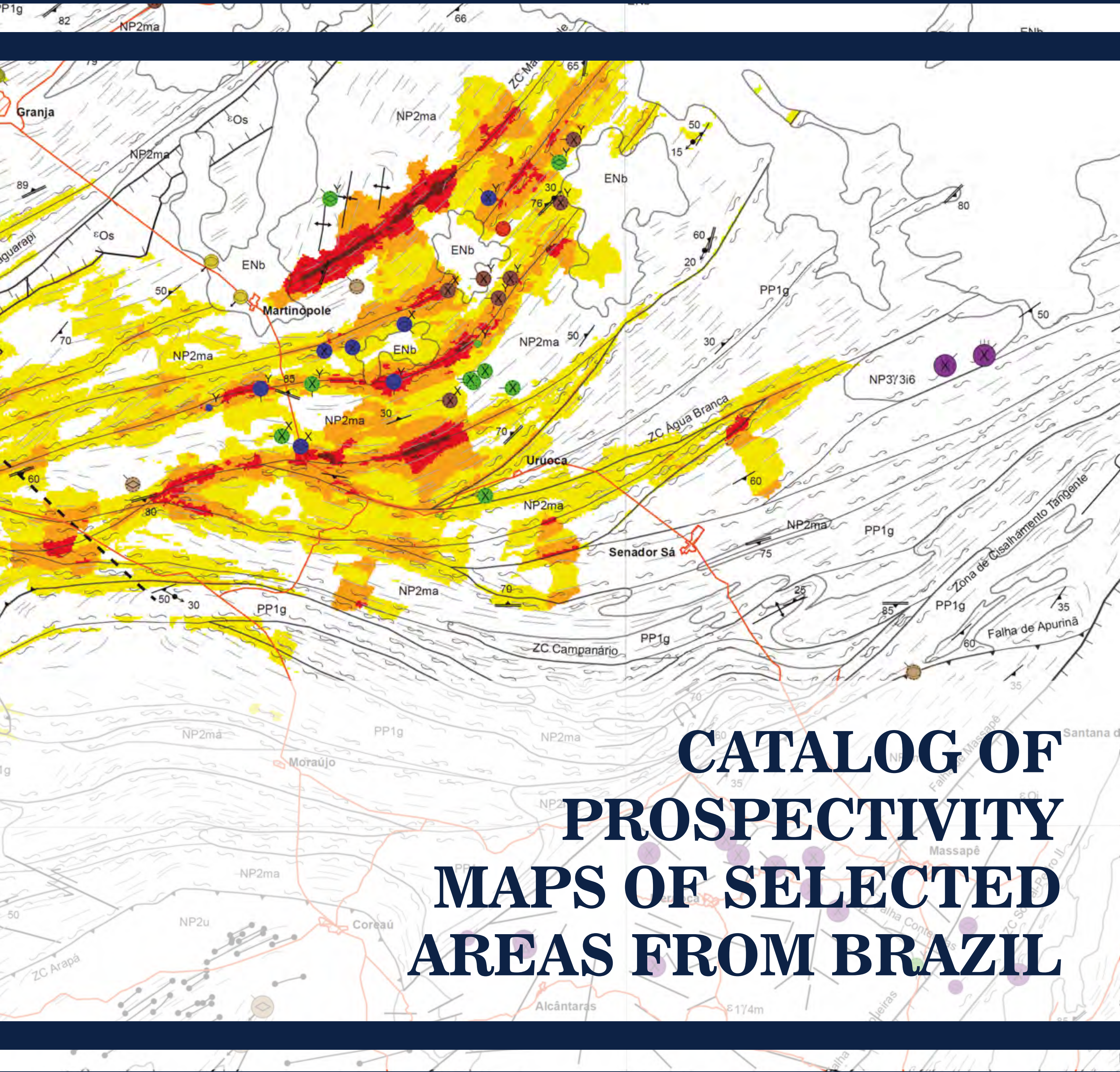
GEOLOGICAL SURVEY OF BRAZIL



CATALOG OF PROSPECTIVITY MAPS OF SELECTED AREAS FROM BRAZIL

GEOLOGICAL SURVEY OF BRAZIL
CPRM

2020

Compiled and organized by:

Felipe Mattos Tavares
Debora Rabelo Matos
Evandro Luiz Klein

CATALOG OF PROSPECTIVITY MAPS OF SELECTED AREAS FROM BRAZIL

Compiled and organized by:

Felipe Mattos Tavares
Debora Rabelo Matos
Evandro Luiz Klein

MINISTRY OF MINES AND ENERGY
SECRETARY OF GEOLOGY, MINING AND MINERAL TRANSFORMATION
GEOLOGICAL SURVEY OF BRAZIL

CATALOG OF PROSPECTIVITY MAPS OF SELECTED AREAS FROM BRAZIL

Compiled and organized by:

Felipe Mattos Tavares
Debora Rabelo Matos
Evandro Luiz Klein

BRASÍLIA
2020

GEOLOGICAL SURVEY
OF BRAZIL – CPRM

TECHNICAL TEAM

ORGANIZERS
Felipe Mattos Tavares
Débora Rabelo Matos
Evandro Luiz Klein

INTRODUCTION
Evandro Luiz Klein
Felipe Mattos Tavares
Débora Rabelo Matos

DATA INTEGRATION AND TARGET GENERATION
Guilherme Ferreira da Silva
Sulsiene Machado de Souza Gaia

COPPER-GOLD FAVORABILITY IN THE THE CINZENTO SHEAR ZONE, CARAJÁS MINERAL PROVINCE
Felipe Mattos Tavares
Junny Kyley Mastop Oliveira
Antônia Railine da Costa Silva
Iago Sousa Lima Costa
Rafael Bittencourt Lima

PROSPECTIVITY MAPPING AND MINERAL SYSTEM ANALYSIS OF THE RENCA AREA, SE GUIANA SHIELD
Leandro Duarte Campos

PREDICTIVE POTENTIAL MAPPING FOR INTRUSION-RELATED GOLD IN THE EASTERN TOCANTINZINHO TREND, TAPAJÓS MINERAL PROVINCE, AMAZONIAN CRATON
Sulsiene Machado de Souza Gaia
Marcelo Lacerda Vasquez
Felipe Mattos Tavares

GOLD FAVORABILITY AT JUMA GOLD DISTRICT, SOUTHEAST AMAZONAS STATE
Raul Eigenheer Meloni
Matheus Silva Simões
Michele Zorzetti Pitarello

ZINC-LEAD-COPPER-GOLD FAVORABILITY IN THE NOVA BRASILÂNDIA DISTRICT, SUNSÁS PROVINCE, AMAZONIAN CRATON
Gustavo Negrello Bergami
Guilherme Ferreira da Silva

PROSPECTIVITY MAPPING AND MINERAL SYSTEM ANALYSIS OF THE GURUPI BELT
Leandro Duarte Campos

COPPER-LEAD-ZINC FAVORABILITY IN THE SUPRACRUSTALS SEQUENCE OF MARTINÓPOLE GROUP, MEDIO COREAÚ DOMAIN, BORBOREMA PROVINCE
Tercyo Rinaldo Gonçalves Pinéo
Alex Franca Lima
Maria Dulcinea Madureira Rolim Bessa
Mariane Dornas Martins
Felipe Rocha Abreu

COPPER-IRON FAVORABILITY IN THE CAMBRIAN JAIBARAS SEDIMENTARY BASIN, MEDIO COREAÚ DOMAIN, BORBOREMA PROVINCE
Tercyo Rinaldo Gonçalves Pinéo
Alex Franca Lima
Maria Dulcinea Madureira Rolim Bessa
Mariane Dornas Martins
Felipe Rocha Abreu

REMOBILIZED CU-AU PORPHYRY DEPOSITS FAVORABILITY IN THE SOUTHERN SEGMENT OF THE GOIÁS MAGMATIC ARC, BRASÍLIA BELT, TOCANTINS PROVINCE
Jônatas de Sales Macêdo Carneiro

TECHNICAL SUPPORT TEAM

RESPONSIBLE LIBRARIAN
Gabriela Vieira Leitão

PUBLISHING
Ricardo Luiz Barreiros Motta
Juliana Colussi de Gouvea

DISCLAIMER:
The favorability maps presented in this catalog are based in map algebra and exploration targetting techniques. While some areas are considered more favorable than others, the models don't eliminate the possibility of exploration in less favorable areas, considering the limitations on the scale of the presented maps, on available geological models and on the database itself.

International Cataloging in Publication Data

T231 Tavares, Felipe Mattos

Catalog of prospectivity maps of selected areas from Brazil / compiled by Felipe Mattos Tavares, Debora Rabelo Matos, Evandro Luiz Klein. – Brasília: ServiçoGeológico do Brasil-CPRM, 2020.

72 p. : il. color.

ISBN 978-85-7499-583-0 (print)
ISBN 978-85-7499-582-3 (pdf)

1. Mineral resources – Brazil. 2. Economic geology. I. Matos, Debora Rabelo. II. Klein, Evandro Luiz. III. Title.

CDD 553.1

Responsible Librarian: Gabriela Vieira Leitão – CRB/1 - 1995

FOREWORD

Brazil is a major producer and exporter of mineral commodities, being a global player regarding Nb, Fe, Mn, Ta, Al, graphite and ornamental stones, and is a relevant exporter at least of Ni, Mg, Sn, Cr, Au, Cu, and kaolin. However, our mineral potential goes far beyond this group of important commodities and the production is still not reflected in the Brazilian Gross Domestic Product. Recognizing the importance of the mining sector for the economic and social development of the country, the Federal Government of Brazil, through the Ministry of Mines and Energy and the Secretary of Geology, Mining, and Mineral Transformation are acting to revitalize the mining industry in Brazil and to create an investment-friendly environment, ensuring regulatory stability and legal certainty, and the increase of the geological knowledge of the Brazilian territory.

The Geological Survey of Brazil (CPRM) is responsible for the last topic. Massive investments in geochemistry and airborne geophysical surveys, geological mapping and metallogenic studies have been undertaken in the last years. Considering that the Brazilian territory is still immature in terms of mineral exploration, projects have been focused in the main mineral provinces to sustain discoveries in these sectors, and in other potential areas aiming to identify priority sites for investments and exploration opportunities.

Part of this effort is summarized in this "**CATALOG OF PROSPECTIVITY MAPS OF SELECTED AREAS FROM BRAZIL**". The catalog presents a compilation of prospectivity maps of nine areas from eight different Precambrian provinces/districts. The results suggest favorable areas for prospecting for metals, including gold, copper, lead, zinc, and iron. The Geological Survey of Brazil fulfills its institutional role in providing pre-competitive geoscience information hoping it can be useful for your work.

This catalog is available in hard copy and can also be downloaded free of charge from www.cprm.gov.br.

Esteves Pedro Colnago
President

José Leonardo Silva Andriotti
Director of Geology and Mineral Resources

TABLE OF CONTENTS

INTRODUCTION

Evandro L. Klein, Felipe M. Tavares, Débora R. Matos

Brazil is a major producer and exporter of mineral commodities. The country is a global player regarding Nb, Fe, Mn, Ta, Al, graphite and ornamental stones, and is a relevant exporter at least of Ni, Mg, Sn, Cr, Au, Cu, and kaolin. However, our mineral potential goes far beyond this group of important commodities and the production is still not reflected in the Brazilian Gross Domestic Product. Therefore, in addition to the political, economic, environmental, and regulatory aspects, efforts must be made in order to improve the geological and metallogenic knowledge of the Brazilian territory.

Regarding this last topic, the Geological Survey of Brazil (CPRM) carried out massive investments in geochemistry and airborne geophysical surveys, geological mapping and metallogenic studies in the last years. Furthermore, considering that the Brazilian territory is still immature in terms of mineral exploration, projects have been focused in the main mineral provinces to sustain discoveries in these sectors, and in other potential areas aiming to identify priority sites for investments and exploration opportunities.

As part of this effort to produce pre-competitive geoscientific information, CPRM is developing a mineral assessment program, in order to support decision-makers of the mineral industry with assertive information. The program includes the revision or determination of critical controls for different mineral systems, mineral potential modeling, and favorability mapping, as well as estimates of undiscovered resources.

The first results of the assessment program are summarized in this "Catalog of favorability maps of selected areas from Brazil". The catalog presents a compilation of favorability maps of nine areas from eight different Precambrian provinces/districts (Figure 1), and the results suggest favorable areas to prospect for five different metals. In the Amazonian Craton, the studies include assessments for copper and gold in IOCG (Cinzento Lineament of the Carajás Mineral Province) and volcanic-hosted massive sulfide ± orogenic deposits, along with sedimentary-supergene iron (southeastern Guiana Shield), intrusion-related gold systems (Tocantinzinho Lineament of the Tapajós Mineral Province, and Juma District), and Broken Hill Type polymetallic Zn-Pb-Cu-Au mineralization (Sunsás Orogen), whereas, in the Gurupi Belt, the assessment is provided for orogenic gold. In the Neoproterozoic Borborema Province, our studies focused on copper and iron from IOCG systems (Jaibara Basin), and in copper-lead-zinc SEDEX mineralization (Martinópole Group). Last, studies indicate favorability for porphyry-related copper and gold in the Brasília Belt (Goiás Magmatic Arc).

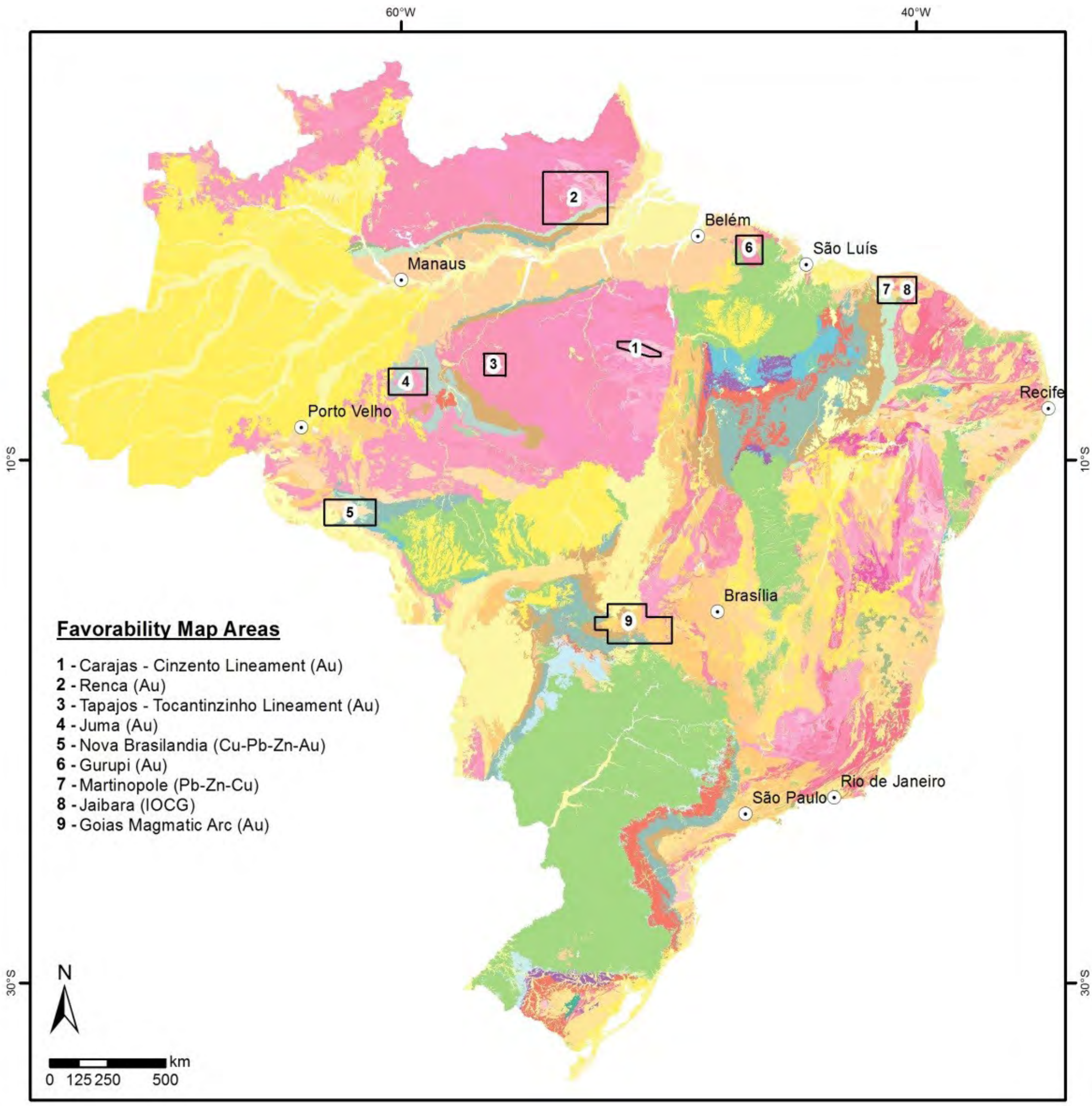


Figure 1 | Simplified tectonic-chronologic map of Brazil with the location of the areas focused in this report.

DATA INTEGRATION AND TARGET GENERATION

Guilherme Ferreira da Silva, Sulsiene Machado de Souza Gaia

INTRODUCTION

The development of a reproducible approach to identify sites with high potential for exploitation of a mineral commodity is the central objective of mineral favorability (or also prospectivity) studies (JOLY et al., 2012). This approach requires a broad set of information consistent from a multiparametric perspective, applicable to the scale of interest. Thus, prospecting models are attempts to emulate the mineralizing forming process, including fluid and metals transport, deposition and dispersion to detect new targets based on established mineral system criteria.

The favorability model can be built based on predefined information (knowledge-driven model) or even based on signatures of a known mineral deposit (data-driven model). Thus, mineral research can be developed through regional knowledge of a geological model for mineralization or similarities of conditions between previously known ore deposits (CARRANZA,2008; JOLY et al., 2012).

Prior knowledge-driven models are often suitable for areas where geological knowledge is limited (greenfield) or the tools available are scarce, with interpreters relying on classical mineralization models and trying to estimate the expected type of response from each field. If the conjunction of responses is as expected, a target is generated to be verified. Otherwise, the mineralization model is changed, or the area is discarded. These models have the advantage of being more versatile but are highly biased and depend solely on the experience of the prospecting team and the similarity between the deposits (CARRANZA,2008).

The favorability maps presented in this catalog were constructed by several authors, experts in each geological setting, using the Mineral Systems concept as a guidance tool in the searching for favorable areas in different parts of Brazil, as an initiative of the Mineral Resources Department of the Geological Survey of Brazil, since 2016. All methods used integration tools in aiming to build Knowledge-Driven Favorability Maps systematically and in semi-detail scales. In the following paragraphs, we discuss the fundamental concepts that have driven modelling in all maps.

MINERAL SYSTEMS

The Mineral Systems concept, initially developed by Wyborn et al. (1994), derives from the analogous understanding of Petroleum Systems, widespread in the petroleum industry from the mid-1980s. Petroleum Systems categorize all processes and geological elements necessary for the formation and storage of gas and oil. Likewise, Mineral Systems were defined as “all geological factors that control the generation and preservation of mineral deposits, whose processes are related to the mobilization of ore from source to the region of concentration, transport and accumulation, and their subsequent preservation throughout geological history” (WYBORN et al., 1994).

Still, according to Wyborn et al. (1994), most ore bodies are less than 1km^2 in expression, thus not constituting a significant target for mineral prospecting. Fortunately, although the deposits are not very large in area and are the result of an extraordinary coincidence of specific geological processes, these processes can be mapped at regional scales and are an essential key to the prospecting process (Figure 2). In other words, although the deposit areas consist of hundreds of meters, the total system of interaction between fluid-embedding rock-mineralization can extend over a few tens of kilometers, being detectable by specific tools (WYBORN et al., 1994).

Critical factors for characterizing any mineral system include:

1. The energy source (sometimes related to thermal gradient);
2. Source of fluids, binder compounds, metals and other components of mineralization;
3. Pathways of migration of the mineralizing fluid;
4. Structures or mechanisms of concentration;
5. Chemical and physical conditions for mineralization deposition.

As foreseen by McCuaig et al. (2010), the Mineral Systems concept has evolved (KNOX-ROBINSON;WYBORN,1997; HRONSKY; GROVES,2008; CZARNOTA et al., 2010; MCCUAIG; HRONSKY,2014) as it has been gradually accepted by industry and academia, being widely applied more than two decades after its introduction (e.g. ALMASI et al., 2017; FORD et al., 2019). It is emphasized that the structuring line of the Mineral Systems concept is associated with the understanding of various geological processes that operate at all scales rather than focusing on understanding the particular characteristics of specific deposits at their local scale.

McCuaig and Hronsky (2014) postulated that the existence of a mineral deposit is conditional upon the overlapping of at least three critical factors, namely Fertility, Geodynamic Favorability and Lithospheric Architecture, followed by a subsequent Preservation of ore concentration zones in a system (Figure 3). Fertility is a tendency of a region or geological epoch to be more favorable to the formation of mineral deposits than others. It varies according to the crust evolution at different times (e.g. rift and collision processes, supercontinents formation, among others). Lithospheric architecture is related to structural patterns associated with mineralization, such as structural trends or oreshoots, as well as crustal dimension structures, which cut layers from basement to

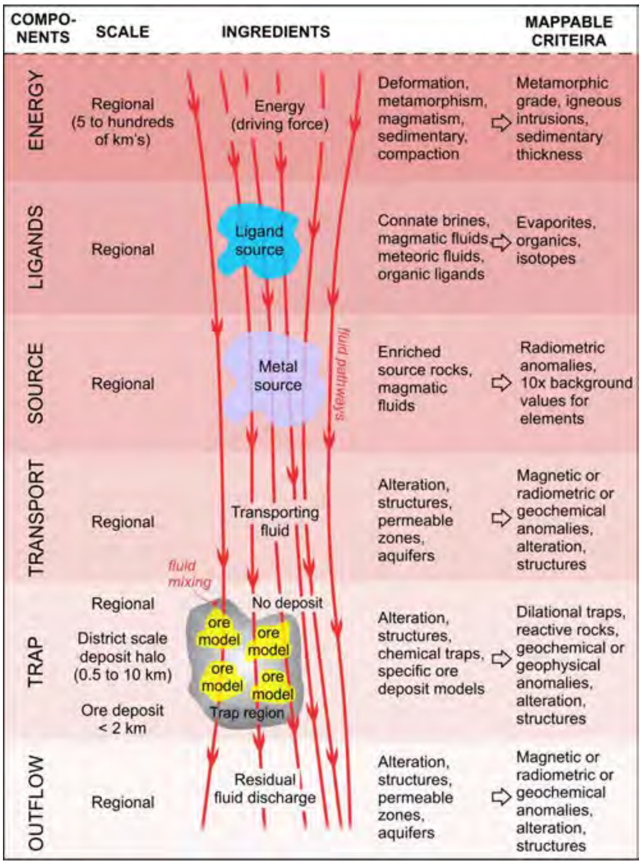


Figure 2 | Mineral systems conceptual model emphasizing the critical components observed in the ore-forming processes and mappablecriteria that can be used in the construction of favorability maps (modified from HAGEMANN;CASSIDY, 2000).

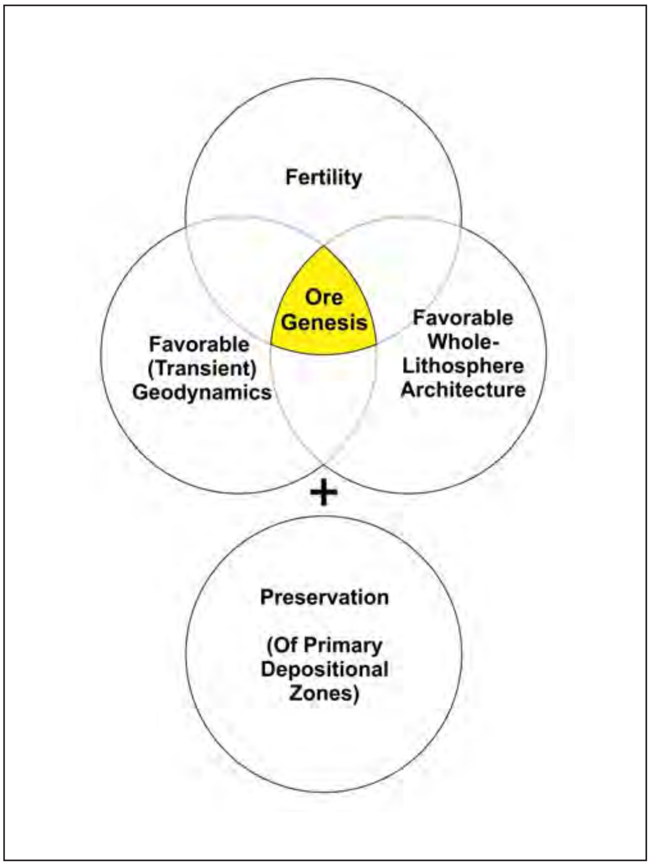


Figure 3 | Critical factors to the formation and preservation of a mineral deposit (MCCUAIG; HRONSKY, 2014).

top and are often used as conduits by mineralizing fluids in the migration process. This criterion is fundamental in hydrothermal processes, but it is also relevant in the formation of magmatism-associated mineral deposits, such as porphyry, greisen or other intrusion-related deposits.

With the evolution of dating techniques, it was possible to realize that large mineral deposits occur at minimal times in geologic history (MCCUAIG; HRONSKY, 2014). Thus, deposits that are distant for hundreds of kilometers from each other may have been formed at the same epoch and geodynamic conditions, within similar situations. This broader, integrated and multi-scaled look to all processes involved in the formation of mineral deposits is an advantage of this approach, which allows several mineralization styles to be identified in a single Mineral System.

Mineral Systems can be classified into three major groups: a) orthomagmatic, b) hydrothermal or magmatic-hydrothermal, and c) sedimentary mineral systems (HAGEMANN et al., 2016). Our focus is in the magmatic-hydrothermal systems, that are rich in Au, Ag, Cu, Pb, Zn, Sn, Mo and ETR, being triggered by geologic events such as plate movement, crustal block collision and microplate accretion (GOLDFARB et al., 1997; SQUIRE; MILLER, 2003; COOKE et al., 2005). Fluids in this system can originate from mantle, magmas, metamorphic devolatilization, and surface water reactions, interacting with the surrounding rocks and dissolving minerals, sulfides, oxides and elements.

Complexities such as overprinting of mineral systems are also present (e.g. Cinzento area), considering that, on a regional scale, mineral systems integrate the tectonic and geodynamic evolution of the terrain and may settle in different temporal windows, but occupying the same environment.

DATA PROCESSING

The systematic data processing was conducted on ESRI® GIS platform ArcGIS™ for desktop, using Spatial Analyst extension and Spatial Data Modeler tools for ArcGIS™ (SAWATZKY et al., 2009), in order to: (1) determine the spatial and temporal distribution of mineralizing processes to understand the critical ore-controlling factors; (2) translate that processes into mappable features and extract information to establish a mineral deposit model; (3) indicate mineral of interest favorable zones with knowledge-driven methods.

Several functionalities were used to highlight favorable spatial features, such as proximity analysis by the use of Euclidean distance and by defining a buffer zone that is considered by the specialist as favorable to the occurrence of a mineral deposit. It is applicable to faults and its intersections, rock contacts, outcrop observations, zones of hydrothermal halos influence, among others. Furthermore, density analysis (Kernel, point and line densities) are applied to faults and lineaments to highlight possible areas of strong structural permeability, which could favor the circulation of hydrothermal fluids.

The magnetic data was managed by the application of filters, such as upward continuation to evaluate the deep structures, as well as the selection of Analytic Signal and Magnetic Vector Inversion anomalies, in positive association with known mineral deposits.

Gammaspectrometric data was processed in aiming to underline K-enrichment zones related to hydrothermal alteration. The F factor method (GNOJEK; PRICHYSTAL, 1985; DE QUADROS et al., 2003) measure K abundance relative to Th/U and Th/K ratios, being useful to indicate hydrothermal alteration zones. The deviation of ideal potassium content, Kd (SAUNDERS et al., 1987; PIRES,1995), is calculated based on K normalization by Th as a lithological control and can be used to identify anomalous potassium enrichment zones. Furthermore, low Th/K ratios can also be used to identify areas enriched in K and are good indicators of hydrothermal alteration. The combination of these three products helps in the identification of potassium alteration zones, mainly associated with the presence of K-feldspar and/or sericite/muscovite.

The processing of geochemical data is given by the analysis of watershed associated with stream sediment and pan-concentrate data. Statistical indicators determine pathfinder elements in association with the sought mineral. Thus, anomalous catchment basin maps are generated to verify their distribution in relation to mineralization sites.

FAVORABILITY MODELLING

The predictive models of favorable areas are generally empirical models, which depict locations where mineral deposits of the type sought plausibly exist (CARRANZA, 2008). There are two conventional knowledge-driven techniques, namely the multi-class index overlay and the fuzzy logic. For data integration and modelling, both methods were used to build the favorability maps presented in this volume.

