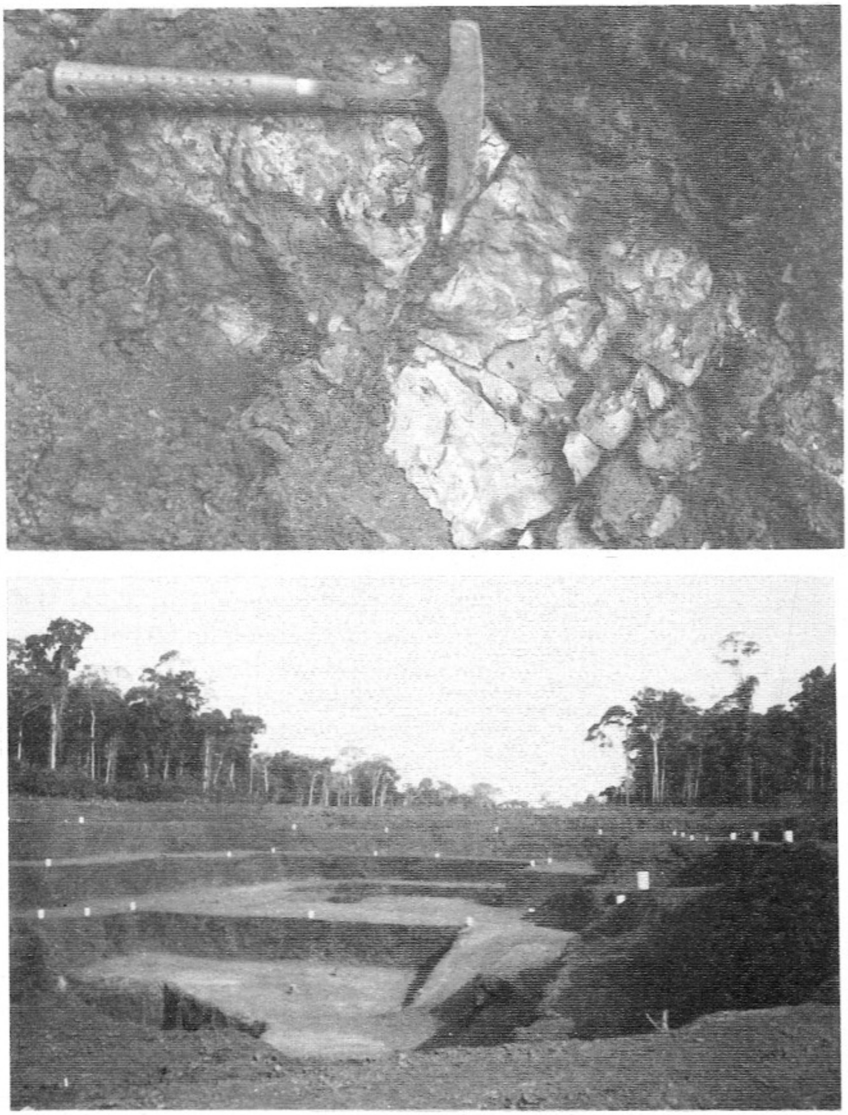

Plate 3 - Photo 1: Fragments of massive hematite from gossan; Photo 2: Open pit in the gold mine at Igarapé Bahia through the gossan/laterite body and surrounding Hileya Amazonica.

for Au, Fe, Co, and Mo in the soil grid of Figure 1, only 211 presented gold values above the detection limit (0.05 ppm), restricted to the mineralized area, on the northeastern part of the Igarapé Bahia plateau. The statistics summary and frequency distributions of these elements are presented in Figure 4. The average gold content is 0.24 ppm, reaching up to 1.28 ppm, where the iron crust outcrops. The samples with values greater than 4.0 ppm (probably related to nugget effect) were excluded in these calculations. Gold and molybdenum present a similar frequency distribution patterns, with a positively skewed asymmetry that approach the lognormal distribution.

