Gold Prospectivity Mapping of Andorinhas Greenstone Belt, Para

Ezequiel Costa e Silva (*), Reinarda Mineração / Universidade de Brasília; Adalene Moreira Silva, Catarina L. B. Toledo - Universidade de Brasília; Augusto Mol, Reinarda Mineração; David Otterman, Troy Resources NL

Abstract

This study involves the integration of information interpreted from regional data sets consisting of high-resolution airborne magnetic gradiometer and gamma-ray spectrometer surveys, geology and other detailed superficial geoscientific data from the Rio Maria Granite-Greenstone Belt, located in southeastern Para State, Brazil. Gis based automated processing methods employing fuzzy logic techniques were used to derive spatial models for generating new orogenic gold exploration targets. Several targets associated with lode-type gold mineralization were outlined over Andorinhas Project area. These targets were subsequently follow-up with field evaluations consisting of geological mapping and geochemical sampling. A follow-up Reverse Circulation drilling program is underway to assess the main target areas where grid soil and rock sampling have delineated anomalous trends.

Introduction

Significant progress has been made in the field of integration and spatial modeling of exploration geochemical and geophysical data, providing better tools to assist the discovery of new gold deposits. The application of these new methodologies is considered to be a very useful tool in the search for new gold discoveries in greenstone belt terrains. Current standard exploration protocols are focused on defining a “footprint” based on known gold deposit which is then applied in a search of available data sets to identify similar or look-alike anomalies.

The approach outlined in this paper is a geophysical interpretation method derived from an integrated GIS-based exploration targeting study for orogenic gold as applied to the Andorinhas region in Para State, within Rio Maria Province. Exploration targets for orogenic gold deposits have been generated for the study area by applying automated Geographic Information Systems (GIS) techniques in a process that is typically known as Prospectivity Analysis. A comprehensive structural analysis was completed based on interpretation of airbone magnetic data. In parallel the radiometric data was used to highlight hydrothermal alteration. Field mapping formed the foundation of this prospectivity analysis and target generation. The current project has generated targets using automated conceptual techniques based on the available data aided by Spatial Data Modeller (SDM) software (Sawatzky et al. 2007), and guided by expert knowledge.

The study area is part of Rio Maria Province, located in the southeast of Para State situated within the Amazon Craton. The area encompasses the cities of Rio Maria and the southern limits of Xinguara, and as far east as Floresta do Araguaia (PA), 260km to the southeast of the principal city of Marabá (Figure 1).

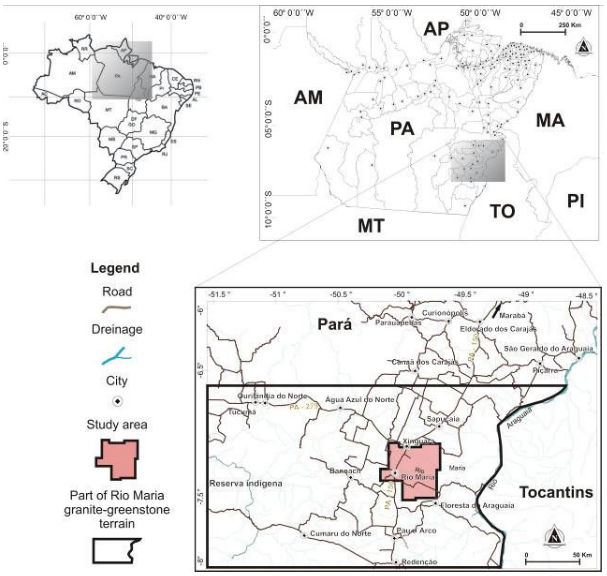

Figure 1 - Study Area Rio Maria Granite-Greenstone Terrain.