Multi-Class Index Overlay

This technique uses a mathematical concept similar to that of Boolean algebra, where the value of each class of evidence is added when there is an intersection of two or more predictive vectors. The more intersections of predictive vectors occur in a specific map region, the higher the score assigned to the intersection zone. Finally, to generate a favorability map, the classes were then combined or summed (S), following the equation below:

$$\overline{S} = \frac{\sum_e^n (P_{ve})(W_e)}{\sum_e^n W_e}$$

where P_{ve} represents the assigned score according to the relevance of that map to mineral favorability, W_e serve the assigned weights (generally, positive integers) that vary with the representativeness and reliability of the survey and n is the total number of evidence maps used in the modelling (CARRANZA, 2008). The weighting process is a subjective process and can be based on field observations and knowledge of the geologist.

Fuzzy Logic

Fuzzy logic (AN et al., 1992; BONHAM-CARTER,1994; BROWN et al., 2003; ELLIOTT et al., 2016) is a sophisticated mathematical tool that converts the likelihood of a determined feature related to the processes of interest into a continuous range of possibilities, varying from 0 to 1, where the more completely an evidence belongs to a favorable fuzzy set, the closer its value is to 1. It is composed by three main processing stages (Figure 4): (1) fuzzification of evidential data; (2) integration of fuzzy evidential maps with the aid of appropriate fuzzy set operators; (3) defuzzification of fuzzy mineral favorability output in order to aid its interpretation and validation.

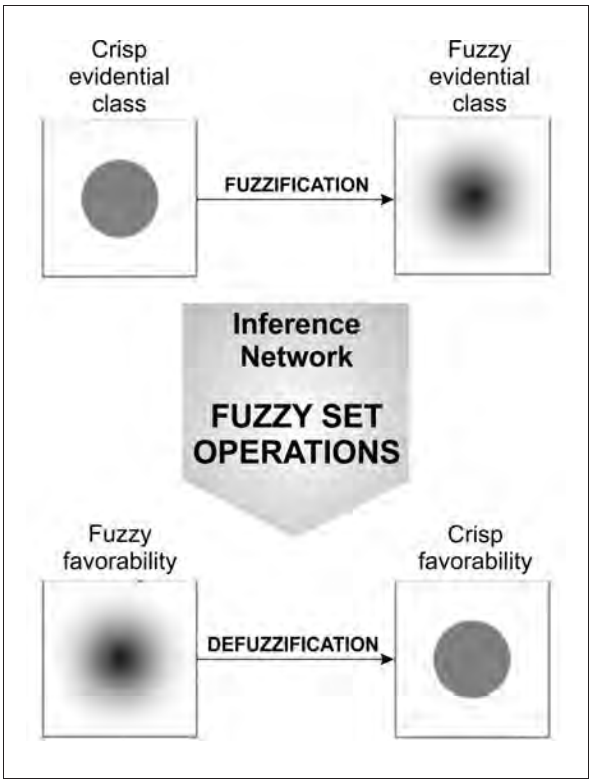


Figure 4 | Main processing stages of the fuzzy logic modelling (modified from Carranza, 2008).

This technique allows the specialist to select the evidential layers that are believed to be the most critical for the particular style of mineralization (ZHANG; ZHOU, 2015) being targeted, thereby taking into account the statistics of each evidential feature and the background values within the study area.

There are several fuzzy membership functions that assist the fuzzification process. After defining the fuzzy membership functions for each evidential map, a variety of operators can be used to combine the membership values, integrating all the information into a single-output fuzzy set. Five fuzzy operators are commonly used in fuzzy mineral favorability modelling: Fuzzy AND, Fuzzy OR, Fuzzy algebraic PRODUCT, Fuzzy algebraic SUM, and Fuzzy GAMMA (γ) operator. These fuzzy operators are useful in mineral favorability mapping mainly because each of them or a combination of any of them can emulate the conceptual model of geological processes involved in ore formation. The description of each of these operators is listed in table 1.

OPERATOR	Fuzzy AND	Fuzzy OR	Fuzzy PRODUCT	Fuzzy SUM	Fuzzy GAMMA
DESCRIPTION	Logical intersection. The output is controlled by the smallest fuzzy membership values, resulting in a conservative estimate of the set membership and has a tendency to produce low values.	Logical union. The presence of any one of the predictor map is sufficient to infer the presence of the respective component, with a tendency to potentialize values.	The combined fuzzy membership values tend to be small due to the effect of multiplying several numbers less than 1. The output is always lower than, or equal to, the smallest contributing membership value.	It is appropriate in combining complementary evidence maps, implying that all fuzzy input scores at a location must contribute to the output, which is greater than or equal to the highest fuzzy score at every site.	This operator is a combination of the fuzzy algebraic product and the fuzzy algebraic sum. It allows a subtle change in the contribution of various components.

Table 1 | Description of the fuzzy operators.

Any of the fuzzy operators can be applied to combine evidential maps according to inferences about the relationships of processes and spatial features that indicate the presence of a mineral deposit. In every step, at least two evidential maps are combined, forming a series of logical rules that sequentially combine evidential fuzzy maps. The fuzzy inference network reflects the knowledge of how the mineral deposits were created and which spatial features indicate where mineral deposits of the type sought may occur. Thus, it adequately represents the conceptual model of mineral favorability.

MODEL VALIDATION

After the generation of a predictive favorability model, it shows high scores colored zones for the areas with most evidential class intersection and most likely targets for mineral discoveries. The evaluation of the map is quantified through examination whether the generated targets actually predict known deposits location. For this analysis, only occurrences that are understood as formed into analyzed mineral system conditions are selected, in order to work as training sites.

All favorability maps in this volume were tested by comparing the number of occurrences within each classified area with its total area. The results are plotted in a graph of the percentage of training sites and research areas versus the final prospective weights. Two evolution lines must plot, showing that as the prospective score increases, the research area decreases considerably. Another test was used in the fuzzy map, the Receiver Operating Characteristics (ROC) (NYKÄNEN et al., 2015) and the Area Under the Curve (AUC) graphs. The training sites are compared to the indicated favorable areas in order to check the accuracy of the model and to measure the relationship between them. The higher this relationship, the closer the ROC curve is to the upper left corner of the ROC graph. The AUC value is a quantitative expression of this relationship, in the range of 0.5 to 1, which corresponds respectively to the random and deterministic relationships, being desirable the value be close to 1.

Reducing the research area is a crucial process to reduce costs and risks in mineral exploration, being the main objective of the mineral favorability maps. The coherence of the final prospective map indicates that the integration of knowledge-based data is an effective tool in reducing the area of mineral research. The final maps are constructed without any layers directly related to mineralization, such as mineral deposit sites or location of occurrences or drilling. They are produced from a set of independent concepts that effectively translate the understanding of the system mineral in GIS-based vectors, leading prospectors to mineralization.

COPPER-GOLD FAVORABILITY IN THE THE CINZENTO SHEAR ZONE, CARAJÁS MINERAL PROVINCE

Felipe Mattos Tavares, Junny Kyley Mastop Oliveira, Antônia Railine da Costa Silva, Iago Sousa Lima Costa, Rafael Bittencourt Lima

INTRODUCTION

The Carajás region, in northern Brazil, hosts a world-class polymetallic mineral province (Carajás Mineral Province), with giant iron deposits and large resources of copper and gold, mostly related to iron oxide-copper-gold (IOCG) deposits. Other important resources include manganese, nickel, tin, EGP, REE, among others. Since the region has a complex geodynamic history, mineral potential modelling can be challenging, due to the overprinting of different mineral systems in several metallogenic epochs.

The Geological Survey of Brazil (CPRM) has developed geological, geophysical and geochemical data integration in the Cinzento shear zone, northern Carajás, as to assess favourable targets to mineral exploration. Thus, we present here the results of the favorability mapping using the mineral systems approach applied to exploration targeting techniques.

TECTONOSTRATIGRAPHIC FRAMEWORK

There are three main rock generation ages in Carajás Mineral Province tectonostratigraphic evolution, namely in the Mesoarchaean (3.02–2.83 Ga), the Neoarchaean (2.76–2.55 Ga) and the Paleoproterozoic (1.88 Ga) (Figure 5). The oldest rocks are gneisses, greenstone belts and granitoids developed under an orogenic system reported as the Itacaiunas Belt (ARAUJO et al., 1988;TAVARES et al., 2018). The peak metamorphism has been dated at 2.85 Ga and metamorphic fabrics are of medium to high amphibolite facies (MACHADO et al., 1991;TAVARES, 2015). This rock association represents the basement of the ItacaiúnasSupergroup (2.76–2.70 Ga), a Neoarchaean, marine meta-volcano–sedimentary sequence probably related to intraplate extension (DOCEGEO, 1988). Coeval bimodal magmatism is represented by several A-type granites and mafic–ultramafic intrusions. Smaller late stage granitic intrusions persisted until 2.55 Ga. Three other sedimentary sequences covered the Mesoarchean basement during the Paleoproterozoic, the marine Buritirama Formation (Siderian, SALGADO et al., 2019), the marine to continental Águas Claras Formation (Rhyacian, NOGUEIRA et al., 1995) and the continental Caninana Formation (Orosirian, PEREIRA et al., 2009). At about 1.88 Ga, the region experienced an anorogenic magmatic event, which also affected all the central–eastern side of the Amazonian Craton and is known as the Uatumã magmatism. This event produced a second generation of A-type granites in the province (DALL'AGNOLet al., 2005), emplaced at shallower depths and related to widespread hydrothermal activity in a brittle, fluid dominated extensional environment.

Neoarchaean and Siderian rocks were majorly deformed and metamorphosed in the Paleoproterozoic. There are two events of ductile to ductile–brittle deformation and metamorphism that can be recognized. The oldest one is the Transamazonian Orogenic Cycle (2.20–2.05 Ga), a collisional system that agglutinated several Archaean nuclei and Rhyacian magmatic arcs and greenstone belts (CORDANI et al., 1984;TAVARES et al., 2018), related in the province to low greenschist (south) to high amphibolite (north) metamorphic fabrics and structures. To the north, the Archaean units are limited by a collisional suture from Rhyacian plutonic assemblages that are imbricated over the province. The youngest one is the Sereno Event, an intracontinental orogeny correlated to Orosirian accretionary–collisional belts that surrounded the Amazonian protocraton at 2.00–1.98 Ga (TAVARES et al., 2018). Sereno fabrics are of very low grade, from sub-greenschist to greenschist facies.

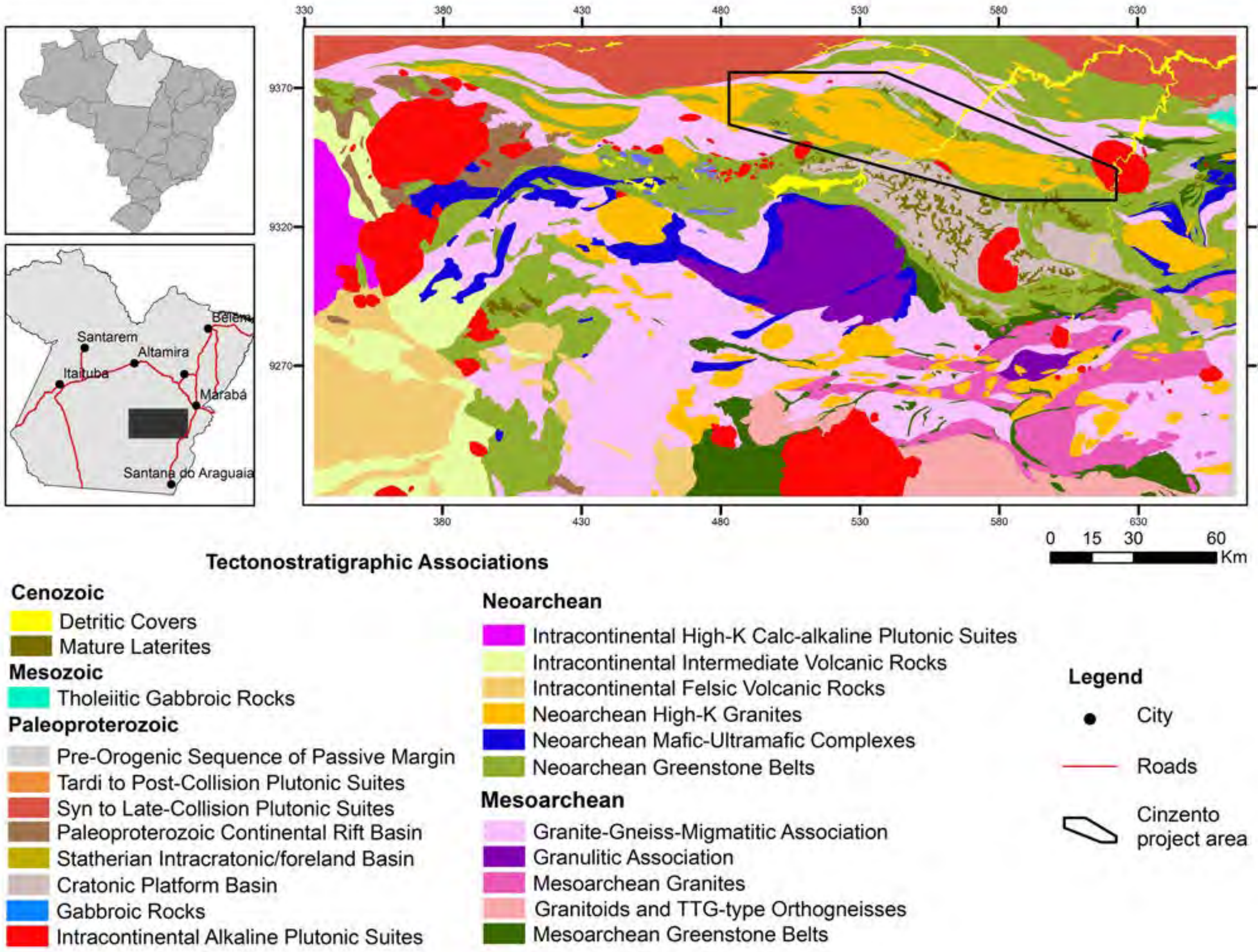


Figure 5 | Map of Tectonostratigraphic Associations of Carajás Province showing the location of the Cinzento Project area (black line polygon).

The Mesoarchaean main structural trend is ductile in character and of an E–W direction, while the Transamazonian trend varies between ENE–WSW and NE–SW. The Sereno structures are widespread, although less penetrative and of a ductile–brittle style, in an X-shaped pair of oblique structures in WNW–ESE and ENE–WSW directions (TAVARES et al., 2018).

GEOLOGY AND METALLOGENESIS OF THE COPPER AND GOLD RESOURCES

The Cinzento region registers at least three mineralization events for Cu and/or Au:

a) in the Neoarchean (2.76 Ga), when deep basement discontinuities were reactivated as extensional faults during the deposition of the ItacaiúnasSupergroup, leading to the formation of syngenetic Cu-Zn volcanic massive sulphides (VMS) deposits;

b) still in the Neoarchean (2.55 Ga), a large-scale hydrothermal system chronologically and spatially related to the late-stage A-type magmatism, generating IOCG deposits;

c) in the Paleoproterozoic, contemporary to the 1.88 Ga A-type magmatism, that generated different polymetallic, granite-related deposits, such as Cu-Au-W-Mo-Sn and Cu-Au-Fe-Mo-Co-REE´s. Some authors believe that a second generation of IOCG deposits were formed in this epoch, although in the Cinzento region they were not yet recognized.

The IOCG orebodies are located along major structures or in their vicinities, with a wide range of host rocks (yet some lithotypes are more favourable for mineralization). The deposits share several characteristics, such as large (kilometric) hydrothermal halos, an intense Fe metasomatism associated with the occurrence of low sulphidation sulphides, LREE enrichment, high yet variable amounts of Co, Ni, Pb, Zn, As, Bi, W and U, spatial and chronological correlation to A-type granitic plutons/dykes and breccia-like textures (TALLARICO, 2005;XAVIER et al., 2012;GRAINGER et al., 2008) However, Archaean and Palaeoproterozoic orebodies differ from each other in their hydrothermal assemblage and ore minerals, reflecting variations in the fluid oxidation stage, pH, fO2 and fS2 (GRAINGER et al., 2008; MORETO et al., 2015). Older deposits are magnetite-rich and thought to be formed at deeper crustal levels, while the secondary younger orebodies are haematite-rich (although can present magnetite as well), silica saturated and developed in shallower environments (XAVIER et al., 2012). In addition, the older deposits were deformed and metamorphosed by the Paleoproterozoic orogenic events, while the younger deposits are post-tectonic, preserving their original textures and mineralogy (TAVARES et al., 2017).

Some of the largest Cu-Au deposits were proven to be related to hydrothermal overprinting of at least two mineralization events, like the Pojuca-Gameleira-GrotaFunda system (Table 1). Pollard et al. (2018) suggest that at least part of the Orosirian components was inherited and reworked from previous IOCG hydrothermal alteration.

PROSPECTIVITY CRITERIA FOR CU-AU MINERALIZATION

Relevant factors were defined regarding the ore generation, transport, and trapping. Subsequently, we attempted to find representative and mappable features of these factors, based on information from the CPRM public database (http://geosgb.cprm.gov.br). The selected data were processed, rasterized and scored, concerning their importance in the ore forming process resulting in evidence maps. Furthermore, each evidence map received a weight related to the degree of uncertainty and reliability of the original data (Table 2). The modeling was performed in a GIS environment, in the ArcGIS program (Spatial Analyst extension). For the modeling, we used the multi-class overlaying method, in which the value of each class of evidence is added when there is an intersection of two or more predictive vectors.

In the case of Cinzento shear zone, we modelled in three stages, following the criteria of each Cu-Au ore forming event. The evidence maps for the VMS system were: lithotypes (metavolcanic and chemical metasedimentary rocks of the ItacaiúnasSupergroup) and contacts between them, deep structures (mapped through Euler deconvolution), geochemical signature (Zn-Cu-Fe-Au-Ag) and distribution of metamorphosed chloritic alteration (dalmatianites), a regional footprint to the exalathive systems. To the IOCG system (2.5 arapéGeladoMetagranite) and their contacts, deep structures, ductile structural lineaments E-W and WNW-ESE, geochemical signature (Cu-Au-U-Th-Fe-Ce-La-K-Ni-Co-Mo-B-Ag-Cr-Ti), distribution of mapped Ca-Na, K, Fe metasomatism, gammaspectrometry anomalies and magnetic anomalies. For the 1.88 Ga deposits, the evidence maps were: brittle to ductile-brittle structural lineaments in NW-SE/E-W and NE-SW directions, shallow structures, geochemical signature (Cu-Au-U-Th-Fe-Yb-Ag-Ti-Sn-Bi), distribution of mapped Si-Ca-Fe metasomatism, distribution of silica-rich hydrothermal breccias and gammaspectrometric anomalies (uranium concentrations normalized using thorium).

The integration of the three products generated a favorability map for Cu-Au of the Cinzento shear zone, with five prospective classes. The location of known deposits was used to evaluate the quality of the product generated. The classes with the highest prospectivity index (8.44% of the project area) mapped 51% of known Cu and Au occurrences, attesting to the good correlation between potential classes and ore occurrence.

This work allowed the identification of new target areas, therefore helping to reduce costs, time and risk in mineral exploration.

Original maps can be assessed at http://rigeo.cprm.gov.br/jspui/handle/doc/20333

	EVIDENCE MAPS		MINERALIZING EVENTS VMS MODEL	2.5 IOCG	1.88 IOCG	COMMENTS
GEODYNAMIC EVOLUTION	Lithology		5	5	-	Map of lithotypes
	Contacts		5	5	-	Contacts between lithotypes that represent potential chemical traps (more reactive to hydrothermal / mineralizing fluids)
STRUCTURAL FRAMEWORK	Deep structures		5	5	5	The structures were obtained using Euler deconvolution and divided into two classes according to depths: shallow and shallow to deep
	Structural Lineaments Dn	Density of structures	-	4	-	Zones with higher density of structures (Kernel Density)
		Distance from structure	-	4	-	Euclidean distance maps (buffers of all structures)
	Structural Lineaments Dn+1	Density of structures	-	-	4	Zones with higher density of structures (Kernel Density)
		Distance from structure	-	-	4	Euclidean distance maps (buffers of all structures).
	Structural Lineaments Dn+2	Density of structures	-	-	4	Zones with higher density of structures (Kernel Density)
		Distance from structure	-	-	4	Euclidean distance maps (buffers of all structures).
HYDROTHERMAL ALTERATION	Silicic breccia (points)		-	-	4	Described points or photointerpreted features
	Hydrothermal Alteration (points)		4	4	4	Points where was described the hydrothermal mineral assembly of each deposit model
	Geochemistry		1	1	1	Although important in targeting, only ~ 45% of the area has a systematic geochemical survey
	Magnetic anomalies (MVI)		-	5	5	Classified in 1st and 2nd anomaly orders
	Radiometric Anomalies (Anomalous U)		-	5	5	Classified in 1st and 2nd anomaly orders

Table 2 | Weights of Evidential Maps for each mineralizing event in the Cinzento Shear Zone.

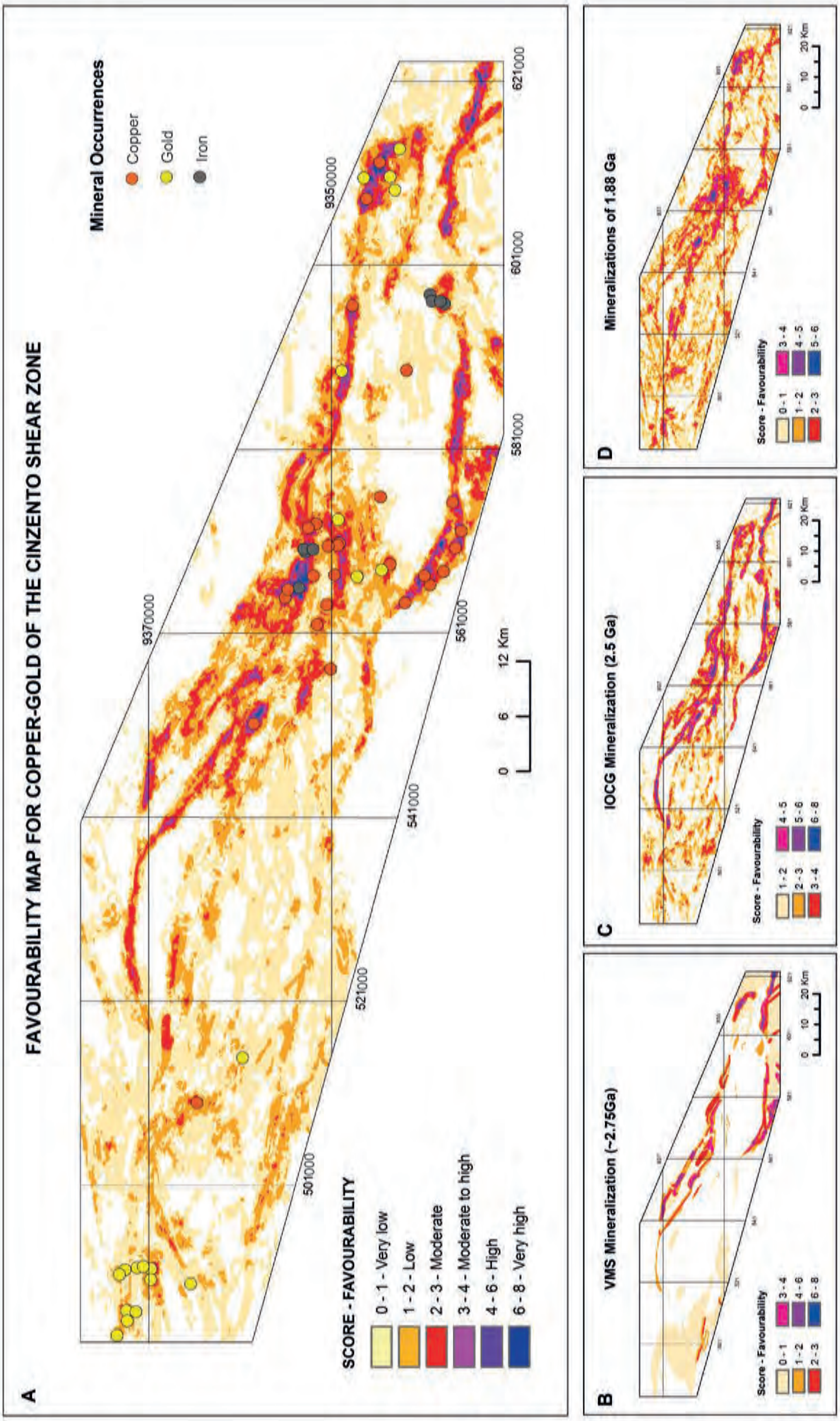


Figure 6 | Copper-Gold Favorability Map in the Cinzento Shear Zone, Carajás Mineral Province.

EVIDENCE MAPS

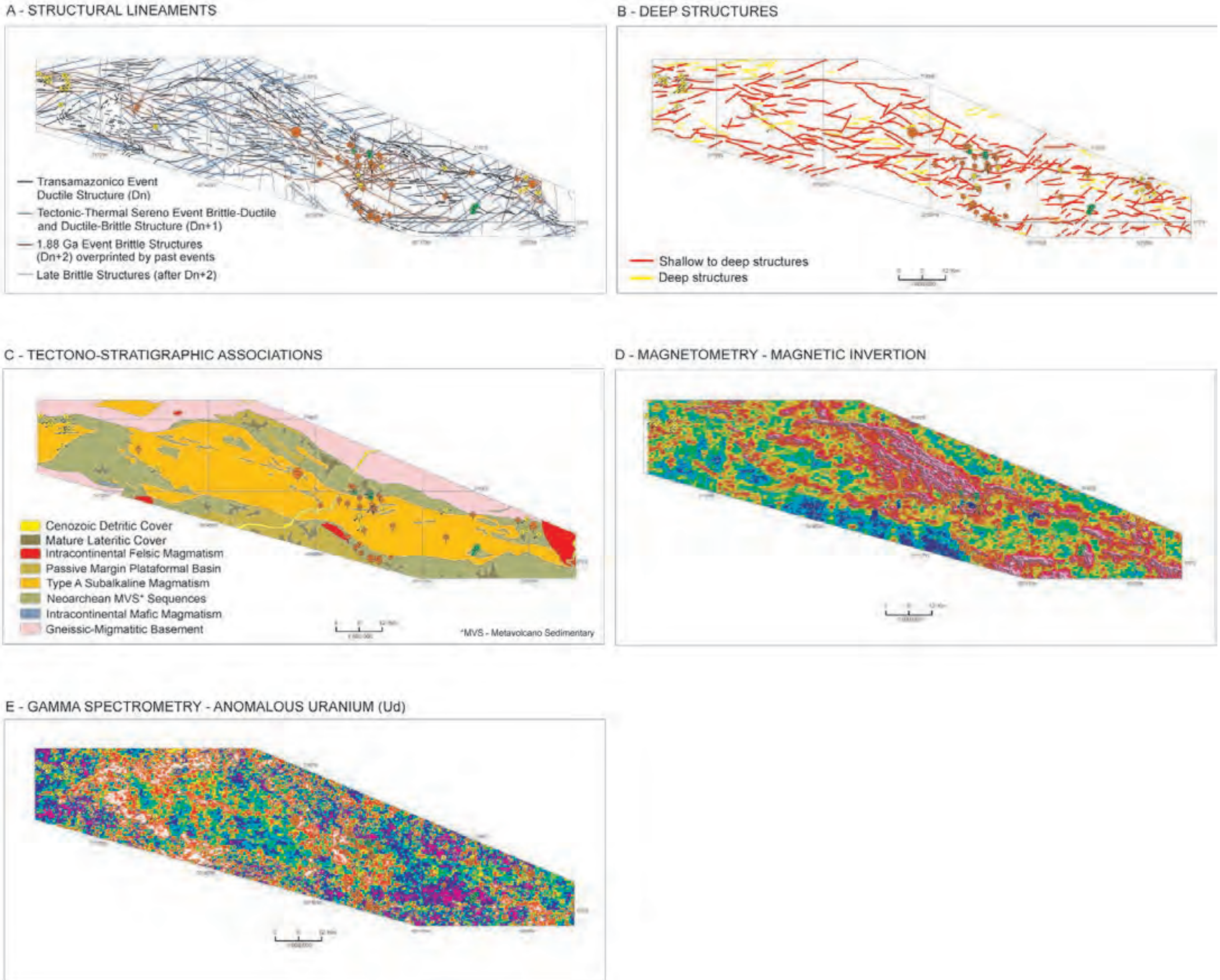


Figure 7 | Evidence Maps of the Copper-Gold Favorability in the Cinzento Shear Zone, Carajás Mineral Province.