Gold distribution in soils outlined the gold anomaly shown in Figure 5. The boundary of the gold anomaly in soils was defined by the 0.1 ppm isocontent line, in a way comparable to that described by Glasson et al. (1988) at Callion area, in Western Australia. This line encompasses perfectly the two more important ore bodies delineated by terrestrial magnetometry (the main body and the C-30 body). The highest gold contents were observed in the southwestern part of the main body, exactly where the gossan and the lateritic iron crust outcrop. On the other hand, the lower gold contents are located in the central part of the main body, where the gold signal is almost undetectable and where the reddish clayey latosol is thicker (5-10 m) (Plate 2). Moreover, in this area, the soil is apparently displaced and mixed with the yellow soils from neighboring areas. The south- and southwestward broadening of the anomaly probably reflects a mobilization on a steep slope toward the Bahia creek. Molybdenum contents in all samples average 11 ppm and reach up to 94 ppm, in mineralized zone. It presents an anomaly in the same site of the gold one (Fig. 6), which corresponds to the gossan outcrop (Fig. 2). The molybdenum concentration also decreases regularly towards the limit of the halo, and induces an indirect relationship between these two elements. The Fe and Co distributions also overlap one another in the area of the gossan/lateritic iron crust outcrops, but with a more scattered distribution, which did not help to delineate the two mineralized bodies.

In the Gossan Profiles

Figures 7 to 9 show the distribution of Au, Ag, Mo, Cu, and Fe along the uppermost 20 to 25 m of different profiles of the main body, encompassing areas with shallow to deep soil cover, as well as cover-free ore bodies (Fig.1). In all these profiles, the gold contents decrease toward the soil horizon.

The higher gold contents

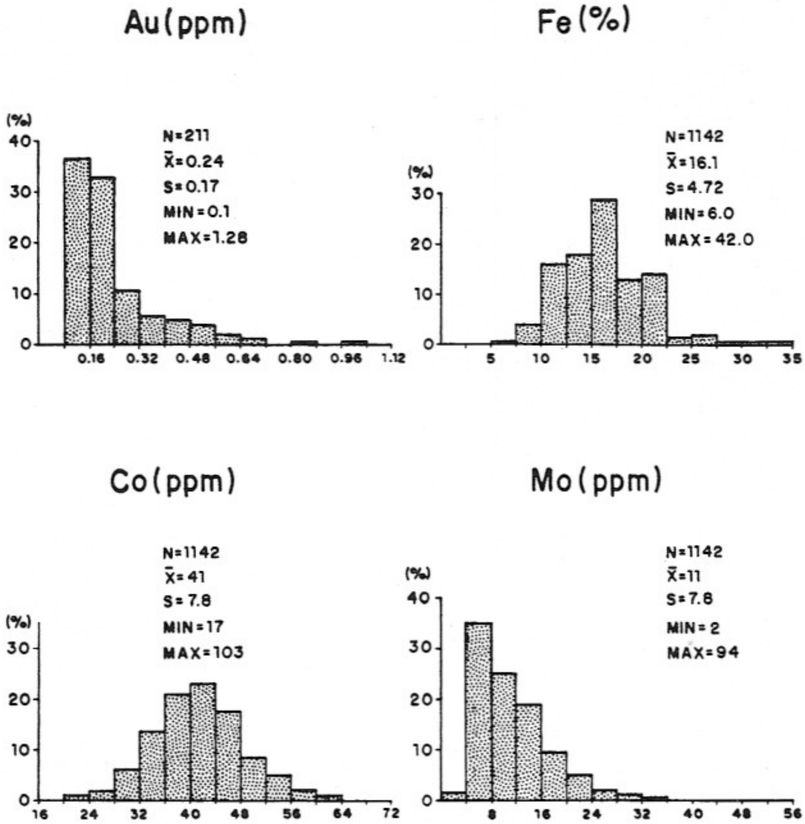

Figure 4 - Frequency distributions and summary statistics for Au, Fe, Co and Mo in soil samples at Igarapé Bahia.

