Mineral Potential Mapping for Orogenic Gold Deposits in the Rio Maria Granite Greenstone Terrane, Southeastern Pará State, Brazil

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Abstract

The Rio Maria granite-greenstone terrain is characterized by extensive surficial cover and a lack of outcrop. Therefore, airborne geophysical measurements play a major role in mineral exploration in this region. A high-resolution airborne survey was used to build a prospectivity model for gold targeting employing a fuzzy logic technique. Within the Rio Maria granite-greenstone terrain, a total of 57 new potential orogenic gold targets were identified. The ability of this processing technique to identify favorable targets with potential for economic gold mineralization was verified by comparing the new predicted targets with known gold occurrences (e.g., Mamão Mine and Lagoa Seca deposits). Geographic Information System (GIS)-based automated processing methods employing fuzzy logic techniques were used to derive spatial models for generating orogenic gold exploration targets.

Two metallogenic approaches were used. The first approach considers orogenic gold deposits hosted at the contact between mafic and felsic rocks. The second approach considers shear zone-hosted veins associated with mafic rocks and iron formations in the greenstone terrain. Detailed models were constructed for different blocks of the study area. A subset of these targets, i.e., Marcinho, Resende, and Votuporanga, were subsequently assessed using field evaluations that consisted of geological mapping and geochemical sampling. A follow-up drilling program is currently in progress and will be used to assess the main target areas where grid soil and rock sampling have indicated anomalous trends. The remaining predicted targets warrant further investigation.

Data integration using GIS modeling and interpretation resulted in the following main conclusions with respect to the orogenic gold exploration potential of the Rio Maria Province: (1) as shown using GIS-based prospectivity analysis, there is considerable potential for orogenic gold deposits along the Andorinhas greenstone belt, and several prospective areas are associated with mafic and iron formation units; (2) several deposits within the Rio Maria and Identidade greenstone belt are associated with felsic units, as demonstrated by the fuzzy logic models; (3) many of the previously known targets that have been re-identified should be reevaluated to identify those the most promising targets for the discovery of a gold deposit; (4) the final prospectivity model shows that many of the most important gold deposits known are located within areas of high favorability, and several other new potential gold-bearing targets were selected; and (5) the proposed method identifies 57 geologically consistent targets and led to the discovery of the Marcinho deposit.

Introduction

SIGNIFICANT progress has been made in the integration and spatial modeling of exploration geochemical and geophysical data, thereby providing better tools to assist the discovery of new gold deposits (Robert et al., 2007). The applications of these new methodologies are particularly useful in the search for new gold discoveries in greenstone belt terranes (Jaques et al., 1997). Current exploration protocols are focused on defining a blueprint based on known gold deposits, which is then applied in a search of available data sets to identify similar anomalies.

The approach outlined here is an integrated geographic information system (GIS)-based exploration method for targeting orogenic gold deposits within the Rio Maria granite-greenstone terrane using spatial analytical techniques. These can be divided into two general categories: data- and knowledge-driven techniques, for which reviews can be found in Bonham-Carter (1994) and Wright and Bonham-Carter (1996).

Data-driven approaches require a priori knowledge (expressed in terms of previously determined probabilities) in the form of known mineral deposits or occurrences (e.g., prospects) for the study area. Spatial relationships between the input data (e.g., evidence maps) and the spatial locations of the mineral prospects are used to establish the importance (i.e., 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 based on the various data (e.g., geochemical and geophysical information) used in the modeling process (Harris et al., 2001). Statistical methods use techniques such as regression, discriminant analysis, data-driven evidential belief functions (Carranza and Halé, 2003), cluster analysis, canonical favorability analysis (Pan, 1993), weights of evidence modeling (Bonham-Carter et al., 1989; Bonham-Carter, 1994), neural networks (see Brown et al., 2000, 2003), and data mining (see Salleb and Vrain, 2000).
Knowledge-driven approaches rely on the geologist’s input to weigh the importance of each data layer (evidence map) as it relates to the particular exploration model being used. This approach is more subjective, but it has the advantage of incorporating the knowledge and expertise of the geologist to build models and generate prospectivity maps. Examples of knowledge-driven approaches include Boolean logic, index overlay (Harris, 1989), analytical hierarchy process (AHP; Harris et al., 1995), and fuzzy logic (An et al., 1992) methods.