PROSPECTIVITY MAPPING AND MINERAL SYSTEM ANALYSIS OF THE RENCA AREA, SE GUIANA SHIELD

Leandro Duarte Campos

INTRODUCTION

The Brazilian government created the RENCA (National Copper and Associated Minerals Reserve) in 1984 in order to protect the potentially poly-mineral district from foreign investment. Since that, only government owned companies were able to explore the Reserve. Exploration conducted mainly during the 1970s and the 1980s focused on gold, iron and base metal. Main results were: (i) one small copper discovery in the Ipitinga Group that intercepted 1m @ 0.7% Cu, 6.5g/tAu, 48g/t Ag (Melo et al. 1985); (ii) an iron ore potential resource estimated in 2 Bton @ 39-63% also in the Ipitinga Group (Jorge João et al. 1978); (iii) a lode gold district with un-estimated artisanal production and one reported mine with estimated resource of 10 ton @ 26g/t Au (Klein and Rosa-Costa 2003). Besides that, Oliveira et al. (1988) reported phosphate laterite, niobium and rare earth elements discovery potential related to mafic-ultramafic intrusive bodies.

Recently, the Geological Survey of Brazil conducted geological mapping, petrological and geochronological studies that allowed a more detailed understanding of the geodynamic evolution and the mineral systems within the Reserve (Rosa-Costa et al. 2017). In order to build an exploration model for the RENCA, Campos et al. (2017) used the mineral system concept (McCuaig and Hronsky 2014, and references therein) to produce multi-mineral prospectivity maps for copper, gold, iron ore, and Nb-rare earth. The final target maps integrated the entire historical database, such as detailed geological maps, diamond drilling, regional and detailed soil/stream sediment geochemistry, together with new geological concepts and airborne geophysical surveys published by the Geological Survey of Brazil.

TECTONOSTRATIGRAPHIC FRAMEWORK

The RENCA sits on the northern portion of the Amazonian Craton, at the Guiana Shield (Figure5). This portion of the Guiana Shield comprises metasedimentary and metavolcanic rocks, granites, ultramafic intrusive complexes and middle to high-grade metamorphic rocks with ages ranging from the Paleoproterozoic to the Mesoarchean (Rosa-Costa et al. 2017). Archean and Paleoproterozoic rocks form preferentially NW-SE trends that follow the general tectonic orientation of the Ipitinga Group, interpreted to represent a Rhyacian greenstone belt (c.a. 2.1 Ga), and the suture zone between two distinct tectonic blocks, the Archean Amapá and the Paleoproterozoic Carecuru blocks. Rosa-Costa et. al. (2017) grouped the lithoestratigraphic units as follows. (1) Mesoarchean basement rocks that comprise orthognaisses of the Tumucumaque Complex (2849 ± 6 Ma). (2) Neoarchean rocks with Paleoproterozoic granulite metamorphism including the Jari-Guaribas Complex, the Baixo Mapari Complex, the Iratapuru Complex, the Ananaí Complex (2597 ± 4 Ma), and the Noucouru Intrusive Suite. (3) Neoarchean gneisses and migmatites of the Guianense Complex (2652 ± 4 to 2605 ± 3 Ma). (4) Neoarchean granites such as the Anauerapucu Granite (2791 ± 23 Ma) and the Riozinho Granite (2626 ± 5 Ma). (5) Rhyacian deformed basins, represented by the Vila Nova and the Ipitinga groups, which comprise metavolcanic and metasedimentary rocks that host the copper, gold and iron ore mineral systems. (6) Rhyacian deformed granites represented by the Carecuru Suite (2140 ± 1 Ma), the Charuto Granite (2218 ± 3 Ma), the Igarapé Cumaru Granite (2185 ± 4 Ma), Urucupatá Alaskite (2146 ±3 Ma), and the Sucuriju metagranite. (7) Syn-tectonic granites comprising the Paru Granite

(2098 ± 2 Ma), the Igarapé Urucu Suite, and the the Igarapé Careta Suite (2074 ± 5). (8) Paleoproterozoic mafic and ultramafic intrusions represented by the Dicó metadiorite (c.a. 2.20 Ga). (9) Statherian anorogenic granites represented by the Mapuera Suite (1.89 to 1.86 Ga). (10) The Mapari alkaline intrusive complex (1753 ± 3 Ma). (11) Ediacarian mafic and ultramafic alkaline complexes such as the Maicuru and the Maraconaí intrusions that host phosphate laterite resources. (12) Phanerozoic sedimentary and volcanic rocks of the Amazonas Basin.

The lithological framework of the RENCA defines a complex geodynamic evolution from the Archean to the Phanerozoic of the eastern Amazonian Craton. Despite its composite nature, the main metallogenic episode is related to the evolution of a Paleoproterozoic orogenic cycle that correlates to the Transamazonian belts of the southern Amazonian Craton and to the West-African Rhyacian belts (Rosa-Costa et al. 2006, 2009). The metamorphic peak is estimated to have occurred between 2.10 and 2.08 Ga (Rosa-Costa et al. 2009). This event is responsible for the isotopic reset and tectonic reworking of the Amapá Block, and for its suture with the Carecuru Block. The suture zone is marked by steep and deep magnetic and gravimetric structures, both related to the eastern limit of the Ipitinga Group (Rosa-Costa et al. 2017).

GOLD MINERAL SYSTEM

Gold is by far the most reported mineral occurrence in the RENCA. There are 93 listed artisanal gold production zones with the majority of those related to the metasedimentary rocks of the Ipitinga Group. Klein and Rosa-Costa (2003) described several occurrences that consist mostly of small lode gold deposits with variable grades. The gold veins were mainly controlled by shortening and transcurrent structures related to the Paleoproterozoic evolution of the Ipitinga Group. Klein and Fuzikawa (2010) reported that the gold mineralization formed from low-salinity aqueous-carbonic fluids with an isotopic signature similar to those of orogenic gold deposits. Moreover, Klein et al. (2009) determined galena Pb-Pb ages between 2016 and 2113 Ma, which despite the large age interval are consistent with the Paleoproterozoic metamorphic peak.

COPPER MINERAL SYSTEM

Faraco (1990, 1997), suggested a VMS model for the copper mineralization located at the northern portion of the Ipitinga Group. The host rocks are mainly hydrothermally-altered tholeiitic and komatiitic metabasalts (quartz-chlorite schist/anthophyllite-cordierite schist) and tectonic breccia with quartz, actinolite, chlorite, cummingtonite, talc, and apatite. An external alteration halo is marked by anthophyllite-cordierite schists that are products of the regional metamorphism of quartz-chlorite shales, the latter generated from oceanic floor alteration. The sulfide assemblage consists mainly of pyrrhotite, pyrite, chalcopyrite, and minor sphalerite.

Faraco (1997) describes the massive sulfide mineralization as controlled by an NW-SE trend, along narrow and irregular layers and breccia zones at the contact of mafic to ultramafic volcanic rock and banded iron formation. The total extension of the copper mineralization is still unknown. Only four drill holes were performed in a restricted area. However, geochemical and geophysical anomalies, as well as favorable geological conditions, point to a possible along-strike continuation of the intercepted mineralization for more than 20 km (Campos et al. 2017).

IRON ORE MINERAL SYSTEM

Occurrences of iron ore in the RENCA are invariably related to banded iron formations and ferruginous quartzites of the metasedimentary sequences of the Ipitinga Group. Jorge João et al. (1978) described the metasedimentary rocks as compact hematite, itabirites (quartz-hematite interlayered rock), banded ferruginous quartzites, quartzites, and amphibolites. Three iron ore samples yielded 39.66%, 58.33% and 63.23% Fe. Based on the volume of three similar-relief residual plateaus (4 km x 1.5 km each) with an estimated iron ore layer of 50 m thick, the authors calculated a “possible geological resource” of 2,367 Mt of Fe.

PHOSPHATE, TI, NB AND REE MINERAL SYSTEM

Phosphate, Ti, Nb, and REE resources are related to primary and supergene concentrations in the Maicuru (alkaline-ultrabasic-carbonatitic) and Maraconaí (alkaline-ultrabasic) intrusive complexes, located in the southwest portion of the RENCA. This alkaline ultrabasic magmatism is related to the extensional tectonics in the Neoproterozoic (Lemos and Gaspar, 2002).

Both intrusive complexes form high relief semi-circular structures that are similar to table-top mountains. This condition favored the development of phosphate-enriched supergene crusts. These crusts also concentrate accessory minerals rich in Ti, Nb, and Co. Circular structures with strong magnetic response and low radiometric signature were considered the main prospective control for this system.

MULTY-COMMODITY PROSPECTIVITY ANALYSIS

For the analysis, integration and interpretation of the data we used the mineral system concept (Hronsky and MacCuaig 2014, and references therein), which considers that mineral deposits are local expressions of much larger processes that occur on a continental scale that focus mass and energy flows in certain regions of the crust. To generate district-scale targets Iused the knowledge-driven multi-class overlay method from Carranza (2009). This method is most suitable for data integration at that scale.

From data integration, evidence maps were generated to represent each geological process associated with the formation of one or more mineralizing system. For the present study, I scored and combined every distinct map specifically according to the related mineral system. Then, evidence maps were integrated into specific sets related to the critical factor(s) of the mineralizing system, and later the final maps of each set were summed together to generate a final predictive map.

For the composition of the final prospectivity maps Campos et al. (2017) used the following predictive maps. (1) Isotopic maps, which represent large scale processes related to rock generation with potential for the generation of mineralizing fluids; (2) geological maps, depicting potential host rocks and fluid generation areas; (3) deep structures, which represent the main areas of fluid circulation in the crust; (4) geological contact map, representing the main zones of deposition of mineralizing fluids; (5) structure density, termination and intersection maps, which represent favorable zones of space opening for mineralization; (6) radiometric map of hydrothermal alteration, which represents zones of active circulation of mineralizing fluids; (7) geochemical maps of soil and stream sediments, which are the main anomalous zones in elements related to mineralizing systems. Each evidence map was scored and weighted according to the proposed table by Campos et al. (2017).

As a main result of the work, the evidence maps were integrated to generate prospective targets for copper (VMS system), gold (orogenic system), iron (supergene system) and phosphate (alkaline ultrabasic system). All final maps successfully indicated known mineralization and highlighted new areas with potential for new discoveries.

Original maps can be assessed at http://rigeo.cprm.gov.br/jspui/handle/doc/18967

FAVORABILITY MAP

Figure 8 | Gold Favorability Map in the Renca Area, SE Guiana Shield.

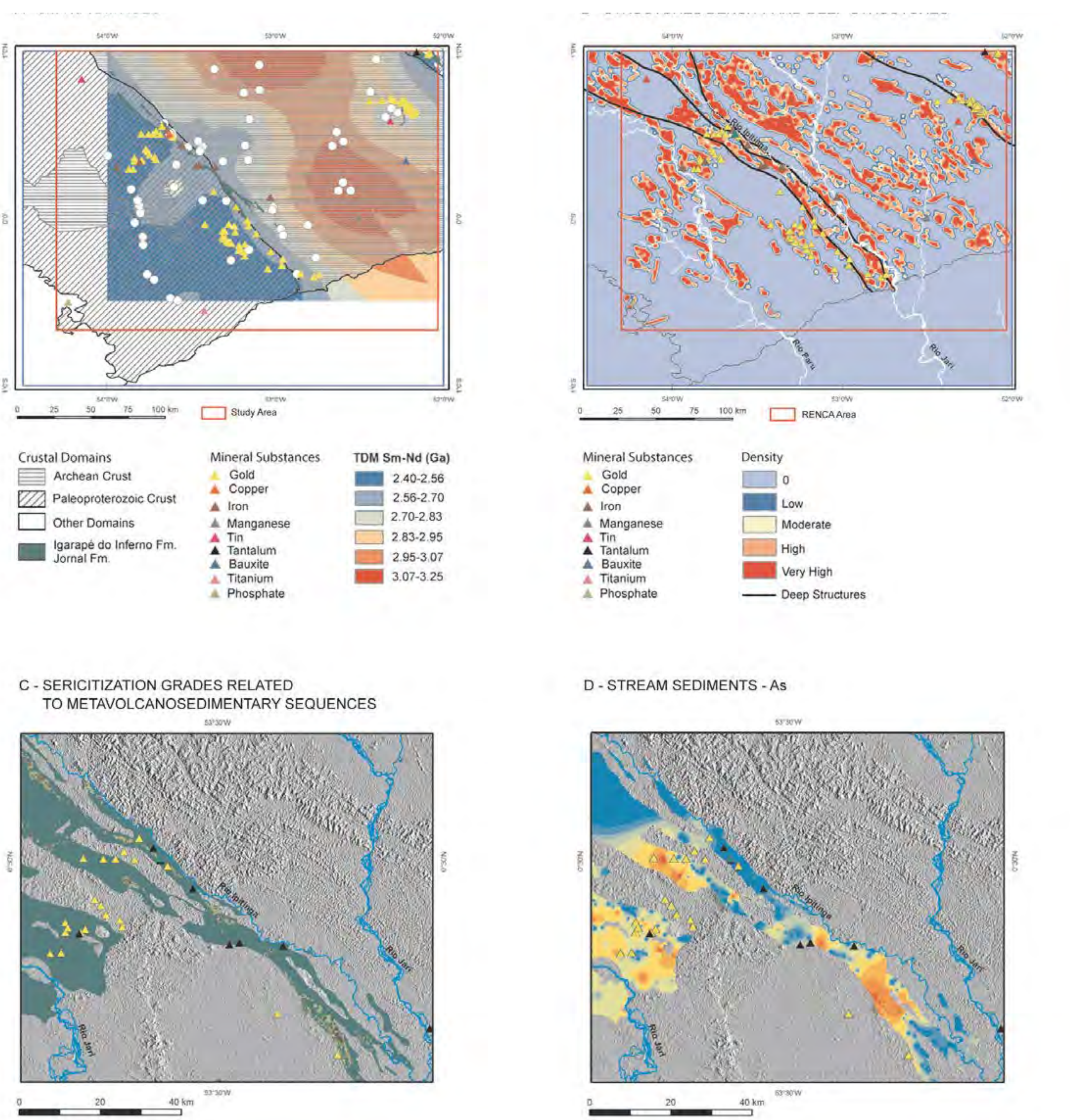


Figure 9 | Evidence Maps of the Gold Favorability in the Renca Area, SE Guiana Shield.

PREDICTIVE POTENTIAL MAPPING FOR INTRUSION-RELATED GOLD IN THE EASTERN TOCANTINZINHO TREND, TAPAJÓS MINERAL PROVINCE, AMAZONIAN CRATON

Sulsiene Machado de Souza Gaia, Marcelo Lacerda Vasquez, Felipe Mattos Tavares

INTRODUCTION

The demand for investment attractiveness in mineral production has driven research around the indication of favorable areas to the occurrence of a certain mineral asset. In this sense, the Geological Survey of Brazil (CPRM) has been developing geological, geophysical and geochemical data integration to predict favorable targets to mineral exploration.

The Tapajós Mineral Province (TMP) corresponds to a Paleoproterozoic tectonic domain in the central part of the Amazonian Craton (Figure 10), which hosts gold deposits of different types and styles, representing different portions of a single structure-controlled mineral system.

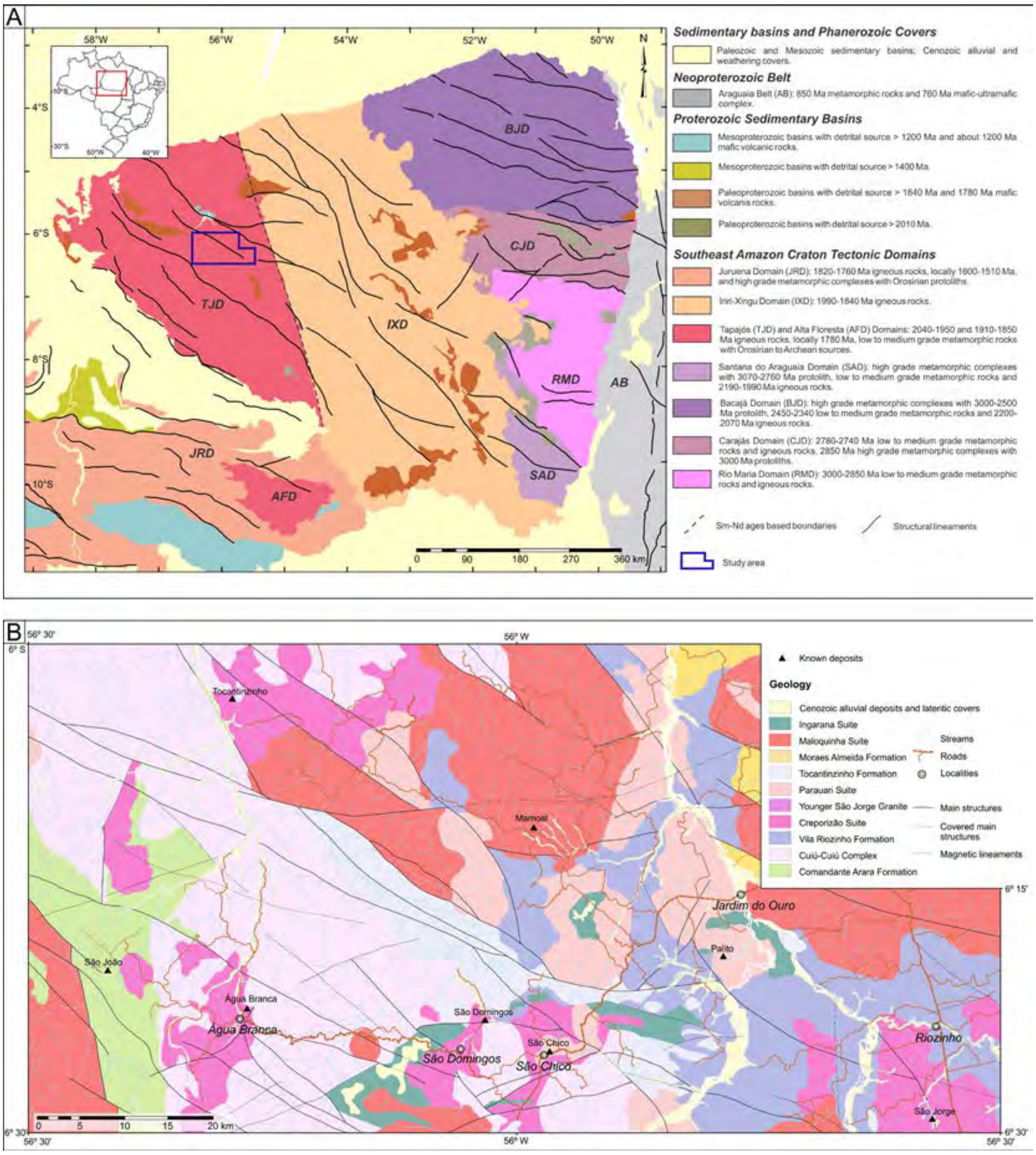


Figure 10 | A) Tectonic domain of southeastern Amazonian Craton and location of the study area; B) Geological map of the study area (after Vasquez et al. 2017).

Other resources include diamond, copper and tin. The main gold deposits are concentrated in the central-eastern part, and oriented along the WNW-ESE Tocantinzinho Trend. This structural corridor marks a strong control of the mineralization by brittle shear zones. We present here the results of a favorability study for intrusion-related (IR) gold in this portion of the TMP, applying the mineral systems approach to exploration targeting techniques.

GEOLOGICAL AND TECTONIC SETTING

The TGP represents an Orosirian accretion to an Archean crust (Carajás Province) that was partially reworked and provided a source for the rocks of this province (SANTOS et al. 2004; LAMARÃO et al. 2005; VASQUEZ et al. 2017).

The following Orosirian volcanic-plutonic and sedimentary events can be distinguished in TGP: (1) 2050-2000 Ma - Deposition of a foreland basin (Castelo dos Sonhos Formation) in eastern part and a forearc basin (Jacareacanga Group) in western part, emplacement of calc-alkaline granitoids (Cuiú-Cuiú Complex) and extrusion of their correspondent volcanic rocks (Comandante Arara Formation); (2) 2000-1950 Ma - Extrusion of high-K calc-alkaline to shoshonitic felsic volcanic rocks (Vila Riozinho Formation) and emplacement of high-K calc-alkaline granites (Creporizão Suite and Older São Jorge Granite); (3) 1900-1850Ma - Emplacement of calc-alkaline granitoids (Tropas Suite), sedimentation of arc basins (Abacaxis, Sequeiro, and Buiuçu Formations), emplacement of high-K calc-alkaline granites (Parauari Suite and Younger São Jorge Granite) and gabbros (Ingarana Suite), extrusion of high-K calc-alkaline felsic (Salustiano Formation) and mafic (Bom Jardim Formation) volcanic rocks and deposition of volcaniclastic rocks (Aruri, Tocantinzinho, and Novo Progresso Formations), emplacement of alkaline (A2-type) granites (Maloquinha Suite) and extrusion of their correspondent volcanic rocks (Moraes Almeida Formation) and formation of continental rift basins (Coatá Formation). The emplacement of dacite, andesite, and lamprophyre (spessartite and vogesite) dikes represent the latest pulses of high-K calc-alkaline magmatism.

These Orosirian events (except the deposition of Castelo dos Sonhos Formation) are related to magmatic arcs accreted to a continental margin: 2050-2000 Ma events to the Cuiú-Cuiú magmatic arc (CMA) and 1900-1850 Ma events to Tropas magmatic arc (TMA). There is controversy about whether 2000-1950 Ma events represent other magmatic arcs (SANTOS et al., 2004), late igneous pulses of CMA (LAMARÃO et al., 2002) or transcurrent post-collisional magmatism (VASQUEZ et al., 2002). Another controversy is about whether late high-K calc-alkaline suites and volcanic formations represent younger magmatic arc (SANTOS et al. 2004) or late stage of the TMA (VASQUEZ et al., 2017).

Three deformation events are recognized in the TMP (KLEIN et al., 2002), which affected the rocks and provided conditions to concentration, transport and deposition of gold. The Jacareacanga Group and Cuiú-Cuiú Complex rocks from southwestern PGT were affected by ductile to ductile-brittle deformation (D1), recognized through subvertical NNW-SSE faults and shear zones. The second event (D2) of ca. 1960 Ma affected the oldest rocks of PGT and controlled the emplacement of the granites of the Creporizão Suite, through transcurrent brittle-ductile shear zones of NW-SE and NNW-SSE directions, resulting from a progressive compressive event of E-W direction. A third event (D3) corresponds to subhorizontal ductile-brittle shear zones oriented to N-S that controlled the emplacement of tonalites of the Tropas Suite at ca. 1900 Ma. The progressive deformation resulted in the change to NW-SE and WNW-ESE brittle transcurrent shear zones that controlled the emplacement of granites of the Parauari Suite and gabbros of the Ingarana Suite at ca. 1880 Ma. A younger extensional brittle event marks of E-W fault systems that controlled the formation of sedimentary basin of the Coatá Formation at ca. 1850 Ma.

CHARACTERISTICS OF THE GOLD DEPOSITS

Primary (hypogene) gold has been explored in PGT since the 1990 decade. In the study area there are well known deposits such as Palito, Tocantinzinho and São Jorge and other deposits that need more research (Água Branca, Mamoal, São Chico, São Domingos and São João). These eight depositss were selected as training sites to test the favorability model.

The main style of mineralization comprises quartz veins, with secondary stockwork and dissemination, and the three styles may occur in the same deposit (e.g. São Jorge). The gold is associated with sulfides, mainly pyrite and chalcopyrite, and some sphalerite, galena, and pyrrhotite. The deposits have hydrothermal halos of variable influence, being the major part of the deposits surrounded by a sericitic envelope. The orebodies occur mainly in structures such as shear zones and have a strong spatial correlation with the emplacement of mafic dikes along these structures in contact zones. There were two mineralization episodes in TMP, one at ca.1960 Ma and other at ca. 1860 Ma (LAFON; COUTINHO, 2008). In the study area, the younger event is present in the São Chico deposit (VASQUEZ et al., 2017), but probably is also present in other important deposit sites (e.g. Palito).

FAVORABILITY CRITERIA FOR IR-GOLD MINERALIZATION

The mineral system approach (WYBORN et al., 1994; CZARNOTA et al., 2010) looks for broad similarities between deposits, considering the fundamental physical and chemical processes involved in the formation of mineral deposits. In this sense, several relevant factors were defined regarding the ore source, transport, trapping and deposition in an IR gold system. The main source data for this work was obtained from CPRM's project São Domingos-Jardim do Ouro (VASQUEZ et al., 2017), and the modeling was performed in a GIS environment, in the ArcGIS software platform, using the Spatial Analyst extension and the ArcSDM tools.

The selected data were processed, rasterized and classified, concerning their importance in the mineral system, each one resulting in an evidence map. They were grouped and combined to represent each ore-forming process, producing intermediate maps. Furthermore, the intermediate maps were combined to generate the mineral system model (Figure 11). All evidential maps were generated by the use of fuzzy memberships, and the intermediate maps and the model were generated and combined using the fuzzy operators, following the criteria presented in Table 3. This technique has the advantage of resulting in a continuous range of possibilities, allowing a gradual approximation of the exact solution and going beyond the Boolean logic of only favorable or not favorable responses.

The evidence maps for the IR-gold system were: favorable host rocks (major potential to Younger São Jorge Granite, Parauari and Creporizão Suites), intrusive contacts (from the most favorable host granitoids and intrusions related to the 1900-1850 event), NW-SE and NE-SW shear zones (extracted from magnetic, gammaspectrometry, imagery and field data), lineaments density (automatically extracted from digital elevation model), mafic dikes proximity (occurrences of mafic dikes of lamprophyres and andesites, closely related to mineralization), proximity to intersections between E-W and NW-SE structures, gammaspectrometry anomalies to highlight intense hydrothermal alteration zones, mainly potassic and sericitic zones (F parameter, anomalous potassium and Th/K ratio), magnetic anomalies based on deposits signature and geochemical signature from stream sediment analysis (Au, Ag-Sn-Mn, and Mo-Bi).

The integration of the four intermediate maps that represent the four key mineral system components (energy/source, migration, trap and deposition/outflow) resulted in a favorability map for IR-gold in the central-eastern part of TGP, where the highest favorability values (over 80%) are concentrated in 2% of the total area, significantly reducing the indicated areas. 62.5% of known deposits were mapped in areas of favorability values over 60%, attesting the good correlation between favorable values and the training sites. Furthermore, the model was tested in comparison with known gold deposits using Receiver Operating Characteristics (ROC) and the Area Under the Curve (AUC) graphs (Figure 12). The results of validation showed an accuracy of 95% and a confidence interval of 0.797-0.969. The results demonstrated the usefulness of fuzzy modeling in mineral exploration.

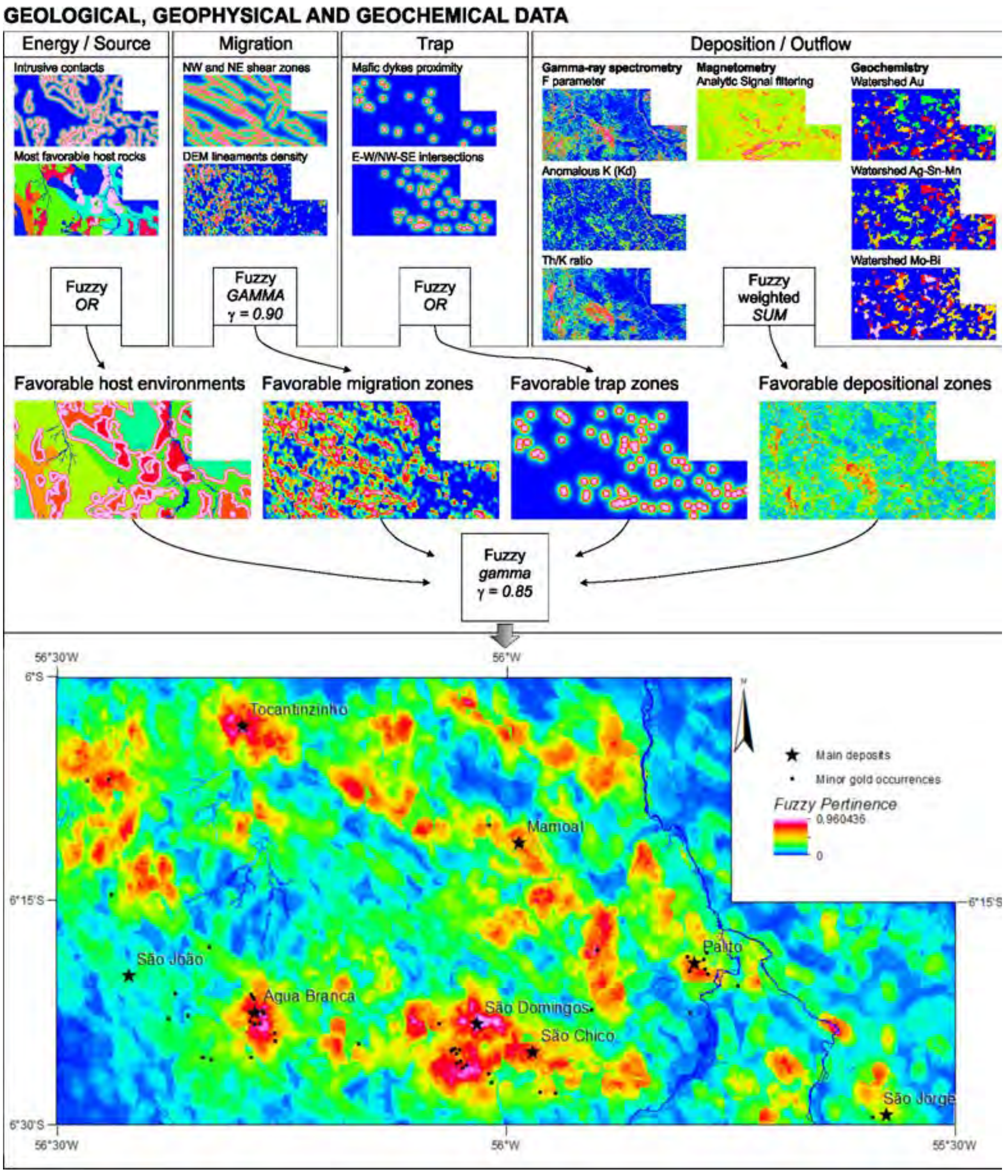


Figure 11 | Intrusion Related-gold system modelling flowchart for the study area.