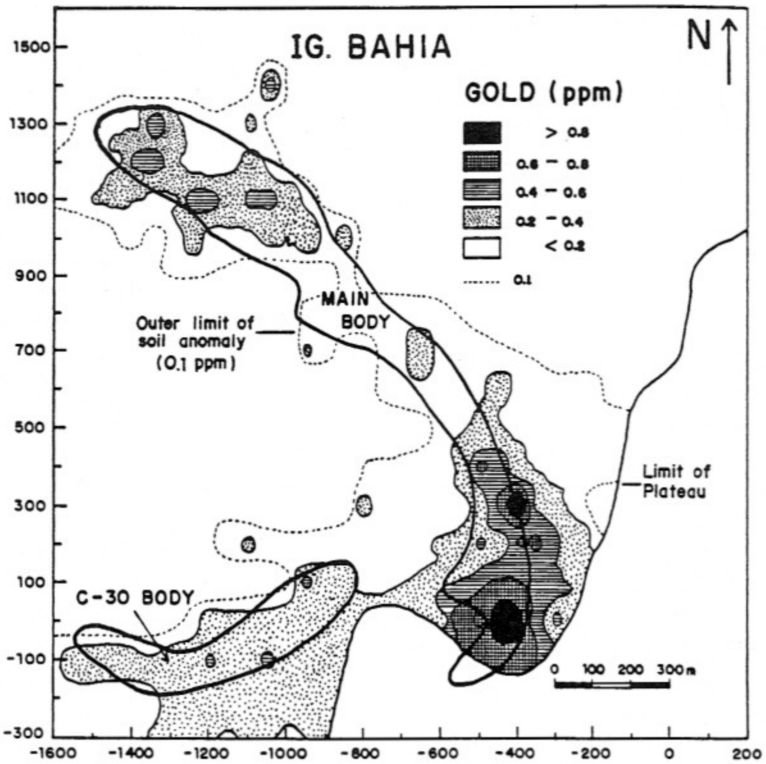

Figure 5 - Gold content distribution in soils over the mineralized area at the northeastern part of the Igarapé Bahia Plateau.

(3 to 89 ppm) are found often in lower parts of the profiles, along the gossan/laterite zone. The good correlation between gold and molybdenum in soils was not observed in the profiles, although molybdenum contents are still higher. Gold presented a better correlation with silver in pits 1 and 2. Copper exhibits a characteristic behavior, with downward content increase that reaches 0.4 %, and has, apparently, no relation with gold.

In pit 1, which is cover-free and 20 m deep, gold contents can reach 10 ppm near the surface (around 1 m below the surface) and up to 89 ppm at 19 m of depth (Fig. 8). Silver distribution presents a good correlation with gold, with 20 ppm for greatest contents. Molybdenum shows a different behavior from gold and silver with two maximum values of 92 and 130 ppm between 12 to 16 m of depth. The greatest molybdenum content was 500 ppm in the drill hole 3. A schematic NE-SW cross-section of the Igarapé Bahia area (main mineralized body) and the distribution of gold through several shallow and deep drill holes are represented in Figure 10. The morphological expression of the body at the depth is a typical mushroom-shape, widening at the top and reaching up to 150 m wide. A similar context was described by Granier et al. (1963) in Ity, Ivory Coast. The supergene profile extends 160 m downward within the main body, while, within the wall rock, it is about 50 to 80 m deep. The gold mineralized zone is restricted to the uppermost 20 to 30 m of the ferruginous-breccia zone, with average gold contents of 5 g/t. Within this zone, gold distribution is very erratic, reflecting the mixing of different weathered lithologies