Geological Setting

The area studied is located in the southeast Carajás Mineral Province known as the Rio Maria Province. The Carajás Mmineral Province lies at the southeastern margin of the Southern Amazon Craton of Brazil and is represented by granitoid-greenstone terrains, intracratonic basins and high-grade metamorphic complexes (Tassinari & Macambira 2004). Recently it has become one of the most studied portions over Amazon area and is considered to be one of the most important Mineral Province of the country with a diversity of rich mineral resources (Dall´Agnol et al. 2006). The Carajás Province comprises two Archean tectonic blocks, the northern Itacaiúnas Belt (Araújo et al. 1988), a tectonic block that hosts the Carajás Basin, and the southern Rio Maria Granite-Greenstone Terrain represented by the Andorinhas Supergroup (Huhn et al. 1988). (Figure 2)

The Rio Maria granite-greenstone terrain and the Itacaiúnas belt can be differentiated in terms of both their geological setting and associated mineral deposits. The

Itacaiúnas belt and Carajás basin form a structural province represented by the major east-west to northwest-southeast trending Carajás and Cinzento strike-slip systems. The Rio Maria granitoid-greenstone terrain is composed largely of east-west; northwest-southeast and northeast-southwest trending shear zones that represent dextral strike-slip faults that have affected chiefly the supracrustal rocks (Holdsworth & Pinheiro, 2000). Synformal structures along the shear directions, previously interpreted as synclines, are considered to be transpressive duplexes. The larger duplexes are related to E-W shear zones whose cores consist of sedimentary rocks and whose borders are defined by thrust faults.

The Rio Maria granite-greenstone terrain is composed of greenstone belts and a variety of Archean granitoids (Dall'Agnol et al., 2006). The former gave ages of 2.97 to 2.9 Ga and consist of meta-ultramafic (komatiites), metamafic (basalts and gabbros) rocks and subordinate intermediate to felsic rocks, with intercalations of metagraywackes, all grouped into the Andorinhas supergroup (Souza et al., 2001). The granitic rocks originated between 2.98 and 2.86 Ga and the oldest granitoids, represented by typical Archean TTG suites, originated between 2.98 and2.92 Ga (Arco Verde, Caracol, and Mariazinha tonalites and Mogno trondhjemite; Docegeo, 1988; Althoff et al., 2000; Souza et al., 2001; Leite et al., 2004; Dall'Agnol et al., 2006).

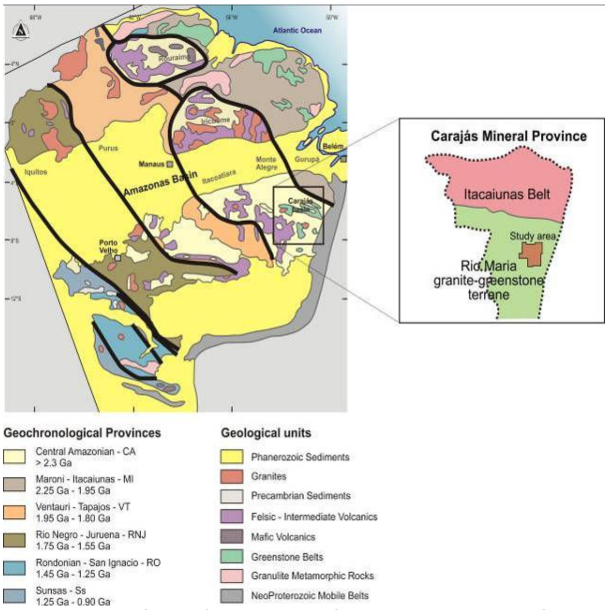

Figure 2 - Simplified Plan of the Amazonian Craton (showing the geochronological provinces according to proposals of Tassinari and Macambira 2004).

Large Archean batholiths cut the greenstone rocks and the emplacement of many anorogenic alkaline to subalkaline A-type granitoid stocks and batholiths occurred in the Paleoproterozoic as well as dikes and sills (Gastal et al. 1987). Similar greenstone sequences (Tucumã, Gradaus, and Sapucaia groups) occur elsewhere. In this area small lode gold deposits such as Mamão, Babaçu, Lagoa Seca, Diadema and Serrinha are located. Currently the only operating gold mine is the Mamão Mine being mined by Troy/Reinarda.

Airborne Geophysical Data

The study area was covered by an airborne geophysical magnetic gradiometer and radiometric survey flown at a constant ground clearance at 100 m above the ground surface. The airborne data were acquired using 125 m spaced flight lines with tie lines spaced 1.500 meters, respectively, N-S and E-W directions. The area covered is approximately 1.952 km^2, which involves about 16.924 km linear.