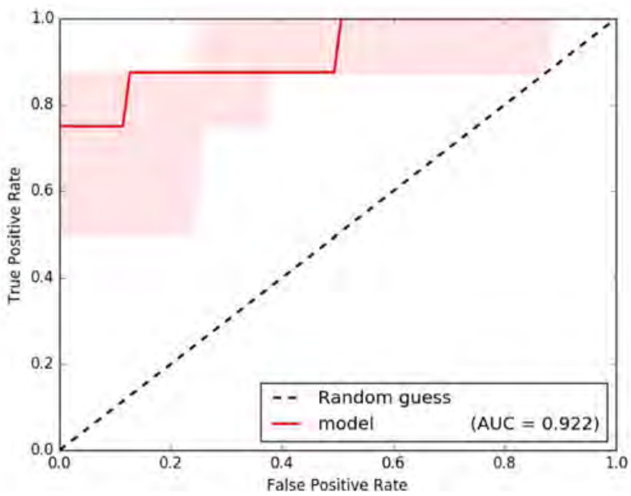


Figure 12 | The ROC (Receiver Operating Characteristics) curve and AUC (Area Under the Curve) show that the model of favorable areas is distant of randomic choices, attesting its effectiveness to predict

		EVIDENTIAL MAP	CRITERIA	FUZZY MEMBERSHIP	FUZZY OVERLAY
KEY MINERAL SYSTEM COMPONENT	ENERGY / SOURCE	Intrusive Contacts	proximity to intrusive bodies contacts. Euclidean distance	Small; Distances < 1000 m	OR; to highlight the maximum of each input evidence.
		Most favorable host rocks	classified data, according to the frequency of occurrences and geochemical signature	Categorical	
	MIGRATION	NW and NE shear zones	proximity to shear zones of the main structural control of deposits. Euclidean distance	Small; Distances < 1000 m	GAMMA, index 0.90; the combination of both is more relevant than individuals
		DEM lineaments density	density of lineaments automatically extracted from Digital Elevation Model (DEM). Line density	Large; Densities > 1	
	TRAP	Mafic dykes proximity	proximity to pontual occurrences of mafic dykes outcrops. Euclidean distance.	Small; Distances < 2000 m	OR; to highlight the equal importance of input evidences.
		E-W/NW-SE intersections	proximity to intersections of E-W/ NW-SE lineaments interpreted from first derivative of Anomalous Magnetic Field. Euclidean distance.	Small; Distances < 2000 m	
	DEPOSITION / OUTFLOW	F parameter	statistical classification of K, Th and U values. Saunders et al. (1987) and Pires (1995) method to highlight geochemical signatures of hydrothermal alteration	Large; values > average + 1 standard deviation	Weighted SUM; each evidence map has an attributed weight into the SUM: F parameter - 0,20 Anomalous K - 0,20 Th/K ratio - 0,20 Magnetic anomalies - 0,14 Watershed Au anomalies - 0,10 Watershed Ag-Sn-Mn anomalies - 0,09 Watershed Mo-Bi anomalies - 0,07
		Anomalous K		MSlarge; values > average + 2x standard deviation	
		Th/K ratio		Small; values < average - ¾ standard deviation	
		Magnetic anomalies	highlighted magnetic anomalies extracted from Analytic signal of magnetic data	Gaussian; values centered in 0,5	
		Stream sediment Au anomalies	multivariate statistical analysis using factor analysis in stream sediment data for gold and important gold pathfinder elements	Categorical	
		Stream sediment Ag-Sn-Mn anomalies		Categorical	
		Stream sediment Mo-Bi anomalies		Categorical	

Table 3 | Criteria for evidence maps in each key mineral system component.

FAVORABILITY MAP

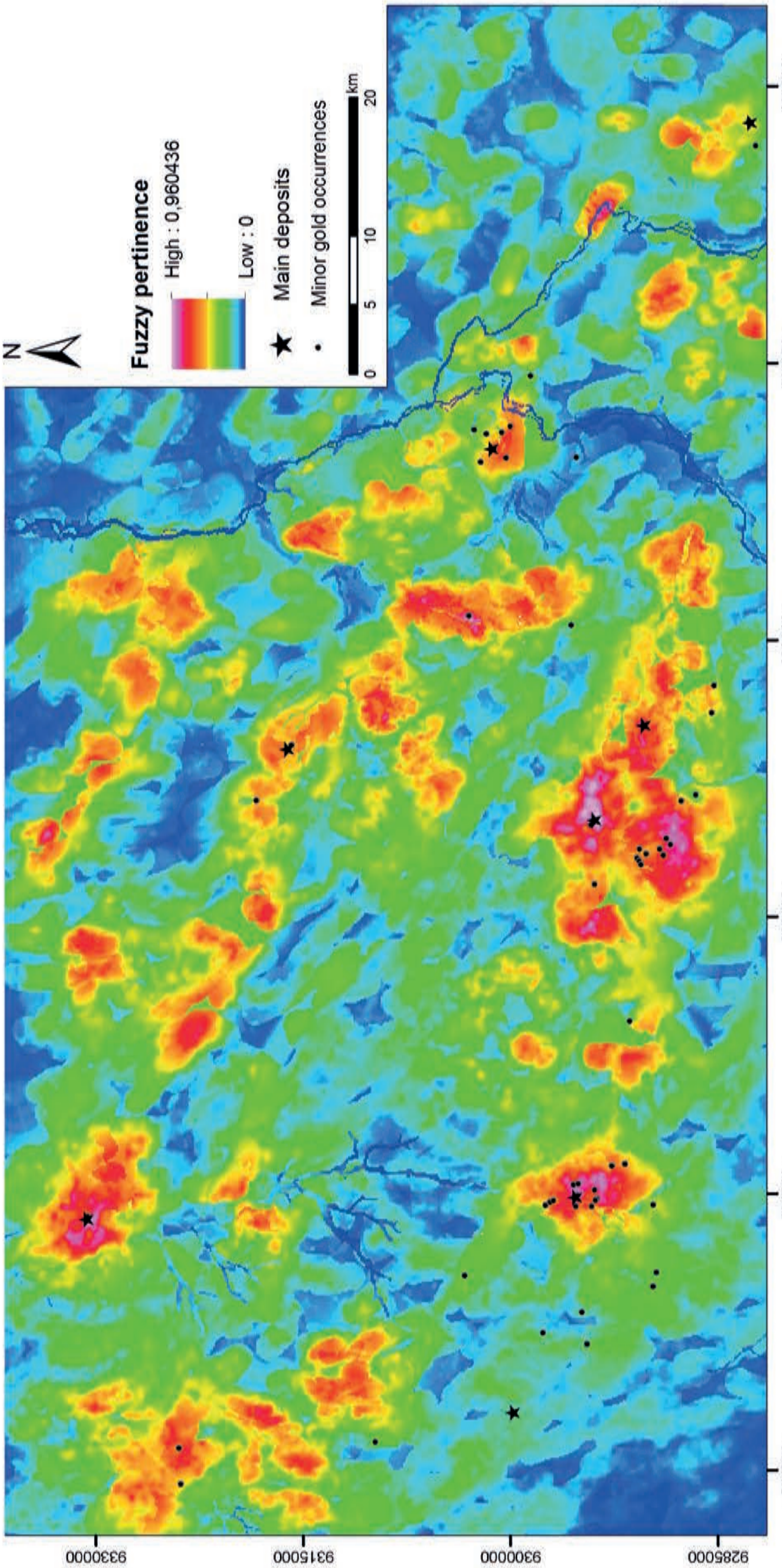


Figure 13 | Intrusion-Related Gold Favorability Map in the Eastern Tocantinzinho Trend, Tapajós Mineral Province, Amazonian Craton

EVIDENCE MAPS

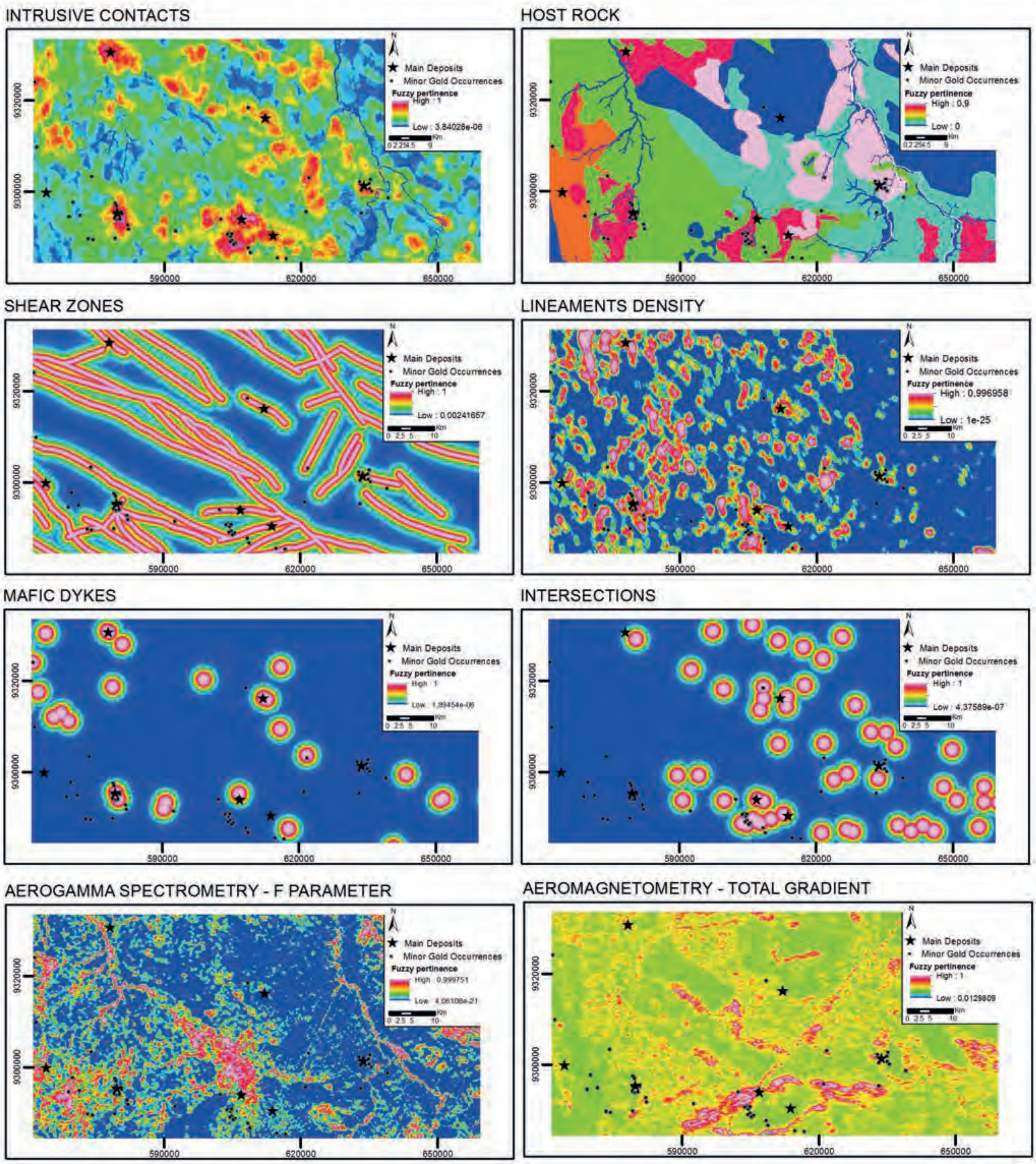


Figure 14 | Evidence Maps of the Intrusion-Related Gold Favorability in the Eastern Tocantinzinho Trend, Tapajós Mineral Province, Amazonian Craton

GOLD FAVORABILITY AT JUMA GOLD DISTRICT, SOUTHEAST AMAZONAS STATE

Raul Eigenheer Meloni, Matheus Silva Simões, Michele Zorzetti Pitarello

Figure 15 | Study Area Location.

INTRODUCTION

Since the occupation of the southeast part of Amazonas State, in the 1970s, a modest gold production on artisanal mines (garimpos) has been going on in this region. In 2007, a gold rush occurred there, attracting thousands of people driven by the discovery of high-grade superficial deposits at the Eldorado do Jumagarimpo, where it has been estimated that around 2~10 tons of gold were extracted by rudimentary means, in a short period of time. This region, known as Juma Gold District (Figure 15), is localized in the geological context of the JuruenaOrogen (DUARTE et al., 2019; SOUZA et al., 2005), which is inserted in the Rondônia-Juruena geochronological province) of the Amazon craton (SANTOS et al., 2000). The extension of this orogen to the south, in the northern part of Mato Grosso State, hosts the well-known Alta Floresta-Juruena Gold Province. Despite its potential for gold, indicated by the presence of numerous gold occurrences and the favorable geological context, mineral exploration activities in the Juma Gold District are still scarce.

In order to provide a better geological knowledge base for future investments in the area, the Geological Survey of Brazil (CPRM) has developed geological, geophysical and geochemical data integration in the Juma Gold District. Thus, we present here a synthesis of the current knowledge about the metallogeny of gold in the area, and the results of the favorability mapping using the mineral systems approach applied to exploration targeting techniques.

TECTONOSTRATIGRAPHIC FRAMEWORK

The Juma Gold District is located near the boundary of two geochronological domains of the southern Amazon craton: the Tapajós (2.10-1.88 Ga), and Juruena (1.82-1.53 Ga) domains (SANTOS, 2003).

The oldest rocks exposed in the Juma Gold District are low-grade metagreywackes attributed to the Abacaxis Formation (SANTOS et al., 2000), which are intruded by the Chuim Granite (1.85 Ga). The latter, together with the Arraia Granite (1.84 Ga), are thought to represent transitional magmatic events between the final evolution of the Tapajós Domain and the installation of the JuruenaOrogen, of which the Colíder Group (1.82-1.78 Ga) is the first litho-stratigraphic unit in the area, where it is composed mainly of quartz-rich rhyolitic pyroclastic rocks. In the Statherian, a rift basin is believed to have begun opening in the area, accompanied by predominantly felsic bimodal volcanism. The Pedro Sara Formation (1.76-1.74 Ga) represents most of the felsic component of this volcanism, which is composed mainly of quartz-poor rhyolitic pyroclastic rocks. Partially intercalated, the Camaiú (<1.75 Ga) and the Vila do Carmo (>1.57 Ga) formations represent, respectively, alluvial fans and deltaic sediments, with a few beds of felsic pyroclastic rocks. Some basaltic flows and sills are present in the Camaiúformation, which display the mafic component of the bimodal volcanism. In the Calymmian, a widespread mafic magmatism occurred in area, represented mainly by large exposures of tholeiitic olivine-gabbro sills of the Mata-Matá Suite (1.57-1.53 Ga; OLIVEIRA; LIRA, 2019; ALMEIDA; COSTA, 2016). This mafic magmatism is considered to be associated with A-type rapakivi granites of the Serra da Providência Suite (1.53-1.51 Ga), and felsic volcanic rocks of the Gavião Group (1.53-1.50 Ga), both of which have been described a few tens of kilometers away from the Juma Gold District (OLIVEIRA; LIRA, 2019; ALMEIDA; COSTA, 2016). Together, these three units define a stage of anorogenic, intracontinental bimodal magmatism in the region. During the Mesoproterozoic and Neoproterozoic eras, continental sedimentary sequences of the Prainha (~1.41 Ga) and Sucunduri Formations covered parts of the study area, and currently are preserved in sites believed to be paleo structural lows. Sedimentary sequences deposited in the context of the Paleozoic Alta Tapajós Basin are locally present in the area, represented by the Silurian-Devonian Juma Formation, which is composed of the lower Borrachudo Member, and the upper São Benedito Member. The lower unit is composed mainly of carbonaceous mudstone and fine sandstones, and the upper unit is composed mainly of siltstones and fine to medium sandstones enriched with phosphatic minerals. Jurassic quartz-arenites of the Rio das Pombas Formation locally cover older rocks at higher elevations.

STRUCTURAL EVOLUTION

For the most part, the rocks in the Juma Gold District show very little to no metamorphic effects, and deformation is mainly in the brittle regime, controlled by normal faults. Where present, metamorphism is of low-grade and restricted to the vicinities of regional structures. Locally, some thin-skinned tectonic folding is present in the volcano-sedimentary sequences.

The oldest deformation event preserved on the area, registered as slaty cleavage, is observable only in a restricted part of the study area, where the metagreywackes of the Abacaxis Formation occur. This deformation is considered to be related with later compressive events of the Tapajós Domain (> ~1.85 Ga), with a N-S structural trend.

The extensional tectonics associated with the rift system installed in the Statherian (<1.75 Ga) was controlled by normal and transtensional faults, with main directions NE-SW and NW-SE, but also reactivated older N-S structures from the basement. Synchronous volcanism during this event produced widespread hydrothermal alteration at shallow crustal level.

At around 1.55 Ga, voluminous mafic magmatism of the Mata-matá Suite was associated with extensional reactivation of older structures, which functioned as preferential pathways to the emplacement of the mafic intrusions of the Mata-matá Suite. At ~1.50 Ga the Juma District suffered distal effects from the QuatroCachoeiras Orogeny (OLIVEIRA; LIRA, 2019), with main compression in the NE-SW direction, locally producing thin skinned deformation on the volcano-sedimentary sequences of the Camaiú and Vila do Carmo formations, and low-grade metamorphism focused on reactivated older large-scale structures.

At around 1.30 Ga, distal effects of the SunsásOrogen affected the area in the form of strike-slip faulting (OLIVEIRA; LIRA, 2019), although it is not yet clear how much it has affected The Juma Gold District.

Normal faulting is believed to have occurred in the Paleozoic as the Alto Tapajós Basin formed. These faults, many of which are probably reactivated proterozoic structures, may have been active until the Cretaceus, placing Paleoproterozoic and Fanerozoic rocks side by side.

GEOLOGY AND METALLOGENESIS OF GOLD OCCURENCES

Although current knowledge about the mineral system responsible for the formation of the gold mineralization of the Juma District is still in a reconnaissance stage, recent works developed by the SGB/CPRM showed that many of them are associated with geological characteristics similar to those found on classic low sulfidation epithermal systems, as defined by Sillitoe&Hedenquist (2003). For example, many of the mineralization are associated with centimeter- to meter-size quartz veins and breccias, which may show drusiform, microcrystalline, comb, and lattice-bladed textures. These textures indicate that these hydrothermal deposits formed in a frankly extensional, epizonal, structural setting. Hydrothermal alteration mineral assemblages include sericite, illite, calcite, florencite and quartz veinlets with adularia. Sulfides are the most probable ore minerals, although their presence is only inferred through relicts such as limonite masses and boxwork textures on quartz veins, due to all of the current known exposures being strongly oxidized.

The Statherian volcano-sedimentary sequence of the Pedro Sara, Camaiú and Vila do Carmo formations host most of the mineralization, although all of the older units also host at least some gold occurrence. Frequently, the mineralization occurs near the contact with mafic intrusions, which may also host mineralization. It is not yet clear the age of these mafic intrusions, but many of them are considered likely to belong to the Calymmian Mata-Matá Suite.

Many of the mineralizations are spatially associated with, and locally hosted in, regional NE- and NW-trending ductile to brittle faults which are thought to have formed in the Statherian, and been reactivated in later events.

Based on the age of the host rocks of the mineralizations, and their characteristics, two events are most probably responsible for their generation:

a) In the Statherian (1.75 Ga), shallow hydrothermal systems associated with bimodal sub-aerial to shallow sub-aqueous volcanism formed in the context of a rift basin during the later stages in the evolution of the JuruenaOrogen. This geotectonic context can be considered favorable for the formation of low-sulfidation epithermal gold deposits according to the classification of Sillitoe&Hedenquist (2003). This interpretation is also supported by a close spatial relationship between the gold occurrences and the Pedro Sara, Vila do Carmo and Camaiú formations. On the other hand, this event cannot explain the presence of mineralizations in gabbros of the younger Mata-Matá Suite;

b) In the Calymmian (~1.55 Ga), the extensive plume-related mafic magmatism might have provided the heat motor and the source of precious metal for the formation of the mineralizations. The crustal intumescence provoked by the placing of a mantle plume can have produced a reopening of older structures, promoting pathways for the formation of shallow hydrothermal systems.

Since with our current knowledge it is not yet possible to determine the exact timing of the mineralizations, the prospectivity model was build taking both hypotheses into consideration.

PROSPECTIVITY CRITERIA FOR AU MINERALIZATION

The prospectivity criteria used for the modelling were defined based on the four critical factors for the generation of ore deposits, according to the Mineral Systems approach (MCCUAIG; HRONSKY, 2014): whole lithosphere architecture, transient favorable geodynamics, fertility, and preservation of the primary depositional zone.

Fertility

Isotopic Sm-Nd data of Statherian volcanic rocks in the study area show model ages between 2,2 - 2,9 G, and detrital zircon U-Pb age determinations from Statherian sandstones frequently show Archean populations (BRITO et al., 2010). These data suggest that there might exist an Archean basement in the area, that could be eroding by the time the mineralizations formed. Although speculatively, we infer that the presence of an Archean basement, possibly tectonically reworked in the Paleoproterozoic, was an important fertility factor in the area since, in general, terrains of this age are highly prospective for gold in the Amazon Craton (e.g. Rio Maria Domain; Carajás Mineral Province). The vectorization of these elements was done through a reclassified lithological map of the district.

Transient favorable geodynamics

A superimposed rifting over an orogenic system is recognized as favorable for the generation of low sulfidation epithermal deposits, especially when associated with bimodal magmatism (HRONSKY et al., 2012). This geodynamic moment was represented in the model by a reclassified lithological map. In this geodynamic setting, ore can be deposited from shallow convective hydrothermal systems. To map zones where the hydrothermal alteration may have occurred more intensely, the following 6 evidential maps were generated:

a) three maps based on geochemical anomaly in soil of As, Ba and Ag;

b) two maps based on gold and florencite grains in stream sediment pan concentrates.

c) one map representing zones of high K radiometric signal from airborne gamma-spectrometric data.

Whole lithosphere architecture

The importance of regional geological structures that extend to the basement on the control of the distribution of hydrothermal mineralizations has been widely recognized (e.g. MCCUAIG; HRONSKY,2014). For the prospectivity model, one evidential map representing these structures was done through the interpretation of airborne magnetometry and satellite gravity data. A buffer of 3 km was drawn around the delimited structures.

Normal and transtensional faults related to rift opening, function as important conditioning factors for the dynamics of the potentially mineralizing hydrothermal fluids.in this setting, by actively creating and impeding rock permeability (ROWLAND; SIBSON,2004). To represent these prospective elements on the model, a structural map was made based on field data and interpretation of magnetometry images. From this map, the structures interpreted as being related to the rift moment, were used for the creation of three evidential maps, representing the following:

a) distance from the center of faults, with descending prospectivity score from 0 until 750 m;

b) spatial density of structures;

c) spatial density of intersections between deep structures and rift related faults.

Preservation

The preservation of epithermal mineralizations on Proterozoic terrains is rare, in great part due to their formation near the surface (<1500 m in depth). Nevertheless, several cases have been reported on the Amazon Craton (e.g.JULIANI et al., 2005). Some factors that may have contributed to their preservation on the Juma Gold District is their formation on the context of a rift basin with active sediment deposition, followed by rapid burial, and the tectonic stability after the formation of the deposits.

CRITICAL FACTORS		VECTORS	EVIDENTIAL MAPS	SCORES	WEIGHS	OBSERVATIONS
WHOLE LITHOSPHERE ARCHITECTURE		Deep structures	3 km buffer	4	5	Structures interpreted from airborne magnetometry and satellite gravity
		Rift structures	750 m buffer	6 - 4	5	Euclidian distance
			Spatial density of structures	7 - 5	5	Kernel density
			Spatial density of intersections with deep structures	7 - 5	5	Kernel density
TRANSIENT FAVORABLE GEODYNAMICS		Geochemical anomaly in soilv	Ag	7 - 5	5	IDW interpolation. ~1/3 area coverage.
			Ba	6 - 3	5	
			As	5 - 3	5	
		Pan concentrate in stream sediment	Gold grains	6 - 2	5	Catchment basins. ~1/2 area coverage
			Florencite grains	6 - 2	5	
		K metasomatism	Radiometric K anomalies	6	4	Extracted from airborne gamma-spectrometry
	FERTILITY	Geological units	Lithological map	8 - 0	4	1:100.000 geological map

Table 4 | Criteria for evidence maps in each key mineral system component for Juma area.

FAVORABILITY MAP

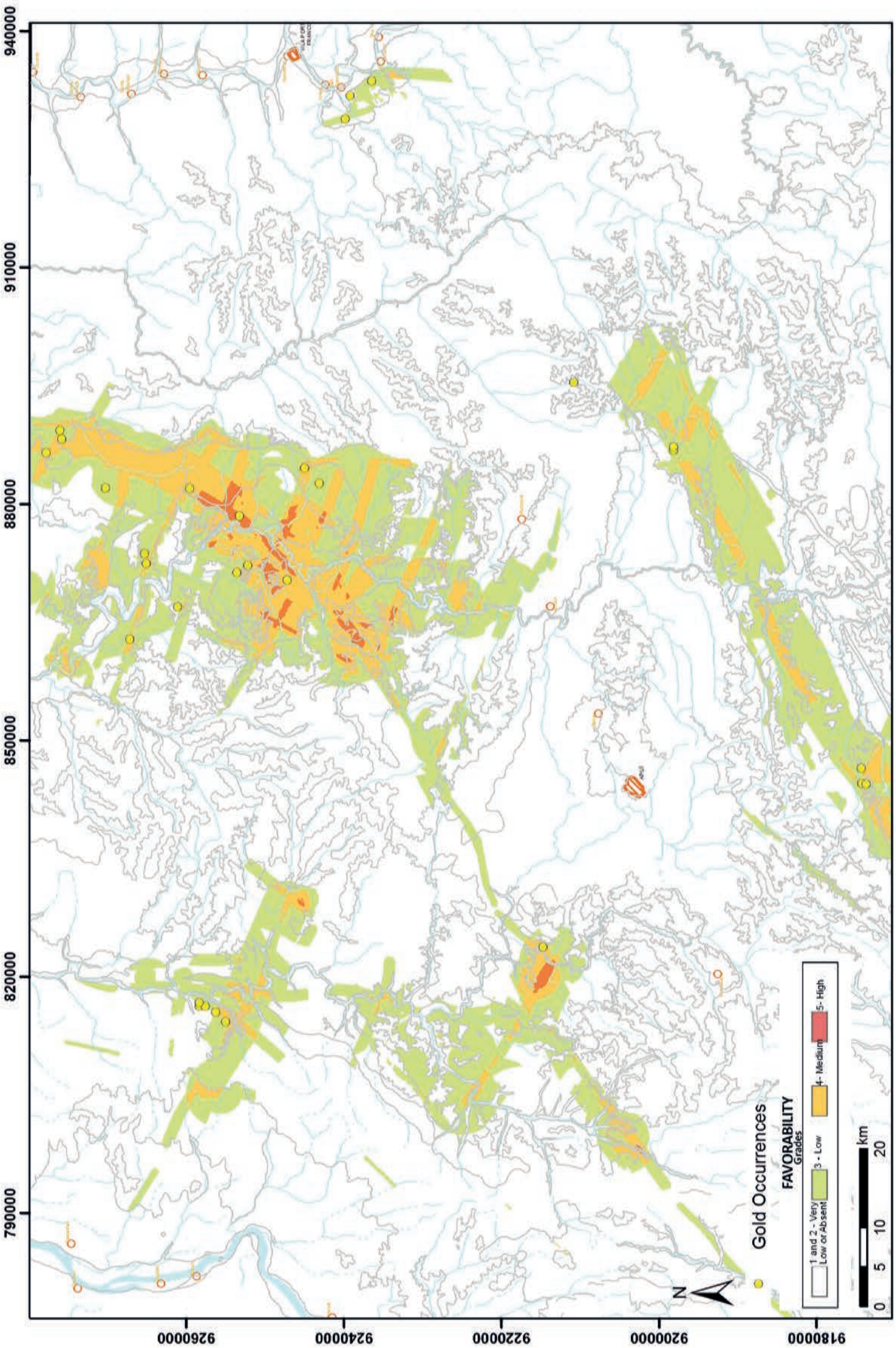
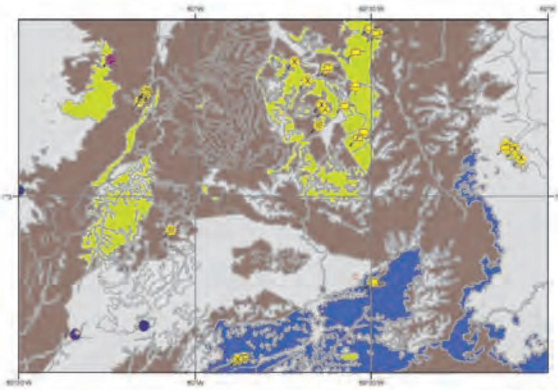


Figure 16 | Gold Favorability Map in the Juma Gold District, Southeast Amazonas State

EVIDENCE MAPS

A - LITHOLOGY



Geological Boundary

Grades

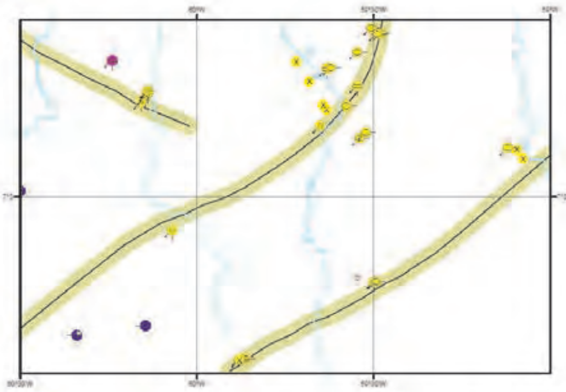
0 -Phanerozoic Sedimentary Cover

5 -Beneficente Gr./Matá-Matá Suite

6 -Colider Gr.