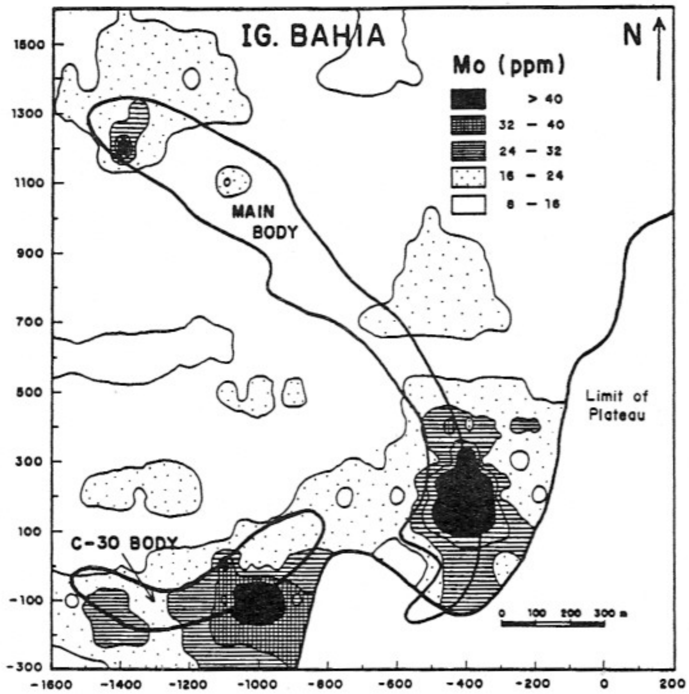

Figure 6 - Molybdenum content distribution in soils over the mineralized area at the northeastern part of the Igarapé Bahia Plateau.

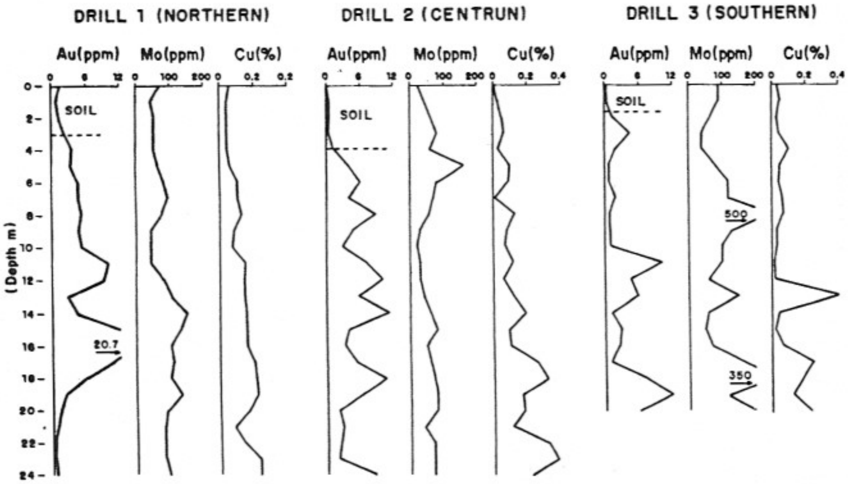

Figure 7 - Au, Mo and Cu distributions throughout shallow drill holes in three different parts of the main body at Igarapé Bahia.

(wall rocks and ore veins).

Recent microscopic examination of free gold particles from the upper latosols revealed the presence of very-coarse-grained gold in vugs and in iron oxy-hydroxides in samples, what supports the theory of dissolution, migration, and reprecipitation of gold in lateritic environments. These conditions have been repeatedly described in the last years by different workers in lateritic terrains of Western Australia, West Africa, India, and also in Brazil (Mann, 1984; Webster & Mann, 1984; Wilson, 1984; Davy & El-Ansary, 1986; Michel,1987; Colin & Lecomte, 1988; Freyssinet et al.,1989; Lecomte & Colin, 1989; Davies et al., 1989; Benedetti et al., 1990; Oliveira & Campos, 1991; Santosh & Omana, 1991; Costa et al., 1993).