The objective of this paper is to evaluate gold potential area, using mineral favorability maps to define areas for further exploration using a fuzzy logic approach (Fig. 1). The Rio Maria granite-greenstone terrane is an ideal area for the development of this type of modeling due to the lack of outcrops and numerous gold occurrences. A large number of datasets were provided by Troy Resources Limited/Reinarda Mineração Ltda., including geologic mapping and airborne geophysical and geochemical data.

**Geologic Setting**

The Rio granite-greenstone terrane (Fig. 2) is located in the southeastern part of Carajás Mineral Province, which in turn lies at the southeastern margin of the southern Amazon Craton of Brazil and consists of granite-greenstone terranes, intracratonic basins, and high-grade metamorphic complexes (Tassinari and Macambira, 2004). This area is one of the most important mineral provinces in Brazil with a diversity of rich mineral resources (Dall’Agnol et al., 2006). The Carajás Province comprises two Archean tectonic blocks: the northern Itaçuinas Belt (Araújo et al., 1988), which is a tectonic block that hosts the Carajás Basin, and the southern Rio Maria granite-greenstone terrane.

The Rio Maria granite-greenstone terrane consists of greenstone belts and a variety of Archean granitoids. The greenstone sequence of the Andorinhas Supergroup is composed of ultramafic and mafic metavolcanic rocks intercalated with iron formations and intermediate to felsic rocks at the base (Babaçu Group) and chemical and clastic metasedimentary rocks at the top (Lagoa Seca Group). U/Pb dates range from 2.97 to 2.90 Ga (Macambira, 1992; Pimentel and Machado, 1994; Dall’Agnol et al., 1999; Almeida et al., 2011). Within the study area, these units are located in three greenstone sequences called the Andorinhas, Rio Maria, and Identidade sequences (Fig. 3). These volcano-sedimentary successions

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**Fig. 1.** Flowchart describing the components involved in mineral potential modeling. This diagram is based on the methodologies of Pan and Harris (2000), Harris et al. (2006), and modified after Nykänen (2005).
overlie high-grade granitic and gneissic rocks of the Xingu and Pium Complexes. These rocks represent the basement, and they show different grades of deformation and greenschist-facies metamorphism (Souza et al., 2001).

The Andorinhas Supergroup is intruded by a variety of Archean granitoids that date between 2.98 and 2.86 Ga. Four groups of granitoids have been distinguished (Dall’Agnol et al., 2006): (1) an older TTG series (2.98−2.92 Ga) is represented by the Arco Verde tonalite and the Caracol tonalite complex; (2) the Rio Maria sanukitoid suite (~2.87 Ga; Oliveira et al., 2009) is predominantly composed of granodiorites with associated mafic and intermediate rocks forming enclaves or, locally, small bodies—these rocks intrude into the greenstone belts and the older TTG series and are intruded by the Água Fria trondhjemite (Leite et al., 2004); (3) a younger TTG series (~2.87−2.86 Ga) is exposed only in the Rio Maria and Xinguara areas of the Rio Maria granite-greenstone terrane and is represented by the Mogno trondhjemite and the Água Fria trondhjemite; and (4) potassic leucogranites of calcalkaline affinity (~2.87−2.86 Ga) are represented by the Xinguara and Mata Surrão granite plutons (Docegeo, 1988; Althoff et al., 2000; Souza et al., 2001; Leite et al., 2004; Dall’Agnol et al., 2006).

Several ductile shear zones are responsible for the prominent deformation observed in these rocks. The main shear zones trend east-west, northwest-southeast, and northeast-southwest with dextral strike-slip faults that have mainly affected the supracrustal rocks (Holdsworth and Pinheiro, 2000). Synformal structures along the shear directions, which were previously interpreted as synclines, are considered to be transpressive duplexes. The larger duplexes are related to E-W shear zones that have cores consisting of sedimentary rocks and borders defined by thrust faults (Holdsworth and Pinheiro, 2000).