Exploration Model - Golden Ore Mineralisation

The methodology used in this study incorporates the geological and geophysical data over the Andorinhas Project area to generate prospectivity mapping for lode-type gold mineralization within the Rio Maria Province. Orogenic style gold mineralization at Andorinhas is generally associated with shear zones with high hydrothermal alteration, variable amounts of sulfide and quartz veining. The gold deposits in general have formed in dilational zones within the shear zones. The targeting method used a unique processing of aeromagnetic and gamma-ray spectrometric data to create images which highlight hydrothermal alteration zones and low magnetic gradients to distinguish potential targets for gold mineralization.

Methodology

Processing of the Airborne Geophysical Data

The general processing of airborne geophysical data in this study involved three steps: data preparation and formatting, processing of airborne data and calculated data/derivative products. The processing of airborne data involved the sequential editing followed by application of a gridding routine, removal of apparent residual errors and microleveling of all data to a common base. Later the data was gridded following the Blum methodology (1999).

The main derivative magnetic products calculated from the total magnetic field data was: analytic signal, first vertical derivative, phase of analytical signal, measured gradients (Gx and Gy) and horizontal gradient analytic signal.

Industry standard processing of airborne gamma-ray surveys require a minimum of four maps (total count, potassium, uranium and thorium) to present the four variables measured. Important information is also obtained from four additional derivative products that involve ratios between the various elements: eU/eTh, eU/K, eTh/K and K/eU/eTh radioelement maps. In this approach were used mainly K/eTh and F Parameter images. The F Parameter (Efimov, 1978) shows the potassium distribution related to the uranium and thorium radioelements and has been used on the discrimination of hydrothermal alteration zones. It is expressed by the formula: F=(K*eU)/eTh.

Processing of the Spatial Analyst

The commercial GIS packages ArcGIS 9.3 from ESRI, enhanced with advanced public domain extensions or add-ons called ArcSDM (Kemp et. al. 2001, Sawatzky et al. 2004) was employed in this study to create assessment of mineral potential within a greenstone belt terrain that is known to be permissive for gold (Figure 3).

Once the data was prepared properly, a GIS approach can be employed in concert with other software packages to manipulate and visualize the data in order to produce a mineral prospectivity map. Many spatial modeling techniques can be employed to produce such a map. However, these methods can be divided into two basic categories; knowledge and data-driven techniques (Bonham-Carter, 1994).

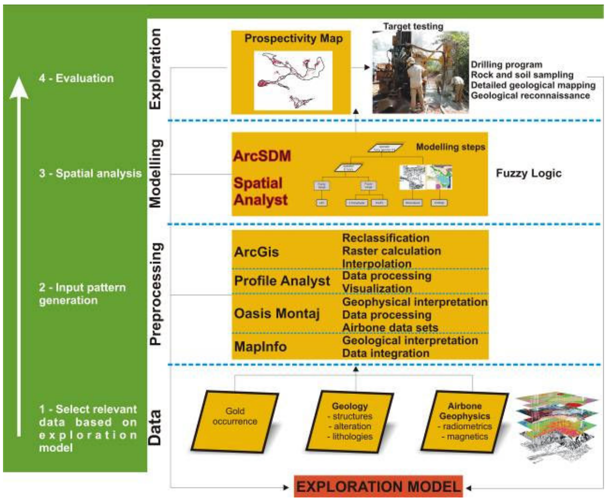

Figure 3 - A Flow chart describing the components involved in mineral potential modelling, roughly following the methodology of Pan & Harris (2000) and Nykanen (2008).

Data-driven approaches require that "a prior" knowledge (expressed in terms of a prior probability) exists in the form of known mineral deposits or occurrences (e.g., prospects) for the study area. Spatial relationships between the input data (evidence maps) and the spatial location of the mineral prospects are used to establish the importance (weight) of each evidence map. In other data-driven approaches, training areas can be established for each mineral deposit from which diagnostic signatures of mineralization can be calculated from the various data (e.g., geochemistry, geophysics, etc.) used in the modeling process.