CONCLUSIONS

The gold mineralization at the Igarapé Bahia area is the first published example of supergene gold related to lateritised gossans in the Amazon region (Costa, 1987). Lateritisation processes, which took place all over the region since Early Tertiary times, disturbed throughly the upper part of the gossan profile, giving rise to a new and wider dispersion of gold and other elements. The main product of these processes is a ferruginous pisolitic to breccia-like horizon, with fragments of the former gossans and the former wall rocks, and the development of complete lateritic profiles around the gossan area. A thick red clayey latosol, which covers invariably the gossan zone, has been formed afterwards.

The lack of further geochemical and mineralogical data about gold particles and also of a better evaluation of the primary mineralization, hinders to make more assertions about gold enrichment in this area. Nevertheless, favorable conditions for mobilization of gold in low temperature supergene environments have already been described elsewhere in tropical regions. These reports also support this thesis for the Igarapé Bahia area.

For a geochemical exploration program in a tropical rain forest such as that of the Ama-

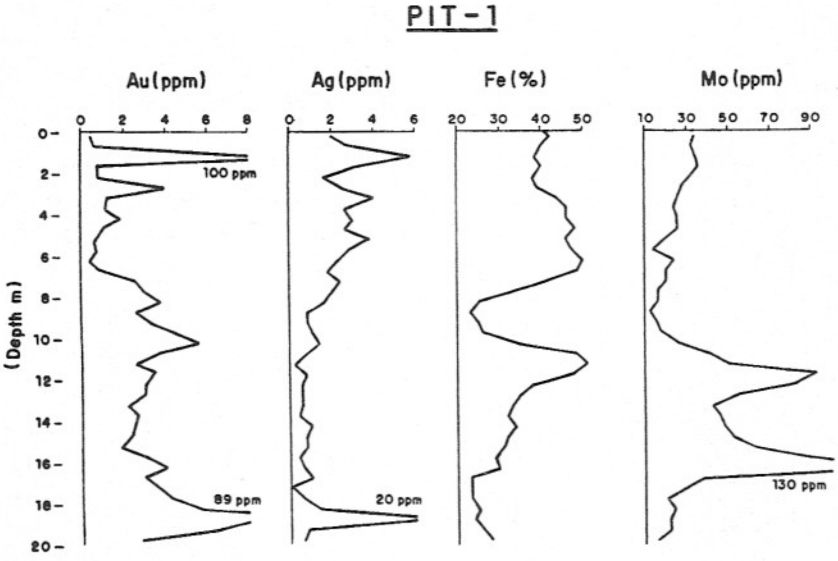

Figure 8 - Au, Ag, Fe and Mo distributions throughout Pit 1 in the southern part of the main body at Igarapé Bahia.

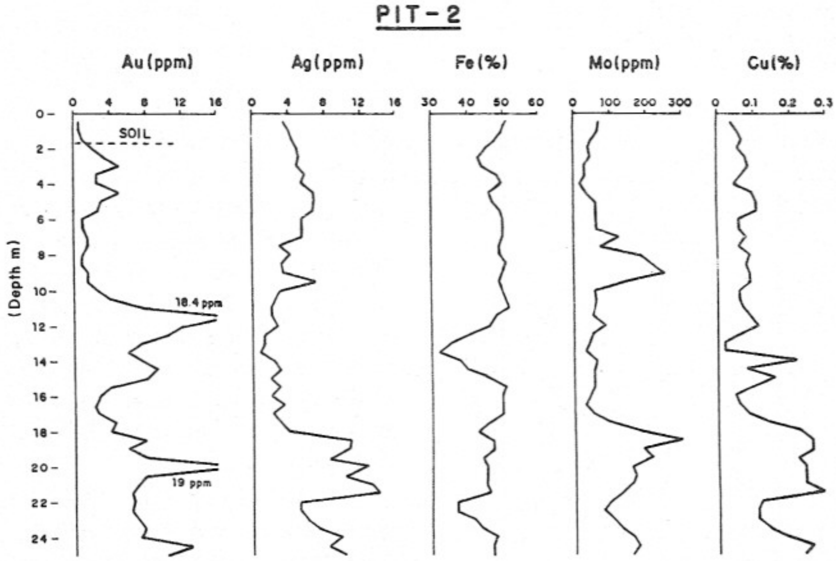

Figure 9 - Au, Ag, Fe, Mo and Cu distributions throughout Pit 2 in the southern part of the main body at Igarapé Bahia.