Paleoproterozoic anorogenic alkaline to subalkaline A-type granitoid stocks and batholiths cut the greenstone belt rocks, dikes, and sills (Gastal, 1987). Similar greenstone sequences (Tucumã, Gradaus, and Sapucaia Groups) occur elsewhere within the craton (Oliveira, 1987; Souza, 1994). Small orogenic gold deposits, such as the Mamão, Babaçu,
Fig. 3. Integrated geologic map of the Rio Maria granite-greenstone terrane, showing the location of the study area.
Lagoa Seca, Diadema, and Serrinha deposits, are located in these greenstone sequences (Huhn, 1992). Currently, the only operating gold mine is the Mamão mine, which is operated by Troy Resources Limited and Reinarda Mineração Ltda. (RML).

**Gold Mineralization in the Andorinhas Greenstone Belt**

Archean orogenic lode gold deposits are the result of large complex mineralization systems (Goldfarb et al., 2005) and are thought to be related to the final stages of terrane accretion in a subduction setting (Groves et al., 1998) or late orogenic extension (Goldfarb et al., 1997). Orogenic gold mineralization in the Andorinhas Supergroup is generally associated with quartz veins in shear zones with hydrothermal alteration and variable amounts of sulfide. In general, the lode gold deposits have formed in dilational zones within the shear zones (Huhn, 1992).

Three main types of orogenic deposits have been distinguished within the study area based on their host-rock environment: greenstone-hosted (e.g., the Mamão mine), turbidite-hosted (e.g., the Lagoa Seca deposit), and BIF-hosted (e.g., the Marcinho target) deposits (Fig. 4). In the latter two types, the gold is associated with disseminate sulfides.

**Lithologic and structural controls**

Lithologic boundaries were interpreted using geophysical data and geologic field mapping. The main lithologies include ultramafic, mafic, and felsic rocks, BIFs, sedimentary rocks, and granites. The main deposits of the study area are hosted in metabasalts (e.g., the Mamão mine), BIFs (e.g., the Marcinho target), and felsic rocks of the Babaçu Group (e.g., Resende target), and the turbidite sequences of the Lagoa Seca Group (e.g., Lagoa Seca deposit).

The Mamão gold deposit is a shear-hosted deposit located in the dilational jogs of a high-strained zone branch within the early foliation present in the metavolcanic rocks of the Andorinhas greenstone keel (Huhn, 1992). There are approximately 74 gold occurrences within the study area. Some of these deposits occur in the main ENE-WSW-trending corridor that hosts the Mamão mine, which contains more than 20 smaller pits and surface workings previously mined by prospectors. The lode gold is hosted in E-W dilatational jogs, which represent secondary structures. Figure 5 shows the distribution of host rocks of the orogenic deposits within the study area and their respective percentile values.

In the Lagoa Seca deposit, the mineralization appears as disseminated sulfides within a turbidite sequence associated with a broad shear zone. This mineralization is best developed along contrasting rheological contacts with intrusive dacites and ultramafic units (Souza, 1999). The remaining gold occurrences in the Rio Maria and Identidade Greenstone Belts are associated with quartz veins in contact between felsic and mafic rocks. These felsic units are related to the Babaçu Group and are represented by dacite, rhyolite, quartz-porphyry, and minor metasediments.

Magnetic lineaments have three dominant orientations: NW-SE (Trend Malvinas), NE-SW (Trend WRM and Mamão/Babaçu), and E-W (Fig. 6A, B). The NW-, NE-, and E-W-trending lineaments were extracted as separate maps. According to the field mapping, the E-W-trending high strain zones, represented by splays and jogs along the NE–SW corridor, have a greater number of gold-bearing mineral occurrences in the three greenstone belts within the study area, including the Andorinhas, Identidade, and Rio Maria greenstone belts.