8 - Volcanic Unit/ Igarape das Lontras Suite/Orosinian Granite, Abacaxis Fm.

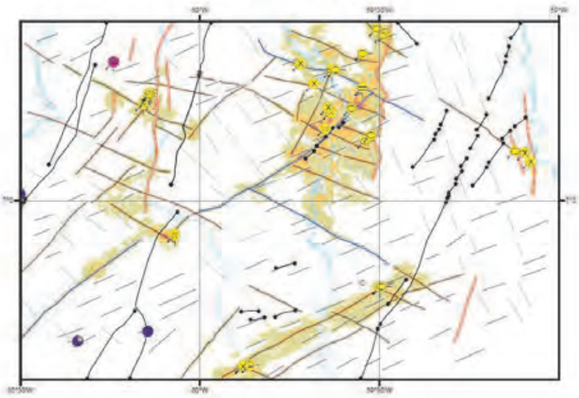
B - DEEP STRUCTURES



4 - Influence Zone

Structures Deeper than ~4km

C - STRUCTURAL LINEAMENTS FROM AERO-MAGNETOMETRY DATA



Inherited basement structures (Dn-2)

Extensional Structures (Dn-1)

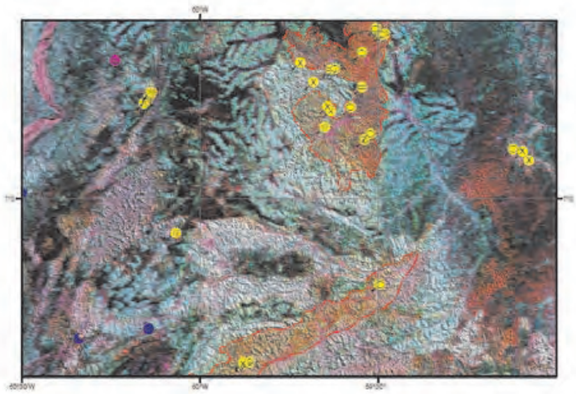
Reactivated structures in ductile-brittle regime (Dn)

Structures related to Sunsas Event (Dn+1)

Brittle Structures (Dn+2)

Magnetic Dikes

D - AERO-GAMMA SPECTROMETRY - TERNARY COMPOSITION AT TDM



6 - Radiometric Anomaly (Potassium)

TDM - SRTM

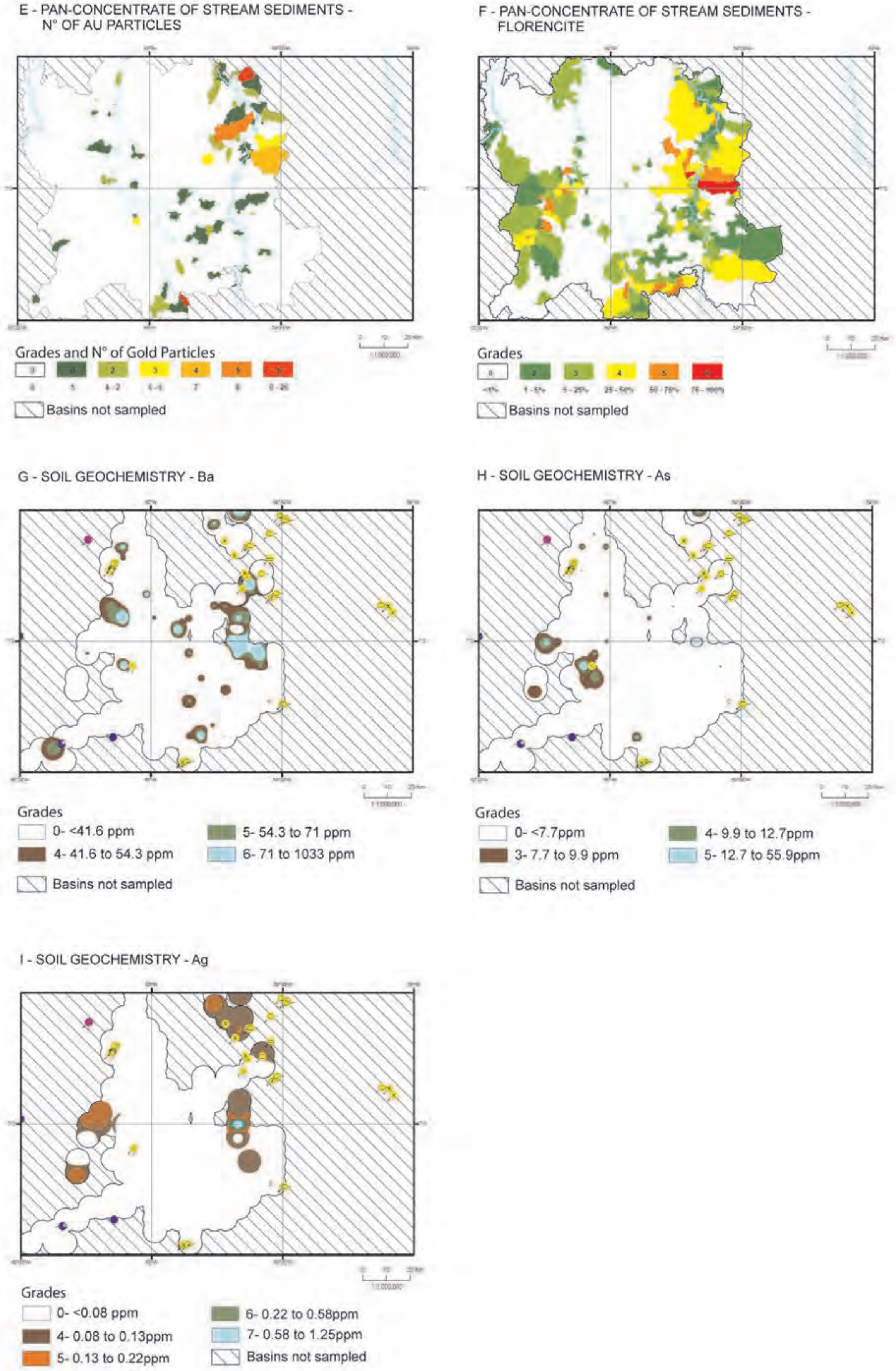


Figure 17 | Evidence maps of the Gold Favorability in the Juma Gold District, Southeast Amazonas State

ZINC-LEAD-COPPER-GOLD FAVORABILITY IN THE NOVA BRASILÂNDIA DISTRICT, SUNSÁS PROVINCE, AMAZONIAN CRATON

Gustavo Negrello Bergami, Guilherme Ferreira da Silva

INTRODUCTION

The Nova Brasilândia District is located in north-western Brazil and presents a series of occurrences of zinc, lead, copper and gold-rich gossans that define a possible polymetallic mineral district of BHT (Broken Hill Type) deposits. The region also displays minor occurrences of lode gold, manganese, magmatic phosphate, and sedimentary-hosted copper.

With the goal of assessing favorable targets to mineral exploration, the Geological Survey of Brazil (CPRM) has developed geological, geophysical and geochemical data integration in the host unit of the BHT mineralization, the Migrantinópolis Formation, of the Nova Brasilândia Group. Therefore, the results of the favorability mapping allied to a mineral systems approach are presented here.

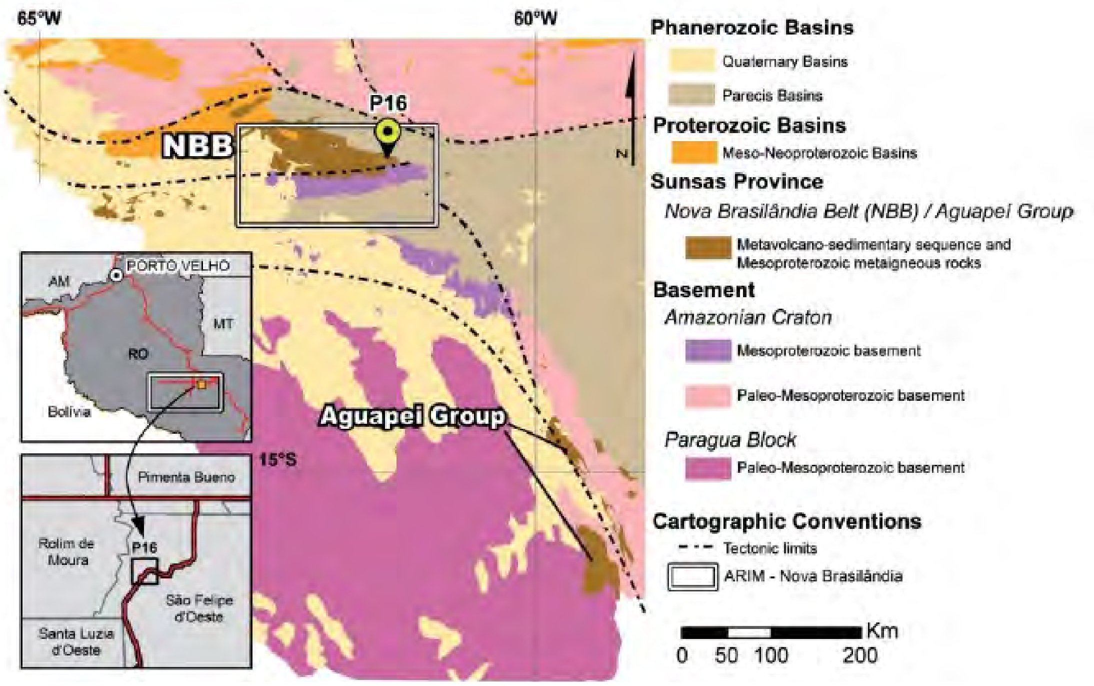


Figure 18 | Southwestern Amazonian Craton simplified map, showing the approximated limits of the main geochronological provinces, mobile belts and tectonic elements. (PRADO et al., 2016).

TECTONOSTRATIGRAPHIC FRAMEWORK

The study area comprises five main periods of rock formation in its tectonostratigraphic evolution. The first is Paleoproterozoic (Statherian; 1.76 Ga), followed by three periods in the Mesoproterozoic (Calymmian; 1.55 Ga and Stenian; 1.24 and 1.0 Ga) and one Neoproterozoic (900 Ma). The oldest rocks are tonalitic and granodioritic gneisses, as well as paragneisses and calc-silicate rocks related to an active margin continental arc. On the basement rocks, the peak metamorphism has been dated at 1.63 Ga and has reached metamorphic conditions of the granulite facies (SCANDOLARA, 2006). After that, at 1.55 Ga, anorogenic, A-type magmatism took place, with the generation of the Serra da Providência Suite. During the same period, another anorogenic suite and sedimentary rocks were being formed to the south of the area. These rocks were then metamorphosed at 1.46 Ga (RIZZOTTO et al., 2013) and 1.33 Ga, under high-amphibolite to granulite facies, giving origin to the São Felipe Complex, composed of A-type orthogneisses and paragneisses. Continental rifting took place at ca. 1.24 Ga and allowed the deposition of the Migrantinópolis Formation as well as the development of a proto-oceanic crust represented by the Rio Branco Formation. Late orogenic to anorogenic magmatism of A-type granites led to the generation of two suites, the Rio Pardo Suite (1.1 Ga) and the Costa Marques Suite (1.0-0.9 Ga), as well as the emplacement of a mafic-ultramafic suite of the same age of the latter, the Novo Mundo Suite. Synchronous sedimentation gave origin to two sedimentary sequences, the Terra Boa and Palmeiral formations. During the Neoproterozoic and the Phanerozoic, another sedimentary phase took place, giving origin to the rocks of the Parecis Basin, represented by glacial-marine sediments on its base (Pedra Redonda Formation; ADÔRNO et al., 2017), followed by shallow continental shelf sediments of the Fazenda da Casa Branca Formation, both of Neoproterozoic age, which are covered by continental sediments of the Parecis Group of Cretaceous age.

The ore host rocks were deformed under ductile to ductile-brittle high amphibolite, to the north, and up to granulite, to the south, metamorphism during the Sunsás Orogenic Cycle (1.11 – 1.0 Ga), a transpressional to compressional intra-continental orogeny. These rocks are limited by a transpressive shear zone with the Calymmian basement rocks to the south and are covered by the Neoproterozoic and Phanerozoic sedimentary rocks to the north. The main structural trend is WNW, with tectonic transport to the south, with steeply-dipping shear zones to the NW direction. There is also a pair of brittle extensional structures, in NW and ENE directions, related to the opening of the Neoproterozoic Basins (BERGAMI; PRADO, 2019).

GEOLOGY AND METALLOGENESIS OF THE ZINC-LEAD-COPPER-GOLD RESOURCES

Formed during a continental rift context, the BHT mineralization developed at two known stages:
a) in the Stenian (1.24 Ga), syngenetic Zn-Pb-Cu-Au volcanic-hosted massive sulfides (VHMS) deposits were formed through the reactivation of deep basement discontinuities as extensional faults during the deposition of the Migrantinópolis Formation;

b) also in the Stenian (1.1 Ga), during the deformation, metamorphism, and metasomatism of the sedimentary rocks and the VHMS deposits, the sulfides were reworked and recrystallized, leading to an increase of the metal grades.

The massive sulfide orebodies are located along major, northwest-trending structures, and are hosted by psammitic gneissic rocks at the transition between the pelitic and volcanic units and the psammitic units. There is an association of the mineralized rocks and the presence of gahnite and also garnet and sillimanite on stream concentrates, along with anomalous quantities of Pb, Zn, Cu, Fe, Ba, In and Sb in stream sediments, spatial correlation with quartz veins, lenses of calc-silicate rocks and amphibolites. The ore is composed mainly of sphalerite, galena, pyrite, pyrrhotite, quartz and calcite, shows breccia-like textures, veinlets, and disseminated textures on a metasedimentary rock, although the mineralization only appears as gossans on the surface. The occurrences display a positive magnetic response due to the presence of pyrrhotite, which seems to be the only magnetic mineral in the region.

PROSPECTIVITY CRITERIA FOR ZN-PB-CU-AU MINERALIZATION

Following a hybrid, data and knowledge-driven approach, important proxies for the mineralization were chosen, related to the ore formation, transport, and trapping and then related to features on map. The information was separated in lithostructural data, geodynamic data, and data related to the mineralizing fluid. This data is then rasterized and scored, giving origin to evidence maps, that are then given weights due to their degree of uncertainty and reliability of the original data. We used a GIS environment to generate the models (ESRI ArcGis - Spatial Analyst extension), and used a method based on multi-class overlaying, with the addition of the value of each class of evidence where an intersection of two or more predictive vectors happens.

For the BHT system at the Nova Brasilândia Belt, we used the following evidence maps: pan concentrates (average of the relative proportions of gahnite, sillimanite, and garnet; Figure 19), stream sediment signature (Pb, Zn, Cu, Fe, Ba, In and Sb; Figure 20), spatial distribution of mapped quartz veins (Figure 21), total magnetic gradient (Figure 22), lithotypes (gossans, paragneisses, schist, amphibolite, calc-silicate rocks, quartzite and granites from the Suite Rio Pardo; in this order of importance; Figure 23), and proximity to calc-silicate rocks and amphibolites (Figure 24).

Brittle and ductile structural lineaments (Figures 25 and 26) and deep structures (determined as lineaments with more continuity and greater magnetic field intensity; Figure 27), as well as high fertility terrains (the Nova Brasilândia Basin, separated through the Bouguer Anomaly map; Figure 28), were also used as proxies for the evidence maps.

The vectors generated were then weighted according to the data's level of confidence (Table 5) and accuracy and are combined to form a six-class favorability map for the Nova Brasilândia District. The highest prospectivity classes corresponded to 3.79% of the project area and encompassed 64% of the Zn-Pb-Cu-Au known occurrences, and that shows the good correlation between the favorable classes and mineralization. In sum, this cost-effective initiative defined new prospective areas, thus helping the development of the mineral exploration industry in Brazil.

Original maps can be assessed at http://rigeo.cprm.gov.br/jspui/handle/doc/20937

KNOWLEDGE AREA	MAP	WEIGHT	COMMENTARY
HYDROTHERMAL ALTERATION	Pan Concentrate	5	Well distributed grid, systematic mineralometric separation
	Stream Sediment	4	Well distributed grid, but dispersion level seems to depend on declivity variations
	Quartz Veins	3	Important marker, but non-systematized identification
	Total Magnetic Gradient	5	Systematic data with high sampling density; Association between the ore and pirrhotyte
LITHOSTRUCTURAL FRAMEWORK	Lithology	4	Detailed geological map (1:50,000) in the Nova Brasilândia Basin
	Brittle Structures	2	Interpreted from remote sensors; coherent with field data
	Ductile Structures	2	Interpreted from remote sensors; many confirmed on the field
	Calc-silicate and Amphibolite Lenses	1	Possible lateral marker or chemical trap
GEODYNAMIC	Deep Structures	2	Channeling of mineralized fluids; needs better characterization
	Fertility Domains	2	Separation between fertile and non-fertile domains; not well founded

Table 5 | Criteria for evidence maps in each key mineral system component for Nova Brasilandia area.

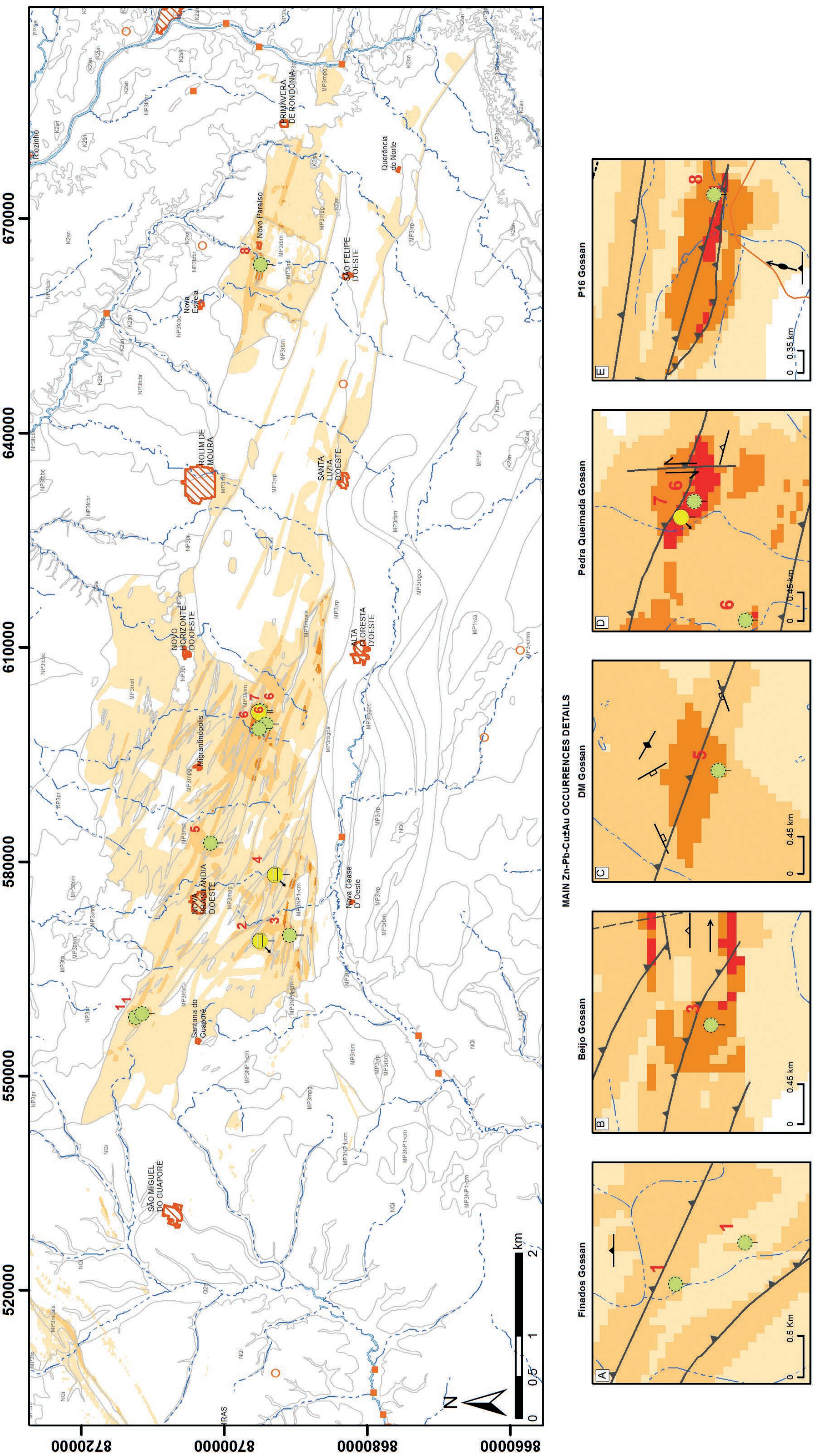


Figure 29 | Zinc-Lead-Copper-Gold Favorability Map in the Nova Brasilândia District, Sunsás Province, Amazonian Craton

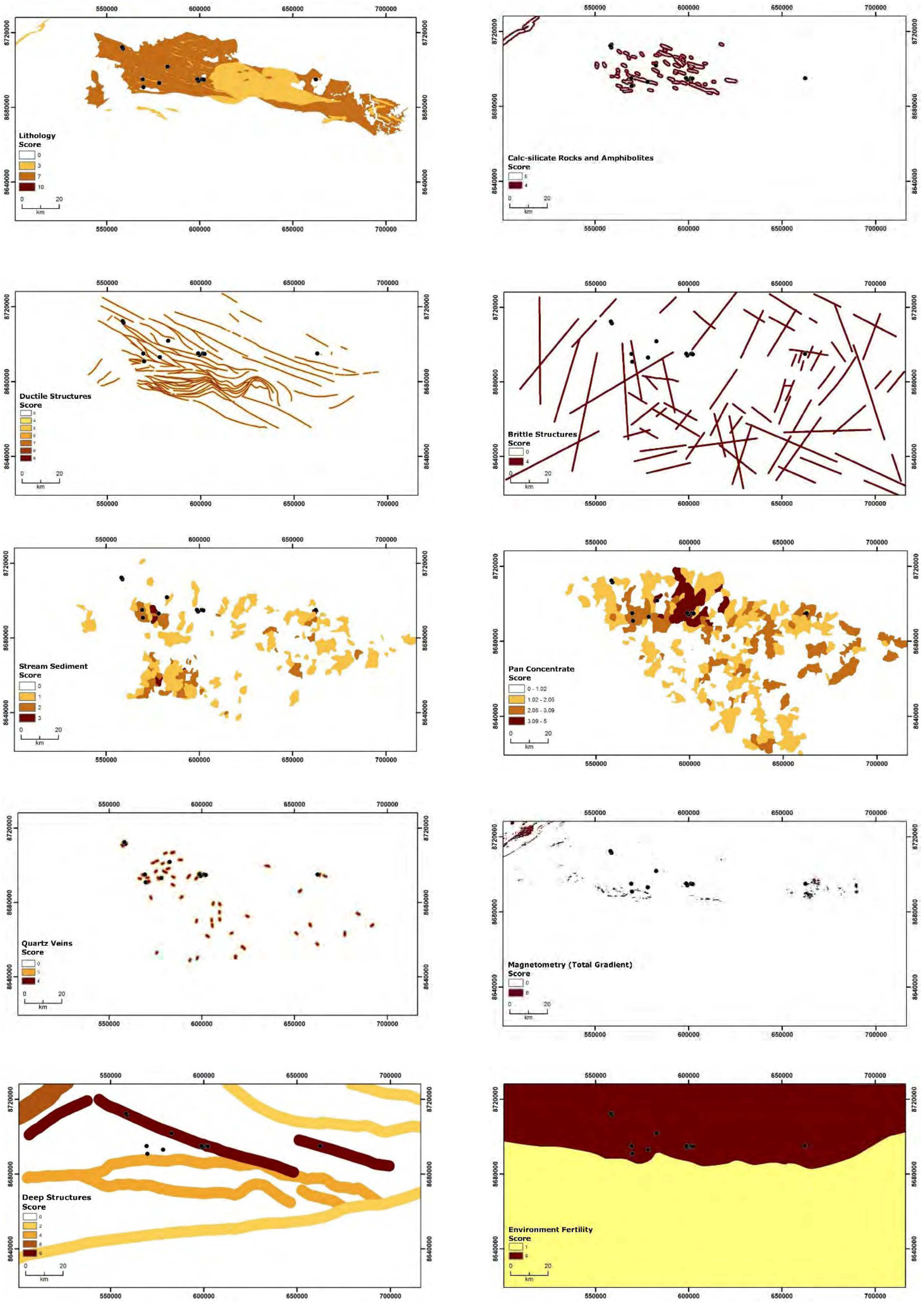


Figure 30 | Evidence Maps of the Zinc-Lead-Copper-Gold Favorability in the Nova Brasilândia District, Sunsás Province, Amazonian Craton.

PROSPECTIVITY MAPPING AND MINERAL SYSTEM ANALYSIS OF THE GURUPI BELT

Leandro Duarte Campos

INTRODUCTION

The Gurupi Belt is a mid-tier gold province located in northeastern Brazil, at the border of the Pará and the Maranhão states. Besides an estimated historical production of 16 tons of gold (KLEIN, 2014), the Gurupi Belt hosts c.a. 5 million ounces of gold resources divided into three known deposits: i) Cachoeira (1.35 Moz @ 1.4 g/t Au, MOSHER, 2013); ii) Chega Tudo (1.26 Moz @ 0.67 g/t Au, MACHADO, 2011); iii) Cipoeiro (2.42 Moz @ 0.87 g/t Au, MACHADO, 2011). Despite being a largely well-known district for artisanal gold production, poor access conditions, the lack of outcropping rocks due to intense weathering, and thick overburden, especially difficult direct exploration techniques and hinder new mineral discoveries. In this regard, I propose to use indirect methods of data survey such as airborne geophysics together with regional stream sediment geochemistry to build integrated maps of mineral prospectivity and generate new gold exploration targets.

In order to produce reliable predictive maps of mineral prospectivity I used the mineral system concept (MCCUAIG; HRONSKY, 2014 and references therein), which is based on the translation of strong geological fundamentals into a set of vector maps that are integrated to form a final exploration target map. The final target map used new geological, geophysical and geochemical database recently published by the Geological Survey of Brazil for the Gurupi Belt (CAMPOS et al., 2017).