Knowledge-driven approaches rely on the geologist's input to weight the importance of each data layer (evidence map) as they relate to the particular exploration model being used. This approach is more subjective but has the advantage of incorporating the knowledge and expertise of the geologist to build models to generate the prospectivity maps. Where empirical methods use statistics to select the evidential layers that show the strongest relationship to the known mineralization and subsequently use statistically-derived weights for combining these layers to generate the prospectivity maps, Fuzzy Logic allows the geologist to select the evidential layers they believe are the most critical for the particular style of mineralization being targeted, and allows the geologist to assign weights to each of these layers based on their expert opinion. Examples of knowledge-driven approaches include Boolean logic, index overlays (Harris, 1989), analytical hierarchy process (AHP) (Harris, Wilkinson, and Broome, 1995); and fuzzy logic (An, Moon, and Bonham-Carter, 1992).

Data Integration

The integration to the modeling process is the preparation of the various types of data comprising geological maps, geophysical images and geochemical data to create evidence maps for input to modeling. These inputs were integrated, processed and modeled using MapInfo, ArcGis, Geosoft, Profile Analyst and ArcSDM/Spatial Analyst software.

Host Rock Lithology

Lithologies were interpreted from the geophysical data and by geological field mapping of the study area. Principle lithologies included; mafic, ultramafic, felsic intrusive, banded iron formation, metasediments, and granites. Higher membership values were assigned to lithological formations that were reported to host the gold bearing deposits or were considered highly favorable, based on mapping. For example, a 0.95 fuzzy membership (definitely anomalous) was assigned to felsic and banded iron formation units. Lithological units such as ultramafic, quartzite, granitoid, and anorogenic granites were assigned lower values because they are not believed to be significant for gold bearing deposits. All thematic layers in the GIS database were converted to raster format prior to further processing.

Structural Controls

According to Huhn (1992), Pinheiro and Miller (internal RML's reports) the E-W trending high-strain zones as splays and jogs hosted along NE–SW corridor have more gold bearing mineral occurrences in the Andorinhas greenstone belt. Therefore, a higher membership value of 0.95 was assigned to the 0 - 100 m structural E-W lineament corridor and 0.5 for 100 - 200 m.

Vector data, such as magnetic lineaments and faults (mapped and interpreted), were transformed to continuous surface maps by dilating (buffering) around each line in successive zones from 0 to 200 meters. In this way the spatial association between gold prospects and selected structural features can be evaluated using Fuzzy logic to determine whether gold prospects are preferentially located closer to geologic structures than would be expected by chance.

Structural data used in knowledge-driven modeling analysis included: (1) deformation zones (NE and NW corridors) interpreted from field observations, airborne magnetic lineaments; (2) E-W, ENE-WSW, ESE-WNW trending zones (mapped in the field and interpreted from horizontal measured gradients - Gx and Gy).

Results and Discussion

Integration by Geophysical Interpretation

Analysis of geophysical features provides new insights into structural history and can help geologists target new areas for mineral exploration (Silva, 1999). Gradiometer magnetic survey data associated with high-resolution gamma ray spectrometric data shows a technological advance on available geophysical technology for low magnetic gradient structures of interest in mineral exploration. Therefore the combination of measured gradients (Gx and Gy) with products derived from combining K, Th and U channels has shown effectiveness in selecting targets for follow-up in tropical terrain.

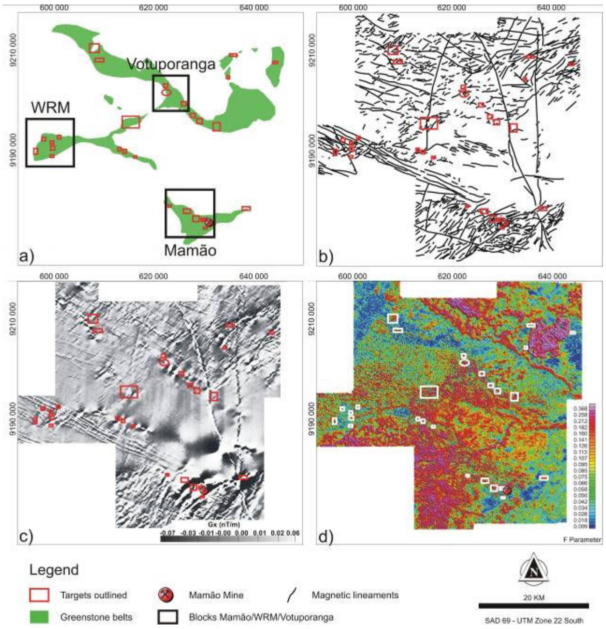

Figure 4 - Main Inputs layers on geophysical interpretation. a) Greenstone contour and the three important target blocks - WRM (West Rio Maria), Mamão and Votuporanga. b) Magnetic lineaments. c) Measured horizontal gradients - Gx. d) F Parameter image. All of them showing the targets outlined in the geophysical interpretation.