**Hydrothermal alteration zones**

The deposits in the Rio Maria Province exhibit varying distinct mineralogical zonation around the lode structures, based on the wall-rock type and crustal level. In the mafic host rocks, the distal alteration consists of chloritization, carbonatization, and sericitization. Inner assemblages are biotitization and sulfidization. In the proximal zones, the total or partial replacement of chlorite by biotite suggests a potassium metasomatism related to hydrothermal alteration. The widths of the alteration zones vary markedly, although the inner alteration zone is generally <10 m wide. A broader (10–100 m) outer alteration zone of chlorite and carbonate alteration surrounds the inner zone (Huhn, 1992). The extent of sulfidization is extreme in the BIF and Fe-rich mafic host rocks, and the predominant sulfides consist of pyrite and pyrrhotite. However, gold concentrations are restricted to sites that experienced the percolation of fluids rich in CO2 and SO2, thereby forming mineralized quartz carbonate veins. This lode usually ranges in width from 5 cm to a few meters.

**Airborne Geophysical Data and Other Multisource Data**

The study area was covered by a high-resolution airborne geophysical magnetic gradiometer and radiometric survey flown at a constant ground clearance of 100 m. The airborne
data were acquired using flight lines spaced at 125 m with tie lines spaced at 1,500 m in the N-S and E-W directions, respectively. An area of approximately 1,952 km² was covered with a linear distance of approximately 16,924 km. The cell size of the interpolated grid was 30 \times 30 m.

A comprehensive digital database covering the entire study area is essential to performing mineral potential modeling, using GIS-based analytical methods. In total, the current GIS database contains more than 12 layers of digital geoscience data, including surficial geology, geochemistry, geophysics, gold occurrences, mineral deposits, and topographic data (Table 1). Each dataset was georeferenced to the Universal Transverse Mercator Coordinate System for the southern hemisphere and zone 22.

A total of 300 rock samples, 1,120 soil samples, and 502 stream sediment samples were collected by Troy Resources Limited/Reinarda Mineração Ltda. within the study area and were used to assist the evaluation of the prospectivity maps. Geologic mapping was conducted for the study area at 1:25,000 scale, with more detailed geologic maps at 1:10,000 over the main areas and 1:5,000 over the main deposits.

**Methods**

**Geophysical processing**

The geophysical data were useful for understanding the geologic and structural setting. The overall processing of airborne geophysical data in this study involved three steps: data preparation and formatting, processing of airborne data, and calculation of data and/or derivative products. The processing of airborne data involved sequential editing followed by the application of a gridding routine, the removal of apparent
residual errors and the microleveling of all data to a common base. The main derivative magnetic products calculated from the total magnetic field data were the analytic signal amplitude and phase, first vertical derivative, and horizontal gradient. These products and the measured gradients (Gx and Gy) were also used (Fig. 7).

The industry standard processing of airborne gamma-ray surveys requires a minimum of four maps (i.e., total count, potassium, uranium, and thorium) to present the four measured variables. Important information is also obtained from four additional derivative product maps that involve ratios between the various radioactive elements: eU/eTh, eU/eK, eTh/eK, and K/eU/eTh. In this approach, K/eTh, F Parameter, and K anomalous (Pires, 1995) images were mainly used to highlight the K enrichment. The F Parameter (Efimov, 1978) shows the potassium distribution related to the uranium and thorium radioelements and has been used for the discrimination of hydrothermal alteration zones. The F Parameter is expressed by the following formula: F = (K*eU)/eTh (Fig. 8).

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 show the advance of available geophysical technology for low magnetic gradient structures of interest in mineral exploration. The measured gradients (Gx and Gy) show better definition of the low magnetic features comparing the gradients calculated from total magnetic intensity (TMI) products. Therefore, the combination of Gx and Gy images with products derived by combining the K, Th, and U channels has been shown to be effective in selecting targets for follow-up in tropical terranes.