TECTONOSTRATIGRAPHIC FRAMEWORK

The Gurupi Belt consists of sedimentary rocks, granites and low- to high-grade metamorphic rocks of varying ages ranging from 2695 Ma to 549 Ma (PALHETA et al., 2009; KLEIN et al., 2012; KLEIN et al., 2017 and references therein). These rock units mainly form NW-SE striking trends that follow the general tectonic orientations on the belt. Klein et al. (2017) grouped the lithostratigraphic units into various tectonic sections as follows. (1) Basement Complex – which comprises the Archean Igarapé Grande metatonalite (2695 ± 3 Ma). (2) Rhyacian plutonic assemblages – which consist of deformed granites, represented by the Itapeva Complex (2167 ± 3 Ma), the Cantão Granite (2163 ± 4 Ma), the Tromaí Suite (2165-2148 Ma) and the Muriá Amphibolite (2150 ± 8 Ma). (3) Rhyacian basins, represented by the volcano-sedimentary Chega Tudo Formation (2160-2148 Ma), and the siliciclastic Igarapé de Areia (<2078 Ma) and Santa Luzia do Pará Formation (ca. 2163 Ma) formations. (4) Post-collision syn-tectonic plutonic suites – comprising the Japiin Intrusive Suite (2116-2089 Ma), the Anelis quartz-syenite (2100 ± 21 Ma) and the Timbozal granite (2084 ± 5 Ma). (5) Neoproterozoic passive margin basins – represented by the Gurupi Group (<980 Ma) and the Cabeça de Porco Formation (591-980 Ma). (6) The Neoproterozoic Caramujinho Metatonalite (624 ± 16 Ma). (7) Neoproterozoic-Cambrian continental rift basin, comprising the Piriá Formation (<591 Ma).

The above-mentioned rock associations define at least two tectonic cycles for the Gurupi Belt. In the Rhyacian the tectonic evolution is marked by the amalgamation of island-arc basins, oceanic crust fragments, arc-related and collisional granites (KLEIN; MOURA, 2008; KLEIN et al., 2012). The Rhyacian metamorphic peak is estimated to have occurred between 2066 ± 17 Ma and 2100 ± 15 Ma (KLEIN et al., 2017). The Neoproterozoic-Cambrian associations are related to the Brasiliano/Pan-African orogeny. This event provided isotopic resetting and tectonic reworking of the south margin of the São Luís-West African plate, with basin formation and limited magmatism (KLEIN et al., 2012, 2017). Neoproterozoic metamorphism is estimated to have occurred between 624 and 549 Ma (KLEIN et al., 2017). The geochronological boundary and main deformational corridor that divides the Neoproterozoic and the Paleoproterozoic belts is defined by the Tentugal shear zone, which is a NW-SE strike slip sinistral structure (HASUI et al., 1984; KLEIN et al., 2005).

GOLD MINERALIZATION

The orogenic gold deposits of the Gurupi Belt, as defined by Klein (2014), are all hosted in structures related to the Tentugal shear zone. Most deposits and occurrences are hosted by rocks of the Chega Tudo Formation and fewer deposits and occurrences are hosted by the calc-alkaline granites of the Tromaí Intrusive Suite, gabbros, and siliciclastic rocks of the Igarapé de Areia. The geological and genetic controls of the deposits are very similar in both supracrustal and granitic rocks. Ore bodies tend to be parallel to the main structural grain of the host rocks, but may also be slightly discordant. At the deposit scale, they are confined to discrete fragile-ductile faults. Known ore bodies are generally discontinuous, subvertical, and cylindrical (KLEIN, 2014).

Three styles of mineralization have been described by Klein (2014): (1) Quartz veins and sets of veins with varying length and thickness, with restricted alteration halos, low sulfide content and free gold. (2) Quartz-carbonate sulfide veins, gold sulfide stringers and disseminations in altered host rocks. In addition to free gold, this style shows gold deposited on both quartz and sulfide microfractures, especially pyrite and arsenopyrite. Gold was deposited in microfractures on quartz and sulfide grains; gold also occurs as inclusions of single particles as Au-arsenopyrite (+ sphalerite) included in pyrite; and as trace elements in pyrite and arsenopyrite, together with Bi, As, Sb and Te. Mineralization is interpreted to have formed during Paleoproterozoic post-collisional evolution.

OROGENIC GOLD PROSPECTIVITY

To generate district-scale targets I used the knowledge-driven multi-class overlay method from Carranza (2008). This method is most suitable for data integration at district scale. For each vector (v) in an evidential map (e) it was assigned a score, P(ve), between 0 and 10, according to the importance of the mapped process in the formation of the mineral deposit. In addition, each evidential map is also associated with a weight, W(e), relative to the degree of uncertainty and reliability of the database that originated the evidential map. Finally, to generate a final predictive map each class was then combined, or summed ($\bar{S}$), following the equation (eq. 1) proposed by Carranza (2008).

Equation 1.

The knowledge-driven multi-class overlay technique uses a mathematical concept similar to the Boolean algebra, where the value of each class of evidence is added when there is an intersection of two or more predictive vectors. The understanding of the auriferous mineral system of the Gurupi Belt was divided into three main spheres of knowledge: 1) geodynamic evolution; 2) structural framework; 3) hydrothermal alteration. Each sphere of knowledge may be represented by mutually intersecting circles, similarly to the logical Venn diagram concept. The more predictive vector intersections occur in a specific region of the map, the higher the score assigned to the intersection zone.

To reflect the geodynamic evolution and the processes associated to the generation and primary migration of mineralizing fluids, I constructed and combined three evidential maps: i) Sm-Nd model age map associated with simplified geology of the Gurupi Belt, ii) metamorphic isograde map, and iii) translithospheric structures with mapped mafic intrusive bodies. To represent the structural framework, I combined three evidential maps: i) distribution of main shear zones strike direction and foliation traces; ii) foliation trace density; iii) fault and fractures strike direction distribution. To represent hydrothermally altered zones I combined four evidential maps: i) interest areas extracted from the ternary

RGB, K/Th ratio (red), F factor (green) and Kd (blue); ii) arsenic distribution in stream sediments; iii) antimony distribution in stream sediments; iv) mercury distribution in stream sediments.

The final target map was generated summing the three combination maps. High score, warm color zones are the areas of most evidential class intersection, and are the most likely targets for mineral discoveries. The efficiency of targeting using any knowledge-driven, or process-based technique can be measured by comparing the relation of the number of gold occurrences within each classified polygon to its total area. Search area reduction is a key process for reducing cost and risk on mineral exploration. Gold occurrences were obtained from the Geological Survey of Brazil mineral resource databased (GeoSGB®). This mineral resource database includes gold deposits, prospects, artisanal diggings, gold bearing quartz veins/hydrothermal alteration, and high grade pan concentrate samples. For this analysis, I considered only primary (hypogene) gold occurrences. Figure 1 shows that with increasing predictive score, the search area diminishes considerably. For example, within scores from 5 to 3, interpreted as high prospectively targets, 37 % of gold occurrences are found within 7 % of the project area.

Original maps can be assessed at http://rigeo.cprm.gov.br/jspui/handle/doc/18041

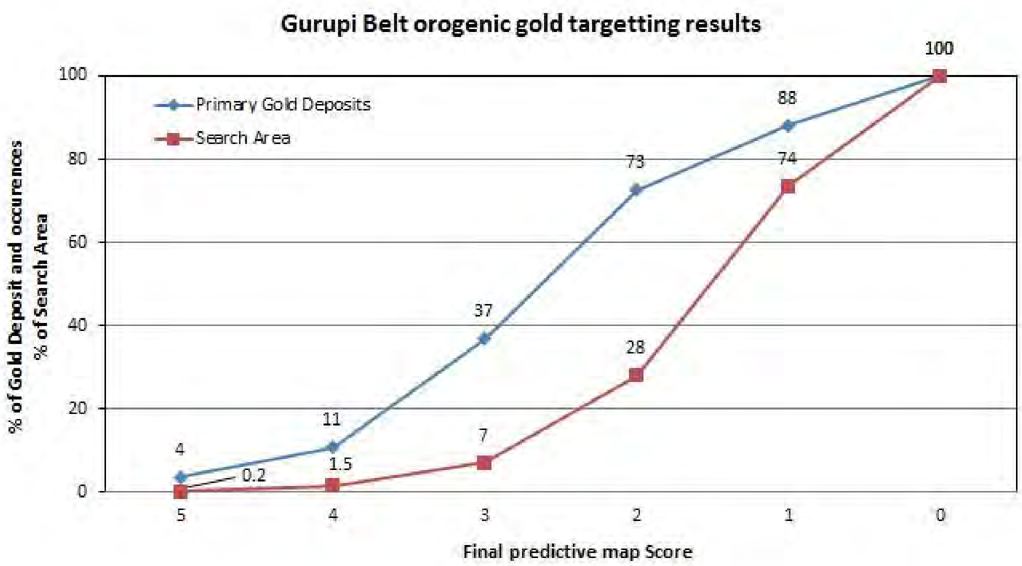


Figure 31 | Percentage of gold deposits and occurrences within predictive score from the final map (blue line), and the percentage of the area occupied by each respective score polygon (red line).

FAVORABILITY MAP

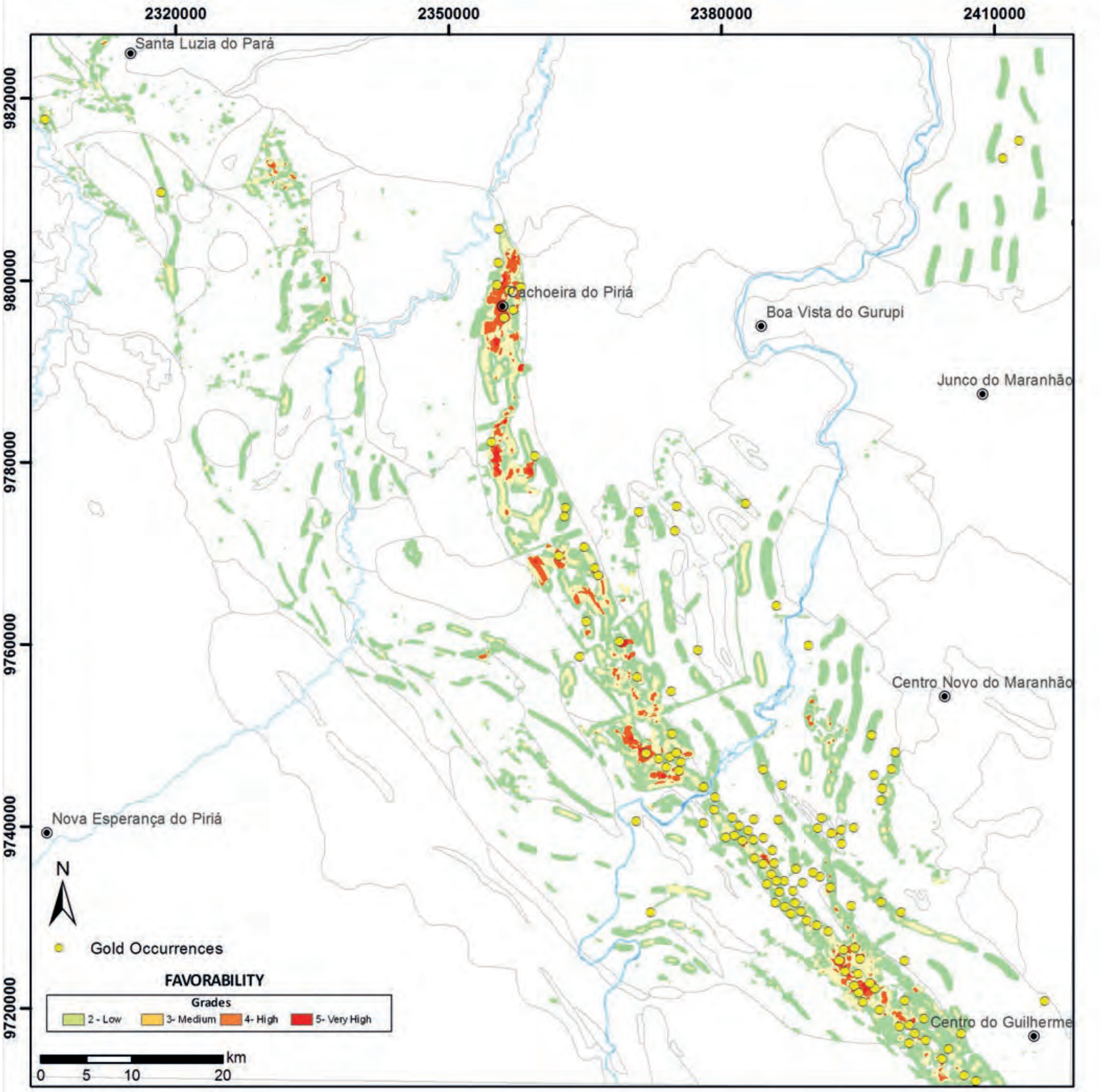


Figure 32 | Gold Favorability Map in the Gurupi Belt, NE Brazil.

EVIDENCE MAPS

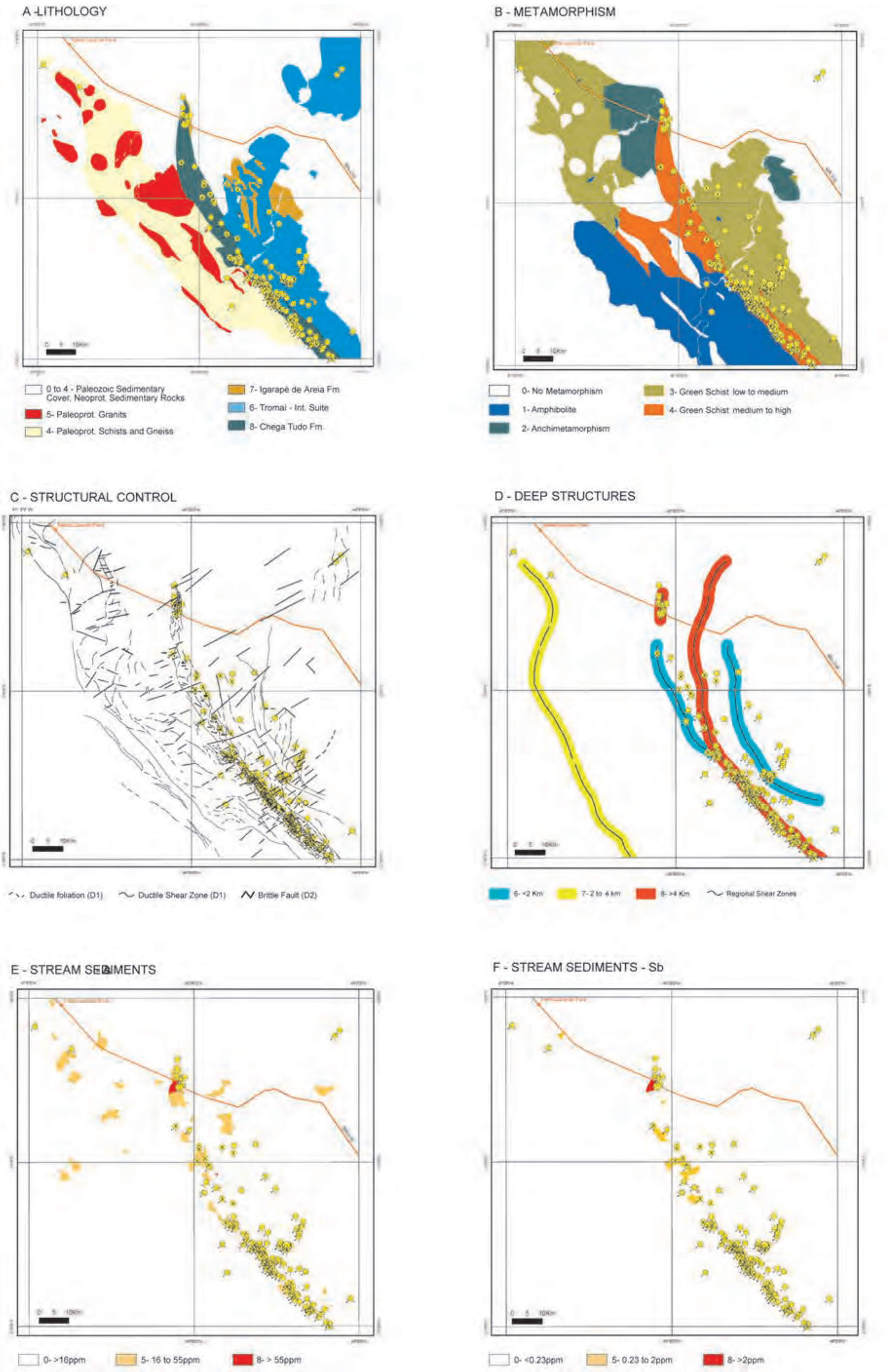


Figure 33 | Evidence Maps of the Gold Favorability in the Gurupi Belt, NE Brazil.

COPPER-LEAD-ZINC FAVORABILITY IN THE SUPRACRUSTALS SEQUENCE OF MARTINÓPOLE GROUP, MEDIO COREAÚ DOMAIN, BORBOREMA PROVINCE

Tercyo Rinaldo Gonçalves Pinéo, Alex Franca Lima,
Maria Dulcinea Madureira Rolim Bessa, Mariane Dornas Martins, Felipe Rocha Abreu

INTRODUCTION

The Geological Survey of Brazil (CPRM) developed a project in the northwest portion of the Ceará State, northeast of Brazil, to investigate the metallogenic potential and identify more favorable areas to prospect for metals. We identified Neoproterozoic Martinópole Group is a supracrustal sequence, which hosts Cu-Pb-Zn sulfide mineralization. Other important resources include silver, manganese, and iron. The obtained geological, geophysical and geochemical data were integrated and the results are presented as Cu-Pb-Zn favorability map, produced by the knowledge-driven modeling technique, which uses the mineral system concept.

GEOLOGICAL FRAMEWORK

The study area is located in northwest portion of the Borborema Province, which was consolidated during the Brasiliano/Pan-African orogenic cycle by the agglutination of the São Luis – West Africa, and São Francisco – Congo cratons around 600 Ma (ALMEIDA et al.,1981) (Figure 34).

The Granja Complex represents the basement of the Martinópole Group and is composed of TTG orthogneisses, paragneisses and granulites of Paleoproterozoic age (2.3 Ga) (SANTOS, 1999). The Martinópole Group is formed by a meta-volcano-sedimentary sequence deposited in a passive continental margin between 800 and 750 Ma (SANTOS, 1999) and subsequently deformed during the Brasiliano/Pan-African orogenic cycle (~600 Ma), and metamorphosed into greenschist to amphibolite facies conditions. The base of the Martinópole Group comprises the Goiabeira Formation, which consists of schists, quartzites and paragneisses. This formation is overlain by the São Joaquim Formation, which is composed of quartzites. The upper Covão Formation comprises schists and phyllites, while the top unit corresponding to the Santa Terezinha Formation, with phyllites, carbonate phyllites, marbles, quartzites, meta-cherts, calc-silicatic rocks, BIF, and meta-volcanic rocks, dated by zircon U-Pb at 777 Ma (crystallization age). This uppermost formation hosts distinct deposits and mineral occurrences, especially of copper, lead, zinc, manganese and iron, which are grouped into three separate targets: Uruoca target, Pedra Verde mine and Serra de São José target.

GEOLOGY AND METALLOGENESIS OF THE COPPER, LEAD AND ZINC RESOURCES

Field observations and data compiled from the literature indicate the potential for SEDEX-type deposits, formed in a passive continental margin between 800 and 750 Ma, followed by hydrothermal reconcentration along the NE-SW structures, during the Brasiliano/Pan-African Orogeny (~600 Ma).

The Uruoca Target is composed of phyllites and quartzites with mylonitic structure, metachert, hydrothermal breccia, meta-rhyodacite, and laterite covers. The metachert contains layers of manganese-iron oxide and widespread bornite and pyrite. The hydrothermal breccia has common box-work texture and is distributed along a NE-SW shear zone.

The manganese mineralization at Uruoca is associated with laterites aligned in the NE-SW direction, with iron hydroxide, hematite, magnetite and quartz fragments filling

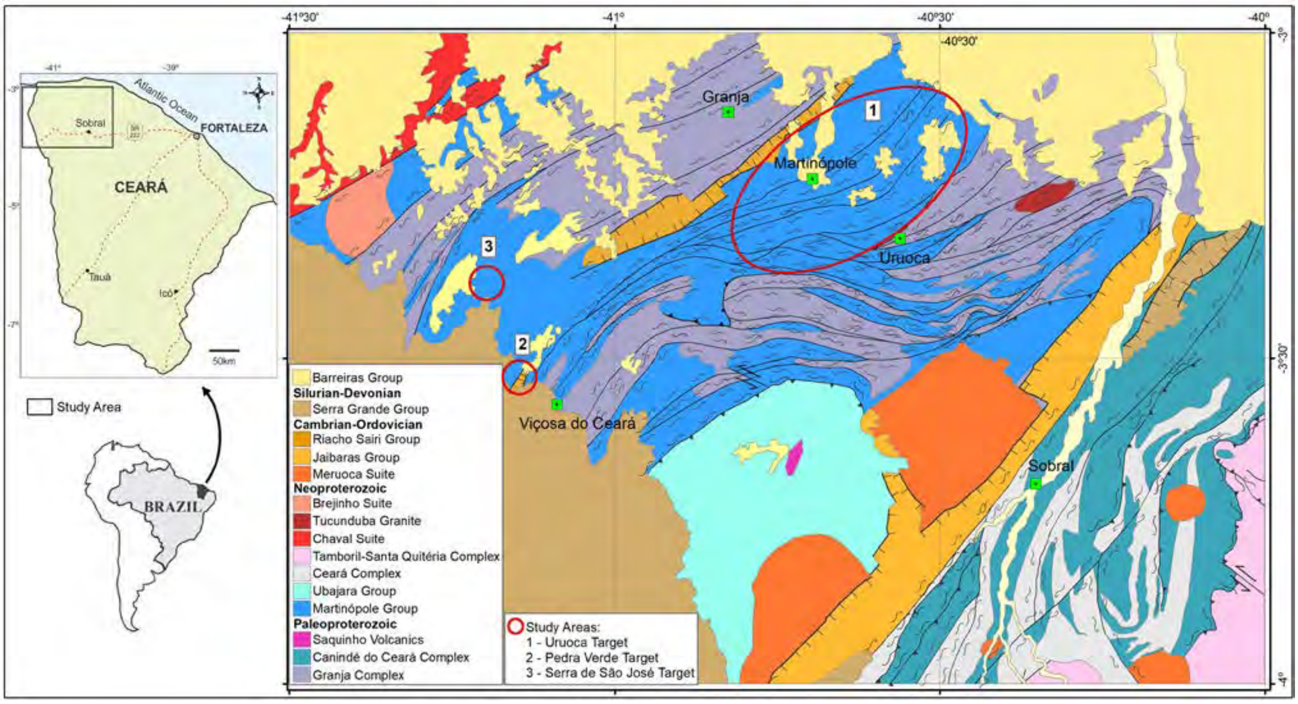


Figure 34 | Geological map of project area.

box-works. The presence of manganese layers and phyllites, both intercalated and folded, suggests a syngenetic occurrence with superimposed weathering processes. Chalcopyrite, pyrite, bornite, sphalerite and galena in fractures and also in veins of meta-carbonate rocks (marbles, carbonaceous phyllites, and calc-silicate rocks) associated with felsic metavolcanic rocks were described from boreholes samples (PRADO et al., 1981).

The Pedra Verde mine is formed by altered phyllite transitioning to carbonated phyllite. The altered phyllite is 22 m thick and contains malachite and azurite as the main secondary copper minerals. The ore is zoned and marked by chalcocite-bornite-chalcopyrite-pyrite-galena-sphalerite (COLLINS; LOUREIRO, 1971). The sulfides occur in two distinct ways: deformed along the mylonitic foliation of the host carbonaceous phyllite, and along carbonate veins indicating a hydrothermal concentration (MATOS, 2012).

The Serra de São José target has barite with associated Ni (500 ppm) and Co (500 ppm) anomalies in folded BIF. The local geology comprises marbles, phyllites, schists, meta-greywackes, meta-cherts and BIF (PRADO et al., 1979). The geophysical data indicates the possible continuity of the target underneath the Silurian sediments of the Parnaíba Basin.

PROSPECTIVITY CRITERIA FOR CU-PB-ZN MINERALIZATION

For modeling, we used geological data, stream sediment geochemical analyses, and airborne geophysical maps. All the data were employed according to their participation in the generation, transport, and trapping of metallic ores.

Initially the selected data were processed, rasterized and scored, concerning their importance in the ore forming process resulting in evidence maps. Then, each evidence map received a weight related to the degree of uncertainty and reliability of the original data. The modeling was performed in a GIS environment, using the ArcGIS software (Spatial Analyst extension). For the modeling, we used the multi-class overlaying method, in which the value of each class of evidence is added when there is an intersection of two or more predictive vectors.

We produced eleven evidence maps for the Martinópole Group, including: i) lithology, ii) outcrops, iii) airborne magnetic anomaly, iv) deep structural lineaments (generated by modeling of airborne magnetic data), v) shear zones, vi) shear zone density, vii) intersection of fragile and ductile structures, viii) airborne radiometric data, ix) copper geochemical anomaly, x) lead geochemical anomaly and xi) zinc geochemical anomaly. The last three evidence maps were produced by processing of results of geochemical analysis of stream sediments collected.

The modelling of all evidence maps resulted in a favorability map for Cu-Pb-Zn of the Martinópole Group, which shows that the most important favorability zone is associated with NE-SW shear zones and represent an area with major possibility to accumulate Cu-Pb-Zn sulfides.

The location of known mineral occurrences was used to evaluate the quality of the product generated. The classes with the highest prospectivity index (5% of the project area) mapped 47% of known occurrences, attesting to the good correlation between potential classes and ore occurrence.

Original maps can be assessed at http://rigeo.cprm.gov.br/jspui/handle/doc/21399

FAVORABILITY MAP

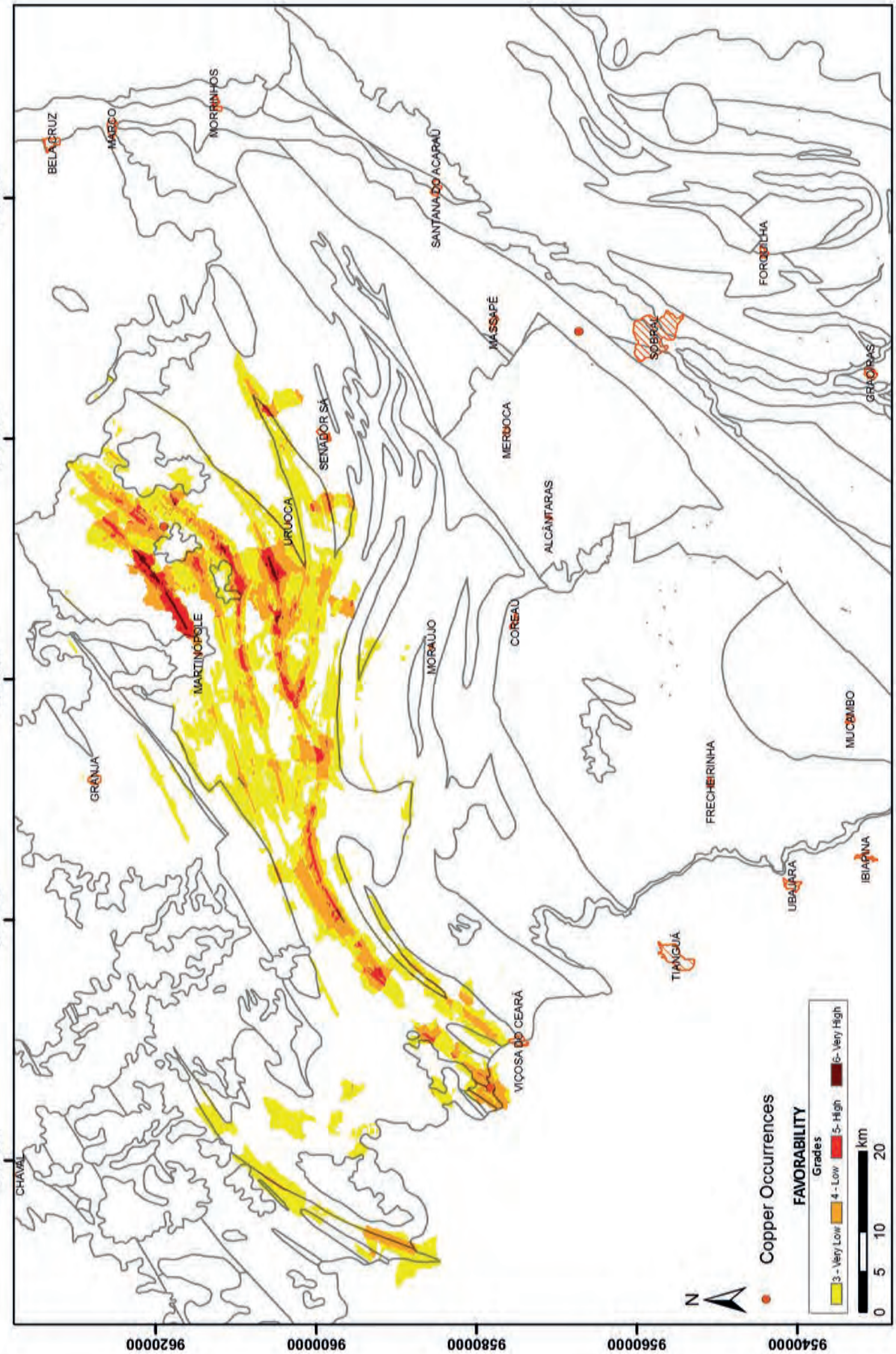


Figure 35 | Copper-Lead-Zinc Favorability Map in the Supracrustals Sequence of Martinópole Group, Medio Coreaú Domain, Borborema Province.