The integration of F Parameter and the measured horizontal gradients (Gx and Gy) have shown that known mineralized zones are mapped by high F Parameter values and low magnetic gradient features. These features also were used as input to the fuzzy logic process.

The targets outlined were based on visual inspection of prospectivity maps and assessment of favorable structural setting and geology. To date, integration with field data shows that the targets are located over shear zone areas with hydrothermal alteration. Twenty seven new exploration targets for ground follow-up in the field were outlined (Figure 5), each areas associated with intersection of NW-SE and NE-SW lineaments, low magnetic relief and coincident or adjacent high-potassium hydrothermal alteration.

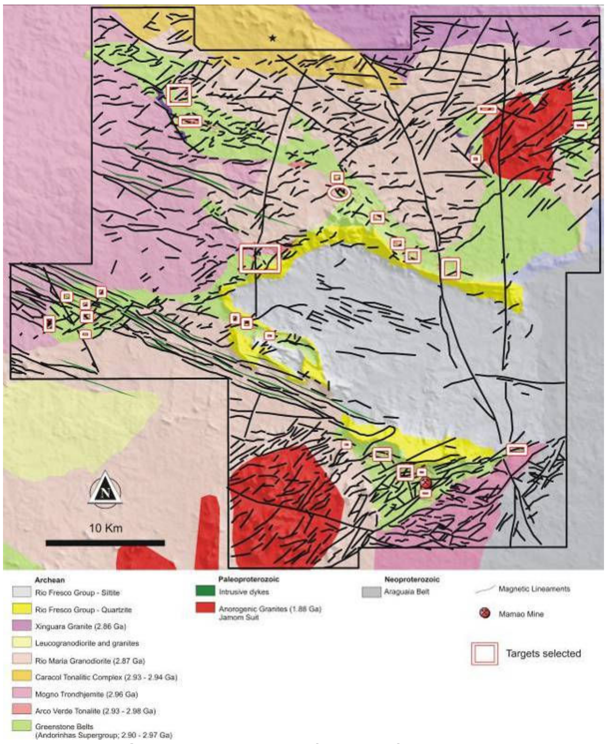

Figure 5 - Geological map of part of Rio Maria granite-greenstone terrain showing the new targets outlined. The map overlies a SRTM image.

Integration by Fuzzy Logic Methods

The integration of parameters into a single prospectivity map was completed using the fuzzy-logic overlay method described by Bonham-Carter (1994). The inference network in Figure 6 is a concise statement of the exploration model for Lode Gold deposit by defining the combination procedure. The integration was done in steps, and the intermediate maps, together with some of the original maps, and the final prospectivity map are shown in Figure 7.

The input layers as geological map, F Parameter, eTh channel, horizontal measured gradients images (Gx and Gy) and E-W low gradient zones were used into the fuzzy logic modeling.

The F Parameter was used to highlight the K enrichment, so was used the large membership functions. The small membership was used to eTh channel. Also the small function was used to highlight the low values of Gx and Gy gradients. For the magnetic evidence layers, the fuzzy algebraic Product was used to combine the individual element groups. Therefore, the resulting combination of the radiometric elements was then achieved by using the minimum operator, Fuzzy AND, to be a sign of favourable K enrichment environment. The final combination was done using the Fuzzy Gamma operator with a ɣ parameter value of 0.90.

The final map prospectivity outlined about forty four targets (figure 7). The fuzzy integration targets should be evaluated on field soon.