Spatial data analysis

Empirical methods, i.e., data-driven techniques, use statistics to select the evidential layers that show the strongest relationship with the known mineralization, and they subsequently use statistically derived weights for combining these layers to generate the prospectivity maps. Conceptual methods, such as fuzzy logic, allow the geologist to select the evidential layers that they believe are the most critical for the particular style of mineralization being targeted. The fuzzy membership values range from 0 to 1 for each of these layers based on their expert opinion, thereby taking into account the statistics of each element and the geologic background values within each area of interest.

After defining the fuzzy membership functions for each evidential map, a variety of operators can be used to combine the membership values. Several operations are available, and the union and intersection operations are commonly used in GIS. An et al. (1991), Bonham-Carter (1994), and Carranza and Hale (2001) described five operators that are used in mineral exploration-related datasets: Fuzzy AND, Fuzzy OR, Fuzzy algebraic product, Fuzzy algebraic sum, and Fuzzy Gamma (γ) operator. In this paper, we used the operators listed in Table 2.

A knowledge-driven approach was used in this study because only one producing mine (the Mamão mine) is present in the study area. Data from only one mine did not provide a sufficient training set to enable a data-driven approach.

The data were processed in a variety of formats, including Oasis Montaj 7.0 from Geosoft®️, MapInfo 9.5 (Pitney Bowes; Mapinfo, 2008), Profile Analyst 10.0 (Encom; Profile Analyst, 2010), and Surpac (Gemcom; Surpac Minex Group, 2009) Software. The majority of derivative products were calculated in Geosoft before being imported to the ArcGis 9.3.1 GIS, where statistical approaches were applied and data were converted to raster form to obtain derivative products that could be used to generate predictive maps. The commercial GIS package ArcGIS 9.3 from the Environmental Research Institute (ESRI), enhanced with advanced public domain extensions and the Spatial Data Modeler for ArcGIS (ArcSDM) add-on (Kemp et al. 2001; Savatzky et al. 2004), was employed in this study to create an assessment of the mineral potential within a greenstone belt terrane that is known to be permissoive for gold.

Data Integration into the Prospectivity Map

Previous exploration and underground development in the Andorinhas greenstone belt by Troy Resources Limited/Reinarda Mineração Ltda. have provided a large database that can be used for spatial analysis with the objective of targeting high-priority exploration sites in the mine area and regional prospects. Specific exploration criteria were used to define

<table>
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<th>Operator</th>
<th>Description</th>
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<tr>
<td>Fuzzy AND</td>
<td>Minimum operator: the output is controlled by the smallest fuzzy membership values at each location; Fuzzy AND results in a conservative estimate of the set membership and has a tendency to produce small values</td>
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<tr>
<td>Fuzzy Algebraic Product</td>
<td>The combined fuzzy membership values tend to be small due to the effect of multiplying several numbers less than 1. The output is always smaller than, or equal to, the smallest contributing membership value.</td>
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<tr>
<td>Fuzzy Gamma</td>
<td>This operator is defined in terms of the fuzzy algebraic product and the fuzzy algebraic sum, which is a combination of these two operations</td>
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The conceptual model for this region of the Rio Maria Province is the association of mineralization with high values of K and structural conditioning, based on the descriptions of fieldwork and studies performed by Huhn (1992), Souza (1994), and Souza et al. (2001). Based on the patterns defined in the descriptive model, it was possible to direct the processing of geological, geophysical, and geochemical datasets to extract useful information for knowledge-driven spatial analyses. Figure 9 introduces the three main blocks and Table 3 shows the summary of gold exploration criteria for the three main blocks in the descriptive model.

**Fuzzification of the evidence layers**

After the conceptual model was proposed, fuzzy membership values based on expert knowledge were applied to the three main blocks. The fuzzy membership datasets use a
Fig. 8. F Parameter image showing the K enrichment within the greenstone sequence.