EVIDENCE MAPS

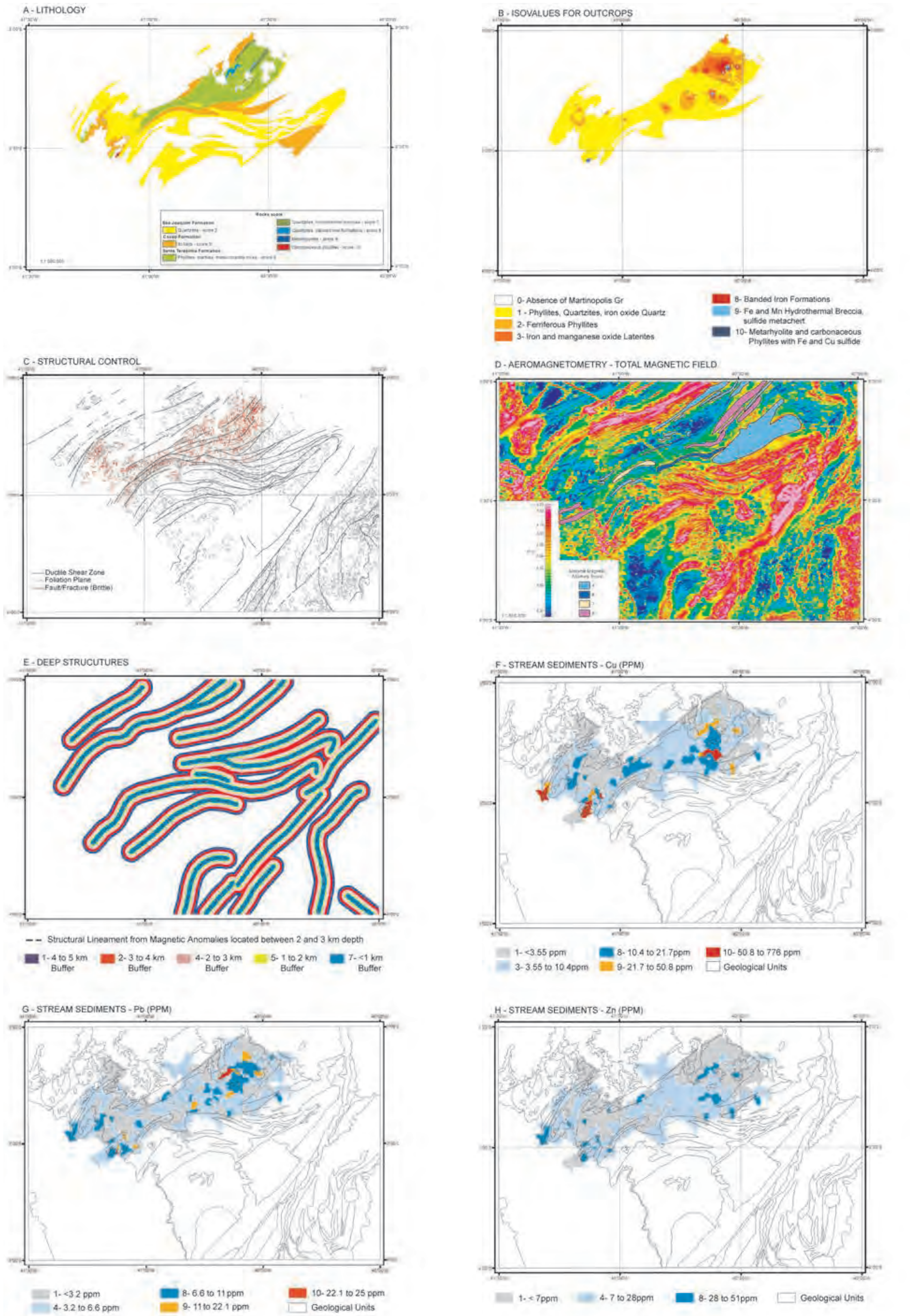


Figure 36 | Evidence Maps of the Copper-Lead-Zinc Favorability in the Supracrustals Sequence of Martinópole Group, Medio Coreaú Domain, Borborema Province

COPPER-IRON FAVORABILITY IN THE CAMBRIAN JAIBARAS SEDIMENTARY BASIN, MEDIO COREAÚ DOMAIN, BORBOREMA PROVINCE

Tercyo Rinaldo Gonçalves Pinéo, Alex Franca Lima,
Maria Dulcinea Madureira Rolim Bessa, Mariane Dornas Martins, Felipe Rocha Abreu

INTRODUCTION

The Geological Survey of Brazil (CPRM) developed a project on the northwest portion of Ceará State, northeast of Brazil, with the objective to determine their metallogenic potential and identify more favorable areas to prospect for metallic minerals. In the east portion of the study area has a sedimentary basin, named Jaibaras Basin, which is in contact with two granite batholiths. Next to these contacts we find the occurrences of disseminated copper and iron sulfides, and of iron oxides within fractures and as metric fragments.

The geological, geophysical and geochemical data obtained on this project were worked together to identify favorable targets to Cu-Fe mineral exploration. The results were presented on Cu-Fe favorability map, produced by the knowledge-driven modeling technique, which uses the mineral system concept.

GEOLOGICAL FRAMEWORK

The study area is located in northwest portion of the Borborema Province, which was consolidated during the Brasiliano/Pan-African orogenic cycle by the agglutination of the São Luis – West Africa, and São Francisco – Congo cratons around 600 Ma (ALMEIDA et al., 1981) (Figure 37).

The Jaibaras Group was deposited in a graben system developed by the activation of the Sobral-Pedro II shear zone. The Jaibaras Group comprises mature siliciclastic continental sediments grouped in three formations, and by bimodal volcanic rocks (COSTA et al., 1973). From bottom to top the Jaibaras Group consists of: i) Massapê Formation, which is composed of polymictic conglomerate without fragments of granitic rocks from adjacent batholiths; ii) Pacujá Formation, composed predominately of sandstone; iii) Aprazível Formation, comprising polymictic conglomerate with fragments of granitic rocks from adjacent batholiths. The volcanic rocks are grouped in the Parapuí Suite (ca. 535 Ma, U-Pb zircon, GARCIA et al., 2010), composed of basalts and rhyolites, which were emplaced between the deposition of the Pacujá and Aprazível formations.

The granites are represented by the Meruoca and Mucambo batholiths. Both comprise reddish alkali feldspar granite and syenogranite, and formed from 523 to 532 Ma (U-Pb in zircon, FETTER, 1999; ARCHANJO et al., 2009).

The lack of granitic fragments of the Meruoca and Mucambo batholiths in conglomerates of the Massapê Formation suggests that the sediment fill of the Jaibaras Basin occurred in two stages.

GEOLOGY AND METALLOGENESIS OF THE COPPER AND IRON RESOURCES

Parente et al. (2011) show that the copper and iron mineralization of the Jaibaras Basin are associated with hydrothermal processes similar to those found in IOCG system, suggesting the possibility of gold existence in this sedimentary basin. Several types of hydrothermal alteration were identified, and at least five typologies of copper and iron occurrences were described by the authors.

Some features of metallic mineralization present in the study area were identified through field work in the volcanic rocks of the Parapuí Suite. Basalts have disseminated pyrite, chalcopyrite, and magnetite, and epidotization is a common alteration. We have also

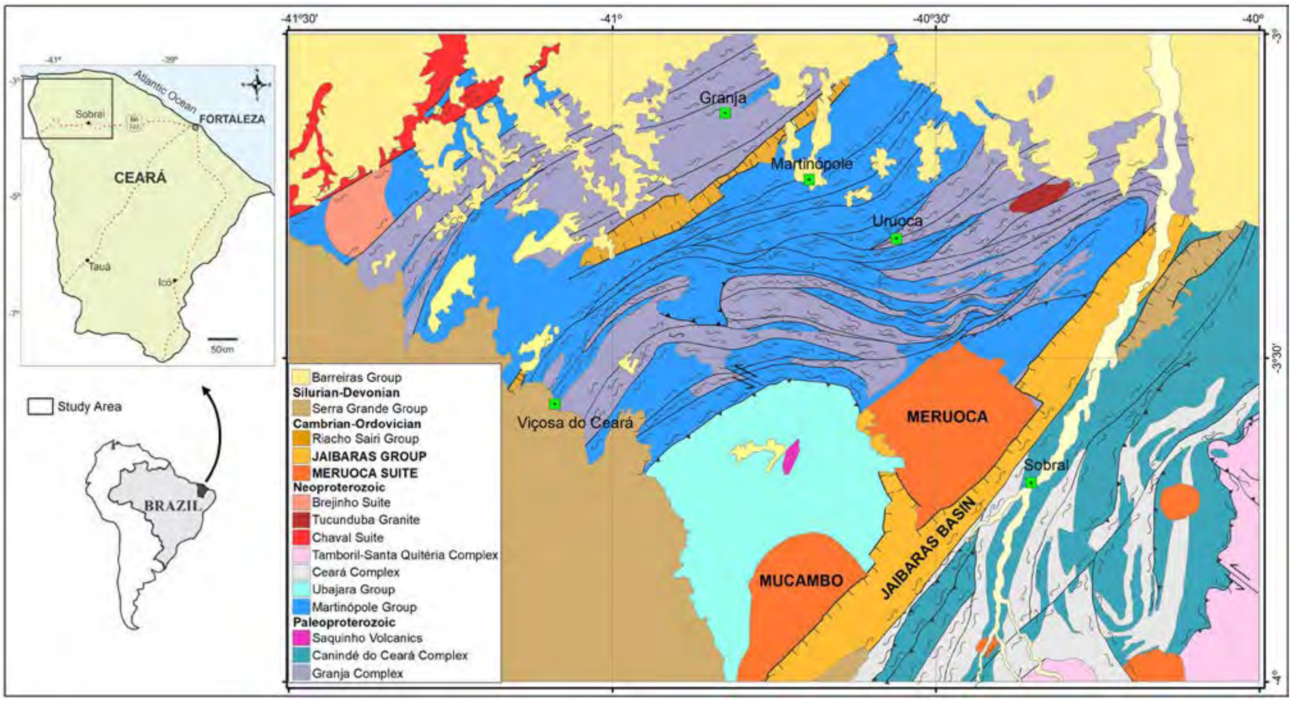


Figure 37 | Geological map of the NW Ceará region. The Jaibaras Basin and the Meruoca/Mucambo batholiths are highlighted.

identified pyrite and chalcopyrite associated with carbonate along fault plane in rhyolites. Fractures filled by carbonate are also common.

The sandstones of the Pacujá Formation have magnetite and hematite occurring as thin layers concordant with the sedimentary stratification, suggesting a syngenetic deposition, and in fractures suggesting hydrothermal remobilization.

A common feature in the east limit of the Meruoca and Mucambo batholiths, in the contact with Jairabas Basin, is the widespread presence of fractures filled by magnetite and hematite. In some places, we found metric blocks composed of magnetite and hematite, with tabular limits, suggesting that they filled fractures.

PROSPECTIVITY CRITERIA FOR CU-FE MINERALIZATION

For modeling, we used geological data, stream sediment geochemical analyses, and airborne geophysical maps. All the data were employed according to their participation in the generation, transport, and trapping of metallic ores.

Initially the selected data were processed, rasterized and scored, concerning their importance in the ore forming process resulting in evidence maps. Then, each evidence map received a weight related to the degree of uncertainty and reliability of the original data. The modeling was performed in a GIS environment, using the ArcGIS software (Spatial Analyst extension). For the modeling, we used the multi-class overlaying method, in which the value of each class of evidence is added when there is an intersection of two or more predictive vectors.

Were produced nine evidence maps for the Jaibaras Basin, which comprise (Figure39): i) lithology, ii) outcrops, iii) airborne magnetic anomaly, iv) deep structural lineaments (generated by modeling of airborne magnetic data), v), lithological contacts vi) copper geochemical anomaly, vii) iron geochemical anomaly, viii) arsenic geochemical anomaly and ix) antimony geochemical anomaly. The last four evidence maps were produced by processing the results of analysis of stream sediments. The used analytical method did not have detection limit to identify gold, therefore we used arsenic and antimony geochemical anomaly evidence maps as pathfinder elements.

The modeling of all evidence maps resulted in a favorability map for Cu-Fe of the Jaibaras Basin. This map shows some favorable zones, with the most important being those clearly associated with the contact between the Jaibaras Group and the Meruoca/Mucambo batholiths.

Original maps can be assessed at http://rigeo.cprm.gov.br/jspui/handle/doc/21399

FAVORABILITY MAP

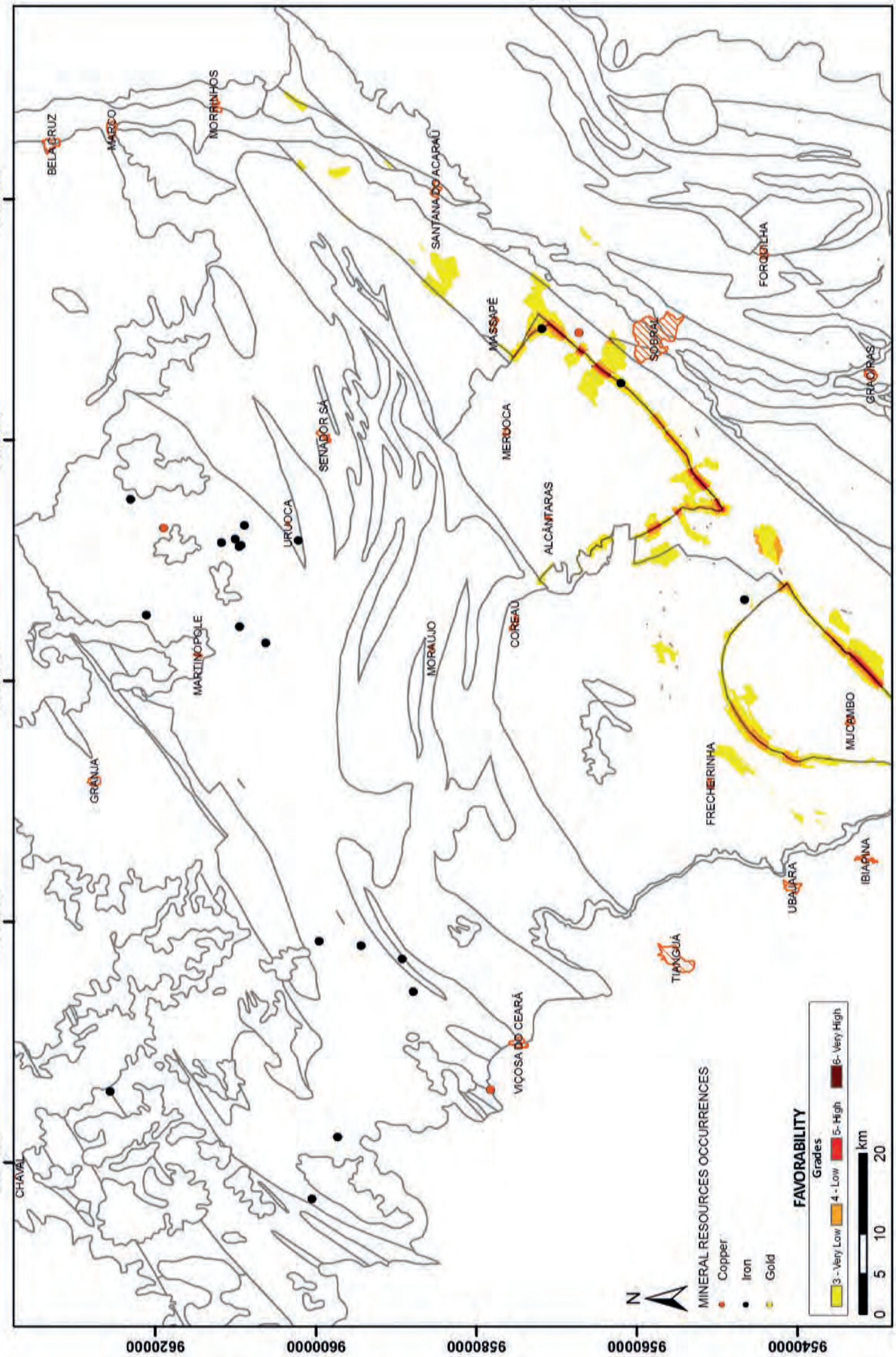


Figure 38 | Copper-Iron Favorability Map in the Cambrian Jaibaras Sedimentary Basin, Medio Coreaú Domain, Borborema Province.

EVIDENCE MAPS

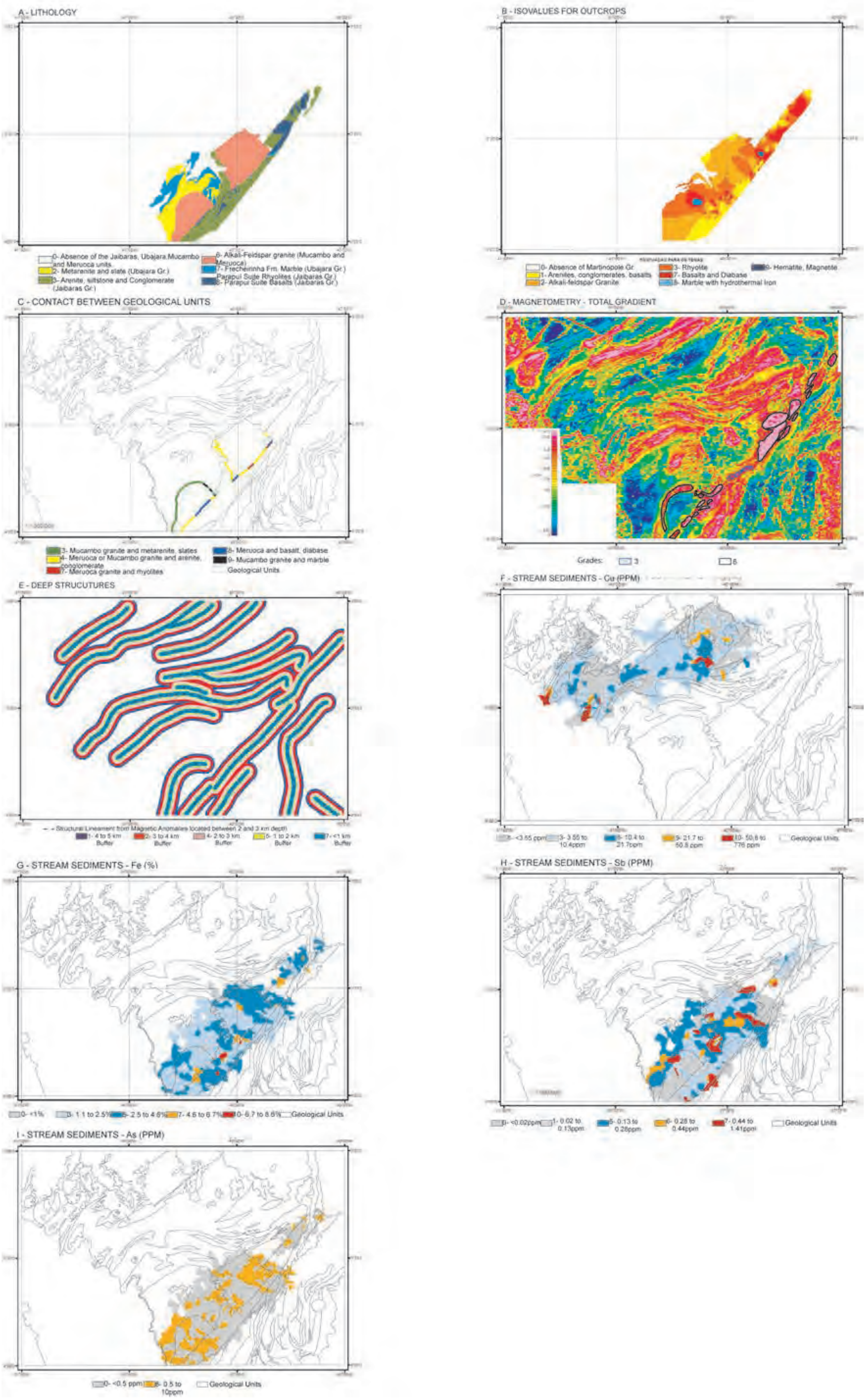


Figure 39 | Evidence Maps of the Copper-Iron Favorability in the Cambrian Jaibaras Sedimentary Basin, Medio Coreaú Domain, Borborema Province.

REMOBILIZED CU-AU PORPHYRY DEPOSITS FAVORABILITY IN THE SOUTHERN SEGMENT OF THE GOIÁS MAGMATIC ARC, BRASÍLIA BELT, TOCANTINS PROVINCE

Jônatas de Sales Macêdo Carneiro

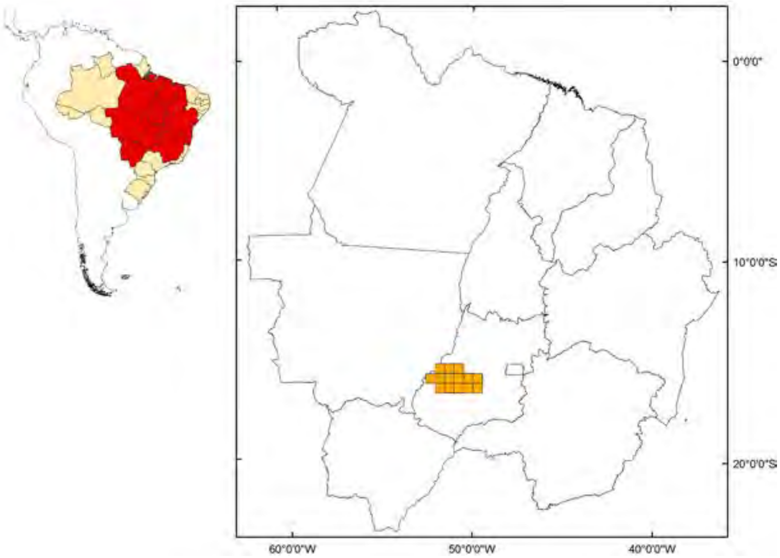


Figure 40 | Study area location.

INTRODUCTION

The Tocantins Province in central Brazil hosts several Neoproterozoic mineral deposits, including important Ni, Cu, Ag and Au resources. One of the compartments of the province is the Goiás Magmatic Arc (GMA), in the Brasília Belt, a tectonic unit almost 1000 km long, which hosts a Precambrian Cu-Au porphyry deposit in its northern segment, which is singular because of the preservation of the hydrothermal alteration zones (Figure 40).

Recently some new prospects were identified in the southern segment of the GMA, which corroborates the potential of this tectonic compartment to host similar deposits. Thus, the Geological Survey of Brazil (CPRM) has modeled in GIS environment the favorability of a portion of the southern segment of the GMA for hosting a remobilized Cu-Au porphyry deposit.

TECTONOSTRATIGRAPHIC FRAMEWORK

The tectonic history of Brasília Belt is marked by an initial island arc stage, followed by a continental stage culminating with the collision between the Amazonian and Congo-São Francisco cratons during the Neoproterozoic (FUCK et al., 2017). During oceanic-oceanic subduction, from ca. 900 Ma to ca. 800 Ma, calc-alkaline, juvenile gneisses and some volcano-sedimentary sequences, such as the Arenópolis Sequence (PIMENTEL; FUCK, 1992), were formed. Small S-type granitic plutons of ca. 780 Ma are interpreted as markers of collision between the São Francisco-Congo Craton and a continental block now covered by the Paraná Basin (PIMENTEL et al., 1999). Around 750 Ma several volcanosedimentary sequences and mafic-ultramafic complexes were formed, mainly in localized rift environments, such as Bom Jardim de Goiás sequence (GUIMARÃES et al., 2012) and the great mafic-ultramafic complexes (GIOVANARDI et al., 2017). The youngest calc-alkaline magmatic event in GMA ranges from ca. 670 Ma to ca. 630 Ma and exhibits isotopic signatures concordant with a reworked source (LAUX et al., 2005).

This convergence of tectonic plates culminates in the amalgamation between Amazonian and São Francisco-Congo cratons. During all this tectonic dynamics, rocks are compressed by EW tension and deformation is accommodated along NS-trending foliations and strike-slip shear zones in the GMA, with secondary NW and NE faults. Posteriorly, those structures are cut by important transcurrent lineaments, such as NE Transbrasiliano Lineament and NS Moiporá-Novo Brasil Lineament.

Initial deformation features are coeval with the metamorphic peak in the area (ca. 640 Ma; DELLA GIUSTINA, 2010).

GEOLOGY AND METALLOGENESIS OF MAIN DEPOSITS IN GMA

The GMA exhibits two main phases of Cu and Au mineralization, both may be remobilized by collisional stage. The first mineralization event is associated with the island arc stage, when the Chapada Cu-Au porphyry deposit was formed, as revealed by the age of the porphyritic diorite pluton (884 ± 6 Ma; OLIVEIRA et al., 2016). It is localized in the intersection between major NNE and NNW with minor EW faults. This deposit is characterized by typical hydrothermal zones metamorphosed in amphibolite facies. Argillic alteration is represented by kyanite-bearing schists and pyrite-bearing quartzites; propylitic zone is marked by hornblende-epidote gneisses, and potassification is associated mainly with biotite schists.

Another event of Cu and minor Au mineralization occurs in ca. 750 Ma and forms mainly VMS-type deposits. One of the deposits is the Bom Jardim de Goiás VMS, hosted in intermediate to acid tuffs of the homonymous metavolcano-sedimentary sequence (GUIMARÃES et al., 2012). Mineralization occurs disseminated and as stockworks, suggesting that it represents a deeper portion of the VMS deposit. Silicification is the larger alteration zone, with chloritization and epidotization also presents. Bom Jardim de Goiás deposit occurs associated with some NE major faults.

Collisional and post-collisional stages form orogenic and intrusion-related gold deposits, examples are Posse and Fazenda Nova deposits, respectively. Additionally, several small lode deposits are registered and may be related to this stage. Oliveira et al. (2016) show that even magmatic and hydrothermal deposits may be remobilized during collisional stages in GMA.

FAVORABILITY CRITERIA FOR REMOBILIZED CU-AU PORPHYRY DEPOSITS IN GMA

Although an important remobilized Cu-Au porphyry deposit is explored in the northern segment of GMA, similar mineralization has not been yet discovered in the southern segment. However, it is notable that some important factors for the generation of such deposits are also present in the meridional portion of GMA. Therefore, the Geological Survey of Brazil – CPRM has used public data, accessible in the GeoSGB database (http:\\geosgb.cprm.gov.br), for modeling favorability criteria of ore generation, transport, deposition and remobilization of such deposits in the southern segment of the GMA. Data were punctuated and weighted in order to obtain a weighted arithmetic average. Data processing was performed in GIS environment in a knowledge-driven approach.

For calculating the favorability of the southern GMA for hosting a deposit similar to Chapada, in northern segment of Brasília Belt, we used the following evidence maps for punctuate tectonic framework and geodynamics: isotopic maps (eNd in time of crystallization, Sm-Nd model age, and 87Sr/86Sr); Bouguer gravimetric anomaly map; metamorphic map; lithological map. Isotopic and gravimetric maps may evidence crustal reworking and thinning, as well as the ascension of metasomatized sub-lithospheric mantle. Metamorphic map reveals the zones of major fluid generation, which occurs in the transition between greenschist and amphibolite facies (PHILLIPS; POWELL, 2010). Lithology shows rocks that may host a Neoproterozoic remobilized Au deposit, as well as indicates carbonaceous schists, which may be another source for gold.

During remobilization, transport of fluids and metals occurred through major structures and deposited in structures of second order. Therefore, I used the major deep lineaments, the ductile-brittle structures, and second order hinge zones and fractures as evidence maps for transportation and deposition of metal.

Evidence maps for trapping were: hydrothermal zones maps; stream sediment As, Te and Bi geochemical anomalies; and anomalous K gammaspectrometry map (with eTh normalization).

Integration of those maps, in a weighted average algebra, yielded a map of confluence of those factors, which may be interpreted as favorability map for remobilized Cu-Au porphyry deposit. The known lode gold deposits of the area plot in the zones of greatest or great favorability, which indicates that this model works well as an approximation for such deposit.