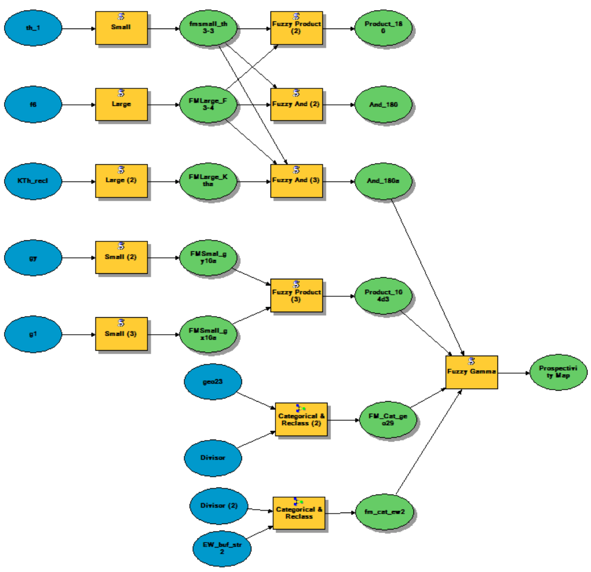

Figure 6 - Flowchart summarizing the modeling methodology invoked in this paper. This methodology involves selection of an exploration model, selection, and preparation of evidence maps and creating a gold prospectivity map using knowledge-driven modeling techniques.

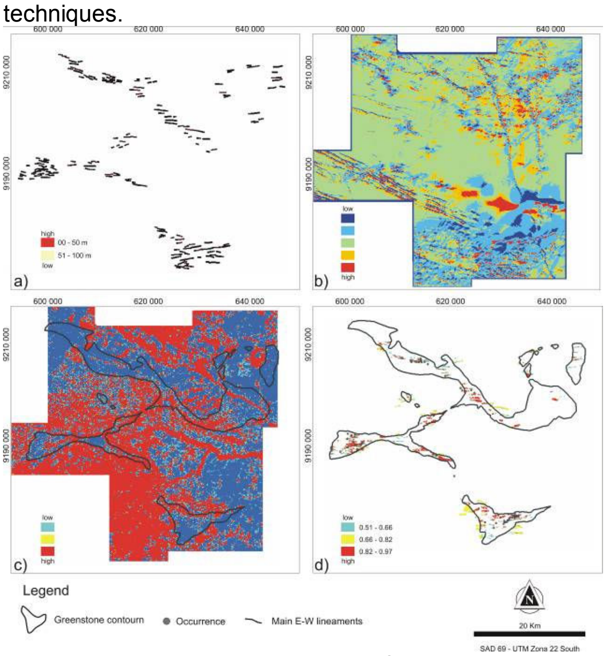

Figure 7 - Prospectivity maps for the Andorinhas greenstone belt. a) Categorical E-W trending zones buffered with 100 and 200m. b) Fuzzy algebraic Product from horizontal measured gradients - Gx and Gy. c) Fuzzy AND from radiometric elements as K, eTh and K/Th. d) Final prospectivity map with a ɣ parameter value of 0.90. The red color represents the higher prospectivity area with high fuzzy membership.

Evaluation of Best Gold Predictors

Target outlined by Integration on Geophysical Interpretation and Fuzzy Logic Methods

The highest ranked target identified on the basis of the geophysical interpretation and also the fuzzy logic model was the Marcinho Target within Mamão block. It is located to the east of the old Marcinho Pit along a WNW striking corridor, just 700m from the processing plant. The target is structurally controlled by NW-SE and NE-SW structures outlined with Gx, Gy and ISA. It is associated with high magnetic features, low Gy gradient and K enrichment as shown in the figure below, and also the F Parameter and K channel profiles (Figure 8 and 9).

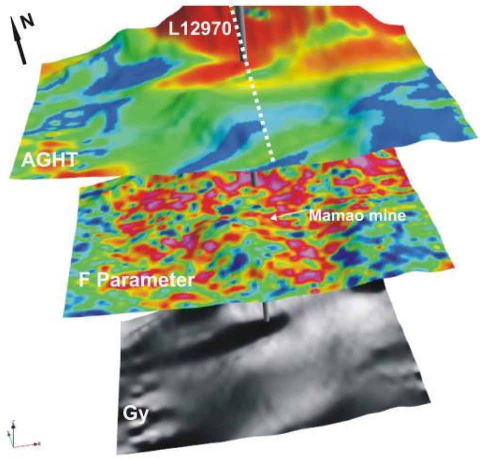

Figure 8 - 2.5D images of AGHT, F Parameter and Gy. The images show the K enrichment over Marcinho target.