Fig. 9. Ternary image overlapping the first derivative image from total magnetic intensity (TMI). The three main mineralized blocks are shown corresponding to the greenstone belts, Identidade, Rio Maria, and Andorinhas.
As in classical set theory, set-theory operations can be applied to fuzzy sets (Nykänen et al. 2008). In this paper, the Fuzzy algebraic product, Fuzzy AND, Fuzzy categorical, and Fuzzy Gamma operator, which is a combination of Fuzzy algebraic sum and Fuzzy algebraic product, were used. The $\gamma$ parameter in the Fuzzy Gamma function has values ranging from 0 to 1. When the $\gamma$ parameter is 1, the combination equals the Fuzzy algebraic sum; when the $\gamma$ parameter is 0, the combination equals the Fuzzy algebraic product.

The fuzzification of the lithology and structures was performed using fuzzy categorical membership. Higher membership values were assigned to lithologic formations that were reported to host the gold-bearing deposits (Table 4). In the study area, two different host-rock types associated with mineralization were reported. The first type consists of felsic and mafic units, and the second type includes mafic and iron formation units. A 0.95 fuzzy membership (definitely anomalous) value was assigned to the felsic and BIF units followed by metamafic rocks. The newly selected targets are related to both host-rock types.

The lithologic units, such as ultramafic, quartzite, granitoid, and anorogenic granite, were assigned lower values because they were not believed to be significant for gold-bearing deposits. All thematic layers in the GIS database were converted to the raster format prior to further processing.

Vector data, such as magnetic lineaments and faults (mapped and interpreted), were transformed to continuous surface maps by dilating (i.e., buffering) around each line in successive zones from 0 to 200 m (Table 5). In this manner, the spatial association between gold prospects and selected structural features can be analyzed using fuzzy logic to determine whether gold prospects are preferentially located closer to geologic structures. Therefore, higher membership values of 0.95 and 0.5 were respectively assigned to the 0- to 100- and 100- to 200-m structural E-W lineament corridors.

The following structural data were used in the knowledge-driven modeling analysis: (1) deformation zones (NE and NW corridors) interpreted from field observations and airborne geophysical data; (2) lithologic contacts in contact with felsic rocks; conduits for Au-bearing fluids; (3) brittle structures displaced by late normal faults; (4) host rock mafic rocks (basals and dolerite); (5) trend N70E; E-W conduits for Au-bearing fluids; (6) radiometrics high K in the F Parameter image; (7) tectonic environment thrust shear zone; (8) metamorphic grade greenschist to low amphibolite; (9) hydrothermal alteration biotite + silicification + pyrite; (10) heat activities no evidence; late, small diorite intrusions unrelated to mineralization; (11) infill gold in quartz vein + pyrite narrow and proximal.
magnetic lineaments, and (2) zones trending to the E-W, ENE-WSW, and ESE-WNW (mapped in the field and interpreted from the horizontal measured gradients Gx and Gy). After generating dozens of predictive models, the best models, when compared with the known deposits, proved to be those that used only the proximal E-W trends.

Integration of the F Parameter and the measured horizontal gradients (Gx and Gy) shows that known mineralized zones are mapped by high F Parameter values and low magnetic gradient features. The input layers of the geologic maps, F parameter, K/Th ratio, anomalous K (Kd), eTh channel, Gx and Gy images, and the E-W low gradient zones were used in the fuzzy logic modeling. Each of the desired evidential layers was then combined using one fuzzy operator or a combination of fuzzy operators.

The F Parameter was used to highlight the areas of K enrichment, which were assigned a large membership value—Fuzzy large. The K/Th ratio and Kd were similarly used, and a small membership value was assigned to the eTh channel—Fuzzy small. In addition, a small value was used to highlight the low values of the 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 achieved using the minimum operator, Fuzzy AND, as an indicator of favorable K enrichment environments. The final combination was performed using the fuzzy Gamma operator with a γ parameter value of 0.90, thereby adding the lithology and main structures.

The integration of parameters into a single prospectivity map was completed using the fuzzy logic overlay method described by Bonham-Carter (1994). The inference networks shown in the models are a concise statement of the exploration model for orogenic gold deposits and clearly define the combination procedure (Fig. 10A-C). The integration was done in steps, and the intermediate maps, together with specific original maps and the final prospectivity map, are shown in Figure 11.