KNOWLEDGE-DRIVEN GIS MODDELLING	WEIGHT OF THE EVIDENCE MAPS FOR THE REMOBILIZED CU-AU PORPHYRY DEPOSIT IN GOIÁS MAGMATIC ARC			
		EVIDENCE MAPS	WEIGHT	MEANING FOR THE MINERAL SYSTEM
	TECTONIC FRAMEWORK AND GEODYNAMICS	Isotopic maps	3	Regions with positive eNd values, juvenile Nd model ages and low Sr87/Sr86 ratios may reveal uplift of the metassomatized sub-lithospheric mantle. Regions of tectonic reactivation tend to be more susceptible to presence of fluid rich structures.
		Gravimetric domains	2	Cratonic areas are less susceptible to Neoproterozoic remobilization.
		Lithology	3	Porphyry-type deposits are related to the juvenile stage of Goiás Magmatic Arc. Therefore rocks of age between ca. 900 Ma and ca. 750 Ma.
		Metamorphic Map	4	The transition between greenschist and amphibolite metamorphic facies produces larges amounts of fluids riches in H2O and CO2.
	STRUCTURAL CONTROL	Major deep structures	4	Major structures allow fluids to be transported from deep regions towards shallower crustal levels.
		Second order structures	4	Second order structures represent areas of pressure relief, where fluids tend to be trapped.
	HIDROTHERMAL ALTERATION	Anomalous K map	4	Areas with anomalous values in the K channel may represent zones of hydrotermal alteration, i.e. potassification.
		Hidrothermal alteration areas	5	Several hydrothermal alteration zones, such as sericitization, biotitization and epidotization. Each one was punctuated according to its proximity in the porphyry deposit.
		Stream sediment geochemistry	5	Catchment area of geochemical anomalies represent pathfinders for the deposit.

Table 6 | Criteria for evidence maps in each key mineral system component for Goias Magmatic Arc area.

FAVORABILITY MAP

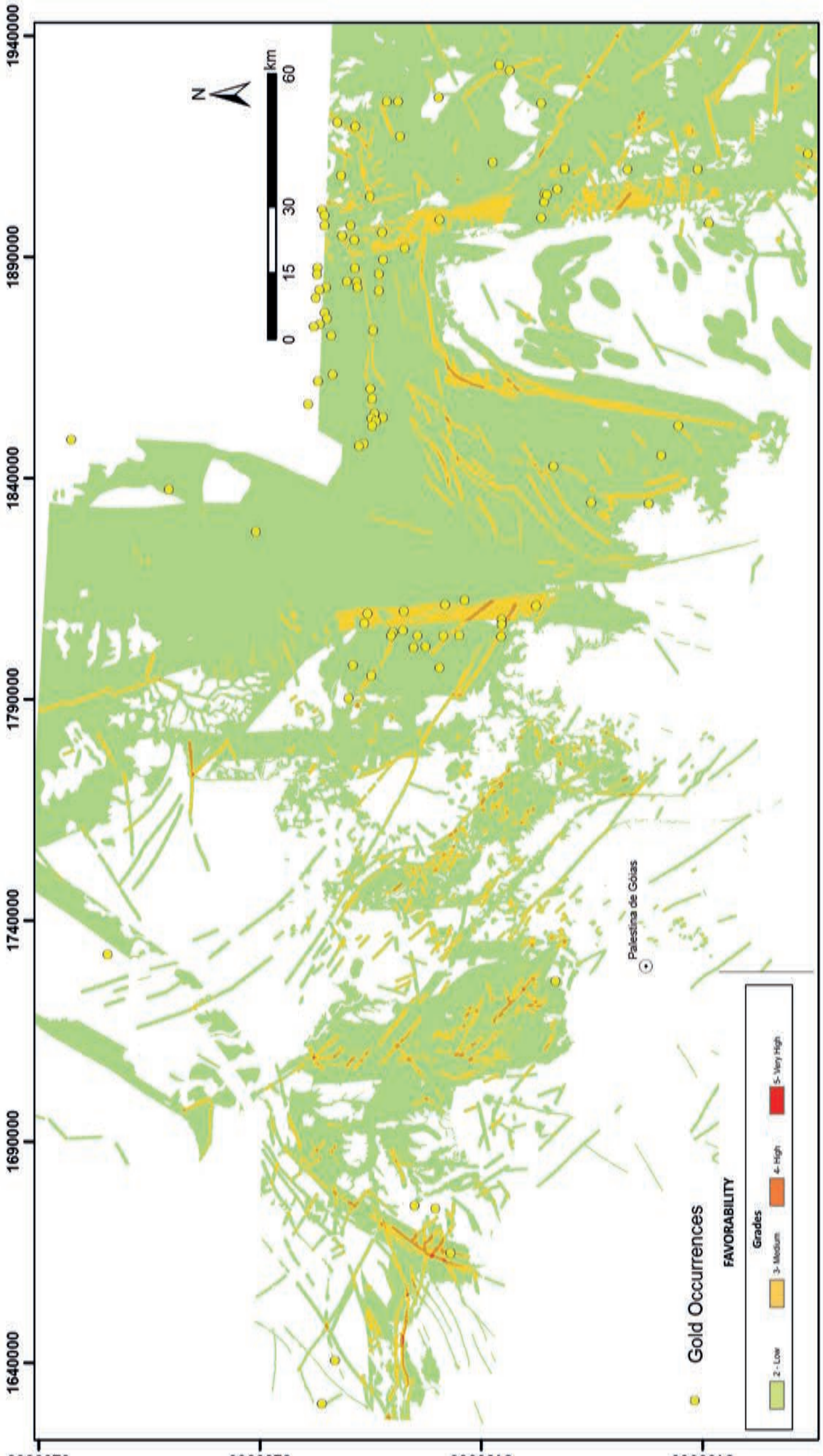


Figure 41 | Remobilized Cu-Au Porphyry Deposits Favorability Map in the Southern Segment of the Goiás Magmatic Arc, Brasília Belt, Tocantins Province.

EVIDENCE MAPS

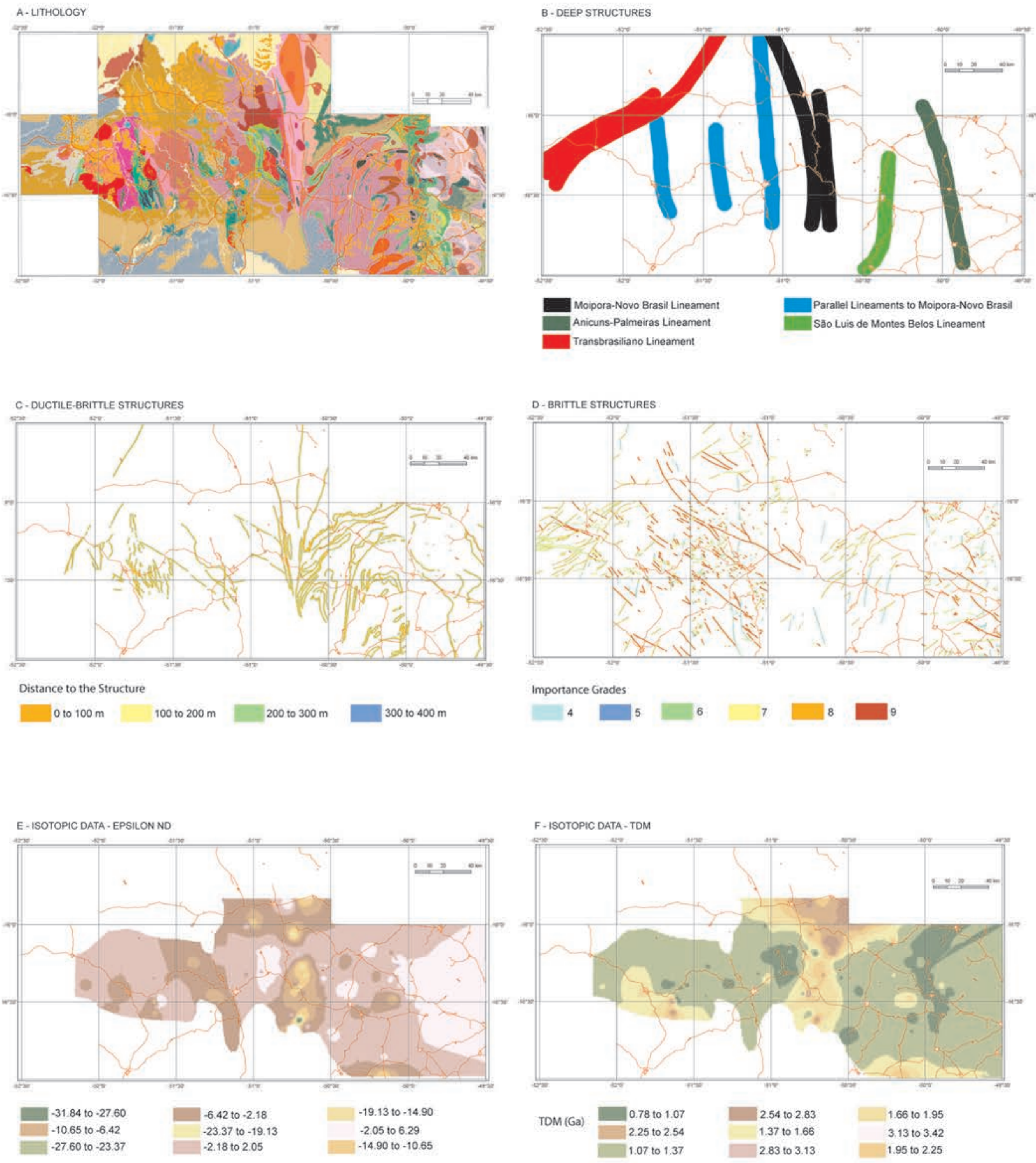


Figure 42 | Evidence Maps of the Remobilized Cu-Au Porphyry Deposits Favorability in the Southern Segment of the Goiás Magmatic Arc, Brasília Belt, Tocantins Province

REFERENCES

ADÔRNO, R. R.; BAHIA, R. B. C.; GUIMARÃES, J. T.; SILVA, L. C.; SILVA, L. G. **Avaliação do potencial de fosfato no Brasil, fase III**: bacia dos Parecis – área oeste, estado de Rondônia. Porto Velho: CPRM. 2017. 80 p. (Informe de Recursos Minerais. Série Insumos Minerais para Agricultura, 19). Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/18991

ALMASI, A.; YOUSEFI, M.; CARRANZA, E. J. M. Prospectivity analysis of orogenic gold deposits in Saqez-Sardasht Goldfield, Zagros Orogen, Iran. **Ore Geology Reviews**, v. 91, p. 1066-1080, Dec. 2017. DOI: https://doi.org/10.1016/j.oregeorev.2017.11.001

ALMEIDA, F. F. M.; HASUI, Y.; BRITO NEVES, B. B.; FUCK, R. A. Brazilian structural provinces: an introduction. **Earth-Science Reviews**, v. 17, issues 1-2, p. 1-29, Apr. 1981. DOI: https://doi.org/10.1016/0012-8252(81)90003-9

ALMEIDA, M. E.; COSTA, U.A.P. **Geologia e recursos minerais da folha Sumaúma - SB.20-Z-D**: estado do Amazonas. Manaus: CPRM, 2016. Escala 1:250.000. (Programa Geologia do Brasil - PGB. Levantamento Geológicos Básicos do Brasil).

ARAÚJO, O. J. B.; MAIA, R. G. N.; JORGE-JOÃO, X. S.; COSTA J. B. S. A megaestruturação da folha Serra dos Carajás. *In*: CONGRESSO LATINO AMERICANO DE GEOLOGIA, 7., 1988, Belém. **Anais** [...]. Belém: SBG, 1988.p.324-333.

ARCHANJO, C. J.; LAUNEAU, P.; HOLANDA, M. H. B.M.; MACEDO, J. W. P.; LIU, D. Scattering of magnetic fabrics in the Cambrian alkaline granite of Meruoca (Ceara State, northeastern Brazil). **International Journal Earth Sciences**, v. 98, issue 8, p. 1793-1807, 2009. DOI: https://doi.org/10.1007/s00531-008-0342-z

AN, P.; MOON, W.M.; BONHAM-CARTER, G.F. On knowledge-based approach of integrating remote sensing, geophysical and geological information. *In*: INTERNATIONAL GEOSCIENCE AND REMOTE SENSING SYMPOSIUM, 92., 1992, Houston. **Proceedings**. Houston: IEEE, 1992 .p. 34-38.DOI: https://doi.org/10.1109/IGARSS.1992.576620

BERGAMI, G. N.; PRADO, E. M. G. (org.). **Áreas de Relevante Interesse Mineral**: evolução crustal e metalogenia da Faixa Brasilândia, Estado de Rondônia. Porto Velho: CPRM, 2019. (Informe de Recursos Minerais. Série Províncias Minerais do Brasil, 19). Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/20937

BONHAM-CARTER, G. F. **Geographic information systems for geoscientists**: modelling with GIS. Oxford: Pergamon, 1994. 398 p. DOI: https://doi.org/10.1016/C2013-0-03864-9

BRITO, R.S.; SILVEIRA, F.V.; LARIZZATI, J.H. **Metalogenia do Distrito Aurífero do rio Juma – Nova Aripuanã–AM**. Brasília: CPRM, 2010. (Informe de Recursos Minerais. Série Ouro, n. 17).

BROWN, W.M.; GEDEON, T.D.; GROVES, D.I. Use of noise to augment training data: a neural network method of mineral-potential mapping in regions of limited known deposits examples. **Natural Resources Research**, v. 12, issue 2, p. 141-152, June 2003. DOI: https://doi.org/10.1023/A:1024218913435

CAMPOS, L. D.; CHIARINI, M. F. N.; COSTA, I. S. L.; ROSA-COSTA, L. T. Integração de dados e geração de alvos. In: ROSA-COSTA, L. T. D.; CHAVES, C. L.; SILVA, C. M. G. D.; CAMPOS, L. D.; ABRANTES, B. K. C.; TAVARES, F. M.; LAGO, A. L. **Área de relevante interesse mineral:** reserva nacional do cobre e Associados - RENCA. Belém: CPRM, 2017. cap. 8, p. 135-150.

CARRANZA, E. J. M. **Geochemical anomaly and mineral prospectivity mapping in GIS**. Amsterdam: Elsevier, 2008.

CAMPOS, L. D.; SOUZA, S. M.; SORDI, D. A.; TAVARES, F. M.; KLEIN, E. L.; LOPES, E. C. S. Predictive Mapping of Prospectivity in the Gurupi Orogenic Gold Belt, North-Northeast Brazil: an example of District-Scale Mineral System Approach to Exploration Targeting. **Natural Resources Research**, v. 26, issue 4, p. 509-534, Oct. 2017. DOI: https://doi.org/10.1007/s11053-016-9320-5

CARRANZA, E. J. M. **Geochemical anomaly and mineral prospectivity mapping in GIS**. amsterdam: Elsevier, 2009. (Handbook of Exploration and Environmental Geochemistry, v. 11).

COOKE, D. R.; HOLLINGS, P.; WALSH, J.L. Giant porphyry deposits: characteristics, distribution, and tectonic controls. **Economic Geology**, v. 100, n. 5, p. 801-818, 2005. DOI: https://doi.org/10.2113/gsecongeo.100.5.801

COLLINS, J. J.; LOUREIRO, A. R. A metamorphosed deposit of Precambrian supergene copper. **Economic Geology**, v. 66, n. 1, p. 192-199, Feb. 1971. DOI: https://doi.org/10.2113/gsecongeo.66.1.192

CORDANI, U. G.; BRITO NEVES, B. B.; FUCK, R. A.; PORTO, R.; THOMAZ FILHO, A.; CUNHA, F. M. B. **Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras**. Rio de Janeiro: Petrobrás, 1984. 70 p. (Ciência Técnica Petróleo. Seção: Exploração de petróleo, 15).

COSTA, M. J.; FRANÇA, J. B.; LINS, C. A. C.; BACCHIEGGA, I. F.; HABEKOST, C. R.; CRUZ, W. B. **Projeto Jaibaras**: relatório final. Recife: CPRM, 1973. v. 1. Convênio DNPM/CPRM.

CZARNOTA, K.; BLEWETT, R. S.; GOSCOMBE, B. Predictive mineral discovery in the eastern Yilgarn Craton, Western Australia: an example of district scale targeting of an orogenic gold mineral system. **Precambrian Research**, v. 183, issue 2, p. 356-377, Nov. 2010. DOI: https://doi.org/10.1016/j.precamres.2010.08.014

DALL'AGNOL, R.; TEIXEIRA, N. P.; RÄMÖ O.T.; MOURA, C.A. V.; MACAMBIRA, M.J. B.; OLIVEIRA, D.C.O. Petrogenesis of the Paleoproterozoic Rapakivi A-type granite of the Archean CarajásMetallogenetic Province, Brazil. **Lithos**, v. 80, issues 1-4, p. 101-129, Mar. 2005. DOI: https://doi.org/10.1016/j.lithos.2004.03.058

DE QUADROS, T.F.P.; KOPPE, J.C.; STRIEDER, A. J.; COSTA, J. F. C. L. Gamma-Ray data processing and integration for Lode-Au deposits exploration. **Natural ResourcesResearch**, v. 12, issue 1, p. 57-65, 2003. DOI: https://doi.org/10.1023/A:1022608505873

DELLA GIUSTINA, M. E. S. **Geocronologia e significado tectônico de rochas máficas de alto grau metamórfico da Faixa Brasília**. 2010. Tese (Doutorado em Geologia) – Universidade de Brasília, Brasília, 2010.

DOCEGEO. Revisão litoestratigráfica da província mineral de Carajás. *In*: Congresso Brasileiro de Geologia, 35., 1988, Belém. **Anexo aos anais**. Belém: SBG, 1988.

DUARTE, T. B.; XAVIER, R. P.; RODRIGUES, J. B. A review of the geodynamic setting of the Volcanic Domain in the Juruena Magmatic Arc, southwestern Amazon Craton, Brazil, based on geochemical, U-Pb and Sm-Nd data. **Journal of the Geological Survey of Brazil**, v. 2, n. 1, p. 37-73, 2019. DOI: https://doi.org/https://doi.org/10.29396/jgsb.2019.v2.n1.4

ELLIOTT, B.A.; VERMA, R.; KYLE, J. R. Prospectivity modelling for Cambrian–Ordovician hydraulic fracturing sand resources around the Llano Uplift, Central Texas. **Natural Resources Research**, v. 25, issue 4, p. 389-415,Dec. 2016. DOI: https://doi.org/10.1007/s11053-016-9291-6

FARACO, M. T. L. **Evolução petrológico-geoquímica das rochas da Suíte Vila Nova na Serra do Ipitinga (NW do Pará).** 1990. Tese (Mestrado em Geoquímica e Petrologia) – Centro de Geociências, Universidade Federal do Pará, Belém, 1990.

FARACO, M. T. L. **Evolução petroquímico-metalogenética das rochas e mineralizações associadas à suíte Vila Nova na Serra do Ipitinga (NW do Pará).** 1997. Tese (Doutorado) – Centro de Geociências, Universidade Federal do Pará, Belém, 1997.

FETTER, A. H. **U/Pb and Sm/Nd geochronological contraints on the crustal framework and geologic history of Ceará state, NW Borborema province, NE Brazil**: implications for the Assembly of Gondwana. 1999. 164 p. Tese (Doutorado em Geologia) – Department of Geology, University of Kansas, Kansas, 1999.

FORD, A.; PETERS, K. J.; PARTINGTON, G. A.; BLEVIN, P. L.; DOWNES, P. M.; FITZHERBERT, J. A.; GREENFIELD, J. E. Translating expressions of intrusion-related mineral systems into mappable spatial proxies for mineral potential mapping: case studies from the Southern New England Orogen, Australia. **Ore Geology Reviews**, v. 111, art. 10294, Aug. 2019. DOI: https://doi.org/10.1016/j.oregeorev.2019.102943

FUCK, R. A.; PIMENTEL, M. M.; ALVARENGA, C. J. S.; DANTAS, E. L. The Northern Brasília Belt. In: HEILBRON, M.; CORDANI, U. G.; ALKMIN, F. F. (ed.). **São Francisco Craton, Eastern Brazil**: tectonic genealogy of a miniature Continent. Switzerland: Springer International Publishing, 2017. p. 205-220. (Regional Geology Reviews).

GARCIA, M. G. M.; PARENTE, C. V.; SILVA FILHO, W. F.; ALMEIDA, A. R. Idade do vulcanismo ácido da Formação Parapuí: implicações na estratigrafia da bacia eopaleozoica Jaibaras-CE. *In*: CONGRESSO BRASILEIRO DE GEOLOGIA, 45., 2010, Belém. **Anais** [...]. Belém: SGB, 2010. 1 CD-ROM.

GIOVANARDI, T.; GIRARDI, V. A. V.; CORREIA, C. T.; TASSINARI, C. C. G.; SATO, K.; CIPRIANI, A.; MAZZUCCHELLI, M. New U-Pb SHRIMP-II zircon intrusion ages of the Cana Brava and Barro Alto layered complexes, central Brazil: constraints on the genesis and evolution of the Tonian Goias Stratiform Complex. **Lithos**, v. 282-283, p. 339-357, Jun. 2017. DOI: https://doi.org/10.1016/j.lithos.2017.03.026

GNOJEK, I.; PRICHYSTAL, A. A new zinc mineralization detected by airborne gamma-ray spectrometry in northern Moravia (Czechoslovakia). **Geoexploration**, v. 23, issue 4, p. 491-502, Dec. 1985.DOI: https://doi.org/10.1016/0016-7142(85)90076-6

GOLDFARB, R. J.; MILLER, L. D.; LEACH, D. L.; SNEE, L. W. Gold deposits in metamorphic rocks of Alaska. *In*: GOLDFARB, R.J.; MILLER, L.D. (ed.). **Mineral deposits of Alaska**. Littleton: Society of Economic Geologists, 1997. p. 151-190. (Economic Geology Monograph Series, v. 9). DOI: https://doi.org/10.5382/Mono.09.07

GUIMARÃES, S. B.; MOURA, M. A.; DANTAS, E. L. Petrology and geochronology of the Bom Jardim de Goiás copper deposit (GO). **Revista Brasileira de Geociências**, v. 42, n. 4, p. 841-862, 2012.

HAGEMANN, S.G.; CASSIDY, K. F. Archean orogenic lode gold deposits. *In*: HAGEMANN, S.G.; BROWN, P.E. (ed.). **Gold in 2000**. Littleton: Society of Economic Geologists, 2000. p. 9-68. (Reviews in Economic Geology, v. 13). DOI: https://doi.org/10.5382/Rev.13.01

GRAINGER, C. J.; GROVES, D. I.; TALLARICO, F. H. B.; FLETCHER, I. R. Metallogenesis of the Carajás Mineral Province, Southern Amazon Craton, Brazil: Varying styles of Arqueanthrough Paleoproterozoic to Neoproterozoic base- and precious-metal mineralization. **Ore Geology Reviews**, v. 33, issues 3-4,p. 451-489,June 2008. DOI: https://doi.org/10.1016/j.oregeorev.2006.10.010

HAGEMANN, S.G.; LISITSIN, V.A.; HUSTON, D.L. Mineral system analysis: Quo vadis. **Ore Geology Reviews**, v. 76, p. 504-522, July 2016. DOI: https://doi.org/10.1016/j.oregeorev.2015.12.012

HASUI, Y.; ABREU, F. A. M.; VILLAS, R. N. N. Província Parnaíba. *In*: HASUI, Y.; ABREU, F. A. M.; VILLAS, R. N. N. **O Pré-Cambriano no Brasil**. São Paulo: Edgard Blücher, 1984. p. 36-45.

HRONSKY, J. M. A.; GROVES, D.I. Science of targeting: definition, strategies, targeting and performance measurement. **Australian Journal of Earth Sciences**,v. 55, p. 3-12, 2008. DOI: https://doi.org/10.1080/08120090701581356

HRONSKY, J. M. A.; GROVES, D. I.; LOUCKS, R. R.; BEGG, G. C. A unified model for gold mineralisation in accretionary orogens and implications for regional-scale exploration targeting methods. **Mineralium Deposita**, v. 47, issue 4, p. 339-358,Apr. 2012. DOI: https://doi.org/10.1007/s00126-012-0402-y

JOLY, A.; PORWAL, A.; MCCUAIG, T.C. Exploration targeting for orogenic gold deposits in the Granites-Tanami Orogen: mineral system analysis, targeting model and prospectivity analysis. **Ore Geology Reviews**, v. 48, 349-383. Oct. 2012. DOI: https://doi.org/10.1016/j.oregeorev.2012.05.004

JULIANI, C.; RYE, O. R.; NUNES, C.M. D.; SNEE, L. W.; CORRÊA-SILVA, R.H.; MONTEIRO, L.V.S.; BETTENCOURT, J. S.; NEUMANN, R.; ALCOVER NETO, A. Paleoproterozoic high-sulfidation mineralization in the Tapajós Gold Province, Amazonian Craton, Brazil: geology, mineralogy, alunite argon age, and stable-isotope constraints. **Chemical Geology**, v. 215, issues 1-4, p. 95-125, Feb. 2005. DOI: https://doi.org/10.1016/j.chemgeo.2004.06.035

KLEIN, E. L. Ore fluids of orogenic gold deposits of the Gurupi Belt, Brazil: a review of the physico-chemical properties, sources, and mechanisms of Au transport and deposition. In: GAROFALO, P. S.; RIDLEY, J. R. (ed.). **Gold transporting hydrothermal fluids in the Earth's crust.** London: Geological Society of London, 2014. p. 121-145. (Special Publications, 402). DOI: https://doi.org/10.1144/SP402

KLEIN, E. L.; FUZIKAWA, K. Origin of the CO2-only fluid inclusions in the Palaeoproterozoic Carará vein-quartz gold deposit, Ipitinga Auriferous District, SE-Guiana Shield, Brazil: implications for orogenic gold mineralisation. **Ore Geology Reviews**, v. 37, p. 31-40, 2010.

KLEIN, E. L.; MOURA, C. A. V. São Luiz Craton and Gurupi Belt (Brazil): possible links with the West African Craton and surrounding Pan-African belts. *In*: PANKHURST, R. J.; TROUW, R. A. J.; BRITO NEVES, B. B.; DE WIT, M. J. (ed.). **West Gondwana**: Pre-Cenozoic correlations across the South Atlantic Region. London: Geological Society of London, 2008. p. 137-151. (Special Publications, 294). DOI: https://doi.org/10.1144/SP294.8

KLEIN, E. L.; MOURA, C. A. V.; KRYMSKY, R.; GRIFFIN, W. L. The Gurupi belt in northern Brazil: Lithostratigraphy, geochronology, and geodynamic evolution. **Precambrian Research**, v. 141, issue 3-4, p. 83-105, Nov. 2005. DOI: https://doi.org/10.1016/j.precamres.2005.08.003

KLEIN, E. L.; RODRIGUES, J. B.; LOPES, E. C. S.; SOLEDADE, G. L. Diversity of Rhyacian granitoids in the basement of the Neoproterozoic-Early Cambrian Gurupi Belt, northern Brazil: Geochemistry, U–Pb zircon geochronology, and Nd isotope constraints on the Paleoproterozoic magmatic and crustal evolution. **Precambrian Research**, v. 220-221, p. 192-216, Nov. 2012. DOI: https://doi.org/10.1016/j.precamres.2012.08.007

KLEIN, E. L.; LOPES, E. C. S.; TAVARES, F. M.; CAMPOS, L. D.; SOUZA-GAIA, S. M.; NEVES, M. P.; PERROTTA, M. M. **Área de relevante interesse mineral cinturão do Gurupi:** estados do Pará e Maranhão. Brasília: CPRM, 2017. Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/18041

KLEIN, E. L.; ROSA-COSTA, L. T. Geology of quartzvein gold deposits in the Ipitinga Auriferous District, northern Brazil, southeastern Guiana Shield. **Géologie de la France**, n.2-4, p. 231-242, 2003.

KLEIN, E. L.; VASQUEZ, M. L.; ROSA-COSTA, L. T.; CARVALHO, J. M. A. Geology of Paleoproterozoic gneiss-and granitoid-hosted gold mineralization in southern Tapajós Gold Province, Amazonian Craton, Brazil. **International Geology Review**, v. 44, issue 6, p. 544-558, 2002. DOI: https://doi.org/10.2747/0020-6814.44.6.544

KNOX-ROBINSON, C. M.; WYBORN, L.A. I. Towards a holistic exploration strategy: using geographic information systems as a tool to enhance exploration. **Australian Journal of Earth Sciences**, v. 44, p. 453-463, 1997. DOI: https://doi.org/10.1080/08120099708728326

LAFON, J. M.; COUTINHO, M. G. N. 2008. Isótopos radiogênicos de chumbo. *In*: COUTINHO, M. G. N. (ed.). **Província Mineral do Tapajós**: geologia, metalogenia e mapa provisional para ouro em SIG. Rio de Janeiro: CPRM, 2008. p. 299-326.

LAMARÃO, C. N.; DALL'AGNOL, R.; LAFON, J. M; LIMA, E. F. Geology, geochemistry, and Pb-Pb zircon geochronology of the