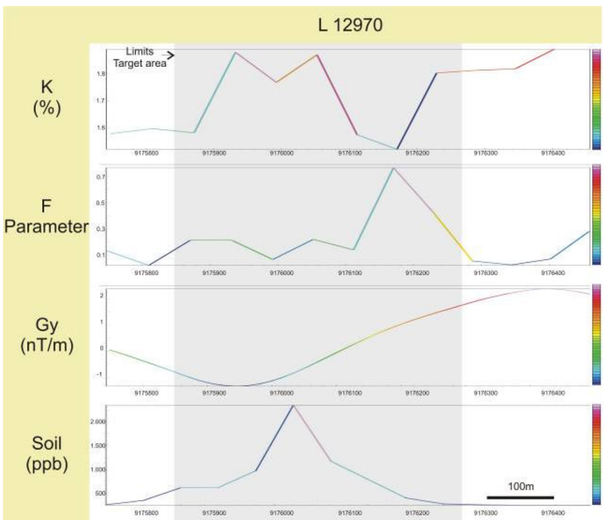

Figure 9 - Profile along the line L12970 showing the high values of K% channel, F Parameter, low values of Gy and anomalous gold in soil up to 2.500 ppb distributed along the target area.

The on ground the evaluation process included a soil sampling program. A 400m long gold-in-soil anomaly was defined with high grades ranging between 343ppb and 2,510ppb. Rock sampling collected to the east of

Marcinho´s Pit, returned high grades of **32.88g/t gold, 22.37g/t gold** and **14.8g/t gold** (Figure 10).

The mineralisation is typical of a BIF-hosted orogenic gold deposit, with silicification, possible carbonate alteration and sulphides of the BIF where cut by en echelon quartz veins and or quartz veins sub parallel to the banding in the BIF. At the top of the hill of outcrop the BIF units are intensively deformed showing drag folds with indications of dextral and sinistral displacement strongly similar to the structural pattern at the Mamão Mine.

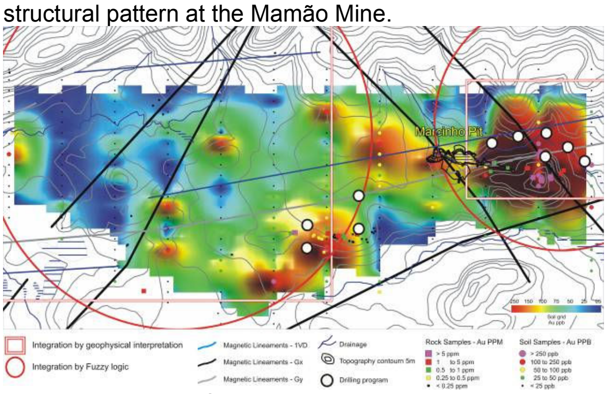

Figure 10 - Map of soil gridding over the two Marcinho targets and the ten planned RC holes.

References

Althoff, F.J., Barbey, P., Boullier, A.M., 2000. 2.8–3.0 Ga plutonism and deformation in the SE Amazonian craton: the Archean granitoids of Marajoara (Carajás Mineral province, Brazil). Precambrian Res. 104, 187–206.

An, P., Moon, W. M., and Bonham-Carter, G. F., 1992, On a knowledge-based approach of integrating remote sensing, geophysical and geological information: Proc. IGARSS'92 (Houston, Texas), p. 34–38.

Araújo O.J.B, Maia, R.G.N., João, X.S.J. & Costa, J.B.S. 1988. A megaestruturação arqueana da Folha Carajás. Inc Simp. Latinoamericano Geol 7, Belém, SBG, proceedings, vol-1, pp:324-333.

Blum, M. L. B. 1999. Processamento e Interpretação de dados de geofísica aérea no Brasil Central e sua aplicação à Geologia regional e à prospecção mineral. Brasília. Tese de Doutorado, UnB, 229p.

Bonham-Carter, G. F., 1994, Geographic Information Systems for geoscientists-modeling with GIS: Pergamon, New York, 398 p.