The fuzzification and data integration using the fuzzy operators described above (Table 6), as well as the validation calculations, were carried out using the ArcGIS extension Arc-SDM, as described by Raines et al. (2000), Raines and Bonham-Carter (2006) and, more recently, by Nykinnen et al. (2008). The Arc-SDM code is freely downloadable from <http://www.ige.unicamp.br/SDM/default_e.html>.

To validate the usefulness of the prospectivity maps for identifying potential zones of gold mineralization, we determined the number of known occurrences within zones of medium to high potential. Several other new targets were also selected over the medium to high favorability area.

The final prospectivity map outlined approximately 57 targets (Fig. 11) in the study area. Two metallogenic approaches were used. The first approach considers orogenic gold deposits hosted with mafic and felsic volcanics. The second approach considers shear zone-hosted veins associated with mafic rocks and iron formations in the greenstone belt terrane. Details of the spatial modeling in the three main mineralized blocks (shown in Fig. 10) are presented below.

**Mamão/Baiaçu block**

An analysis of the results shows that the highest favorability of the Mamão-Baiaçu area is associated with mafic rocks and, secondarily, lenses of iron formation (Fig. 10A). The majority of prospects, such as the Coruja NE, Luiz, and Piauí deposits, along the northeast corridor are represented by medium and/or high favorability. The model shows that the Mamão mine is situated within a medium favorability domain in the orogenic gold prospectivity map, this classification occurred because the mine area is only associated with mafic metavolcanics and not iron formations. In addition, the highest fuzzy membership used in the lithology analysis corresponded with iron formations followed by mafic metavolcanics. Approximately 18 targets were selected as medium and/or high favorability areas.

**West Rio Maria block**

As noted by Raines et al. (2010), after completing the model or models, it is important to validate the results. If there are known examples of the data being modeled (i.e., known deposits), these can be used to test how well the model classifies known examples. Therefore, the model was validated using important historically mined regions, such as the Manoel, Anastácio, Bezerro and Resende targets (Fig. 10B). The area of high favorability in the West Rio Maria block is associated with sheared felsic units hosted in mafic rocks, and the Resende target is associated with sheared granitoids in contact with metamafic units. The model showed ten new areas, three of which are in the granite-greenstone contact. The model also showed several lithologic effects to the west of the Manoel prospect due to the highest potassium values from sediment units.

**Malvinas block**

Similar to the West Rio Maria block, the modeling analysis shows that the highest favorability in the Malvinas block...
Fig. 10. The inference network and prospectivity map. Evidence layers and fuzzification type are the same for all blocks, except the inputs highlighted in red. A. Mamão/Babaçu block—the majority of prospects are located within medium and/or high favorability areas. The prospectivity results also identified the known gold occurrences, which are highlighted in black. B. West Rio Maria block—the model highlights previously mined prospects and discovered new targets such as the Resende target. C. Malvinas block—the model highlights important known prospects, such as the Gerson, Combi, Américo, and Pampeana targets. The model identifies the Votuporanga target, which has been evaluated using field studies and will be subjected to a future drilling test program.
is associated with felsic intrusive-quartz porphyry. Historic prospects, such as the Gerson, Américo, and Panpeana deposits, are situated within a favorability zone of >0.75. Votuporanga, which is one of the most important targets that was generated, was also located within an area of high favorability (Fig. 10C). Eight small, new targets were identified in this block as medium and/or high favorability areas.

Validation and Evaluation of the Best Gold Predictors—Drilling Program

The ultimate test of this fuzzy logic model for orogenic gold deposits is the predictive ability of the favorability map. The optimal and most difficult test is whether this prediction leads to new discoveries. According to Raines (1999), practical tests address the following questions: does the fuzzy membership make sense, and are the known orogenic gold deposits located in areas of high favorability?