zon region, a number of factors need to be considered:

1) The nature of the laterite and gossan profiles, in terms of sequence of horizons, erosive truncation, and presence of either autochtonous or allochtonous topsoils, have to be regarded since these geological base is fundamental to the interpretation of the geochemical data;

2) Soil geochemical surveys should consider the sample amplitude and the presence of different rock-debris occurrences (gossans and laterite fragments, concretions, stonelines, etc.);

3) A clear distinction of the nature of different autochtonous and allochtonous soil covers, which may either distinguish or conceal ore bodies. At Igarapé Bahia, the characteristic color, varying from yellow latosols (unmineralized area) to red latosols (mineralized area), is one of the best examples of the necessity of mapping different soil covers.

The acquisition of additional geochemical exploration models for the Amazon region scene must take into account not only the extent of preservation of pre-existing profiles (Butt,1987), but also the mature or immature character of the profiles (Costa, 1993). These profiles present different evolution degrees and structures which control supergene mineralization, specially for gold, and the further development of soil covers.

Under current weathering conditions, both laterites and gossans have been intensively destroyed (weathered), where the different final products (the loose clayey latosols) are put side by side (Fig. 11), with different geochemical signatures and broadening of the

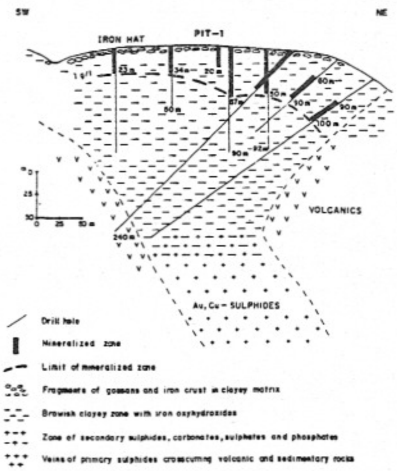

Figure 10 - General NE-SW cross-section in the southern part of the main body showing the gold mineralized zone and the typical mushrom-shapped dispersion pattern.

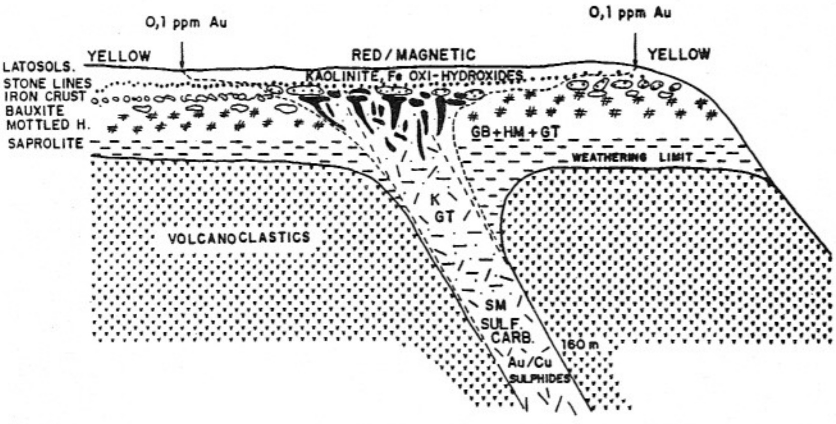

Figure 11 - Schematic model for the gossan/laterite profile at Igarapé Bahia and the general dispersion pattern of gold contents.

geochemical halos.

In the Igarapé Bahia plateau, the gold geochemical follow-up depicted successfully the present known mineralized zone with the 0.1 ppm isocontent line (Fig. 11) and the use of multi-element chemical analyses ensured a better evaluation of the nature and influence of the parent rocks.

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