Dall'Agnol, R., Oliveira, M.A., Almeida, J.A.C., Althoff, F.J., Leite, A.A.S., Oliveira, D.C. & Barros, C.E.M. 2006. Archean and Paleoproterozoic granitoids of the Carajás metallogenetic province, eastern Amazonian craton. In: Dall'Agnol, R., Rosa-Costa, L.T., Klein, E.L. (eds.). Symposium on Magmatism, Crustal Evolution, and Metallogenesis of the Amazonian Craton. Abstracts Volume and Field Trips Guide. Belém, PRONEX-UFPA/SBGNO, 99-150.

DOCEGEO (Rio Doce Geologia e Mineração - Distrito Amazônia) 1988. Revisão litoestratigráfica da Província Mineral de Carajás, Pará. In: CONGRESSO BRASILEIRO DE GEOLOGIA, 35, Belém. Anexos..., vol. Província Mineral de Carajás - Litoestratigrafia e Principais Depósitos Minerais. p. 11-54.

Efimov A.V. 1978. Multiplikativniyi pokazatel dlja vydelenija endogennych rud aerogamma spectrometriceskim dannym. In: Metody rudnoj geofiziki, Leningrado, Naucnoproizvodstvennojc objedinenie geofizica Ed., 59-68.

Gastal M.C.P. 1987. Petrologia do Maciço Granítico Musa, sudeste do Pará. Dissertação de Mestrado, Universidade Federal do Pará, Pará, 316 p.

Harris, J. R., 1989, Data integration for gold exploration in eastern Nova Scotia using a GIS: Proc. Remote Sensing for Exploration Geology (Calgary, Alberta), p. 233–249.

Harris D. A., and Pan, R., 1999, Mineral favourability mapping: a comparison of artificial networks, logistic regression and discriminant analysis: Natural Resources Research, v. 8, no. 2, p 93–109.

Harris, J. R., Wilkinson, L., and Broome, J., 1995, Mineral exploration using GIS-based favourability analysis, Swayze Greenstone Belt, northern Ontario: Proc. Can. Geomatics Conf. (CD-ROM), National Defense.

Holdsworth R. & Pinheiro R., 2000. The anatomy of shallow-crustal transpressional structures: insights from the Archean Carajás fault zone, Amazon, Brazil. J. Struct. Geol., 22: 1105-1123.

Huhn, S.R.B., 1992. Geologia, controle estrutural e gênese do depósito aurífero Babaçu, região de Rio Maria, sul do Pará. UnB, Brasília, Dissertação de Mestrado, 169p.

Kemp, L.D., Bonham-Carter, G.F., Raines, G.L. & Looney, C.G. 2001. Arc-SDM: Arcview extension for spatial data modelling using weights of evidence, logistic regression, fuzzy logic and neural network analysis. http://www.ige.unicamp.br/sdm/. Accessed January 15th, 2011.

Leite, A.A.S., Dall'Agnol, R., Macambira, M.J.B., Althoff, F.J., 2004. Geologia e Geocronologia dos granitóides arqueanos da região de Xinguara–PA e suas implicações na evolução do Terreno Granito-Greenstone de Rio Maria, Cráton Amazônico. Revista Brasileira de Geociências 34 (4), 447-458.

Silva, A. M, 1999. Geophysical and geological data integration using a new statistical approach for mineral target selection applied to the Rio das Velhas Greenstone Belt, Quadrilátero Ferrífero.

Souza Z. S., 1994. Geologia e petrogênese do Greenstone Belt Identidade: implicações sobre a evolução geodinâmica do Terreno Granito- "Greenstone" de Rio Maria, SE do Pará. Universidade Federal do Pará, Instituto de Geociências, Programa de Pós-Graduação em Geologia e Geoquímica. 2. v. (Tese de Doutorado).

Tassinari, C.C.G., Macambira, M. 2004. A evolução tectônica do Craton Amazonico. In: Mantesso – Neto, V.; Bartorelli, A.; Carneiro, C.D.R.; Brito Neves, B.B. (Eds.), Geologia do Continente Sul Americano: Evolução da obra de Fernando Flávio Marques Almeida. São Paulo, p. 471-486.