The geochemical data were used to rank all targets, and the three best ranked targets identified on the basis of the fuzzy logic model were the Marcinho (Mamão/Babaçu block), Resende (WRM block), and Votuporanga (Malvinas block) targets. The Marcinho target is located to the east of the old Marcinho Pit along a WNW-striking corridor approximately 700 m from the Mamão processing plant. The target is controlled by NW-SE and NE-SW structures outlined with Gx, Gy, and ISA. The target is associated with low gradient features in the Gy image.

Field testing was performed using detailed geologic mapping, sampling of outcrops, soil sampling and, later, drilling. The grid soil sampling (620 samples) over the main targets selected in the Mamão block area highlighted 400 m of an anomalous E-W trend with high grades of up to 2,300 ppm Au. Subsequently, a drilling program, consisting of 15 reverse circulation (RC) holes at a spacing of 50 m along the shear
were planned over the Marcinho target (Fig. 12A). To date, only seven holes have been completed totaling 476.6 m. The holes intersected mafic rocks intercalated with BIFs (Fig. 12B). The shear zones crosscut the host units. Thin lenses of quartz veins and minor to major amounts of sulfides are associated with gold in an iron formation. Most holes revealed two mineralized intervals at shallow depths. Figure 12B shows the MAC118 cross section. The hole revealed an interval of mineralization from 32 to 38 m downhole with an average of 3.18 g/t Au. This interval is associated with mafic rock and iron
forms and contains 5 to 10% pyrite. Additional promising results included hole MAC116, with narrow lenses of 5.19 g/t Au at shallow levels from 17 to 18 m, and hole MAC117, with 4.02 g/t Au at 23 to 24 m.

Other targets within the Malvinas and West Rio Maria blocks have shown gold potential according to field evaluations using rock and soil sampling. The discovery of the most important target area (Resende) within the West Rio Maria block confirmed that the employed methodology was effective in generating targets for follow-up mineral prospecting. In the Resende area, field validation, consisting of geologic reconnaissance, identified two previously mined pits. Three quartz vein float samples taken within the pits and along the strike to the east, returned assay results of 7.43, 29.64, and 1.64 g/t of gold. The best assay received was derived from a sample with visible gold.

Within the Malvinas block, the Votuporanga area was evaluated in the field and is considered to be the most important target generated using the fuzzy logic modeling approach. Quartz vein samples collected along the contact of the quartz porphyry and mafic units returned assay results of 18.98, 10.51, 5.48, and 4.25 g/t of gold. Some of the samples had visible gold. Grid soil sampling was carried out and 500 m anomalous trends were delineated. A follow-up RC drilling program has been planned to assess the main target areas for which surface geochemistry has delineated anomalous trends.

**Discussion and Conclusions**

This case study demonstrates the practical aspects of a fuzzy mineral favorability index in identifying exploration targets for orogenic gold deposits in a portion of the Rio Maria granite-greenstone terrane in Brazil. The proposed method identified 57 geologically consistent targets for further detailed exploration. According to the final prospectivity maps, many of the most important known gold deposits were located within areas of high favorability, and several other new potential gold targets were identified.

Prior to conducting follow-up work, it is important to evaluate the gold prospectivity maps based on how well each map has predicted the known gold prospects. The potential of this map was demonstrated using follow-up evaluations, which led to newly discovered targets, such as the Marcinho, Votuporanga, and Resende. A follow-up RC drilling program is currently being implemented at the Marcinho target, which exhibits promising grades, and similar programs are proposed for other targets.

Data integration using the GIS and subsequent interpretation resulted in the following primary conclusions with respect to the orogenic gold exploration potential in the Rio Maria Province.

1. According to the GIS-based prospectivity analysis, there is considerable potential for orogenic gold deposits along the Andorinhas greenstone belt, and several prospective areas are associated with mafic and iron formation units.
2. Several deposits within the Rio Maria and Identidade greenstone belts are associated with felsic units, as demonstrated by the fuzzy logic models.
3. Many of the previously known targets that were reidentified should be reevaluated with a focused research effort to identify those targets that show the most promise for the discovery of a gold deposit.

4. The proposed method identified 57 geologically consistent targets and led to the discovery of the Marcinho deposit. RC drilling is planned for other selected targets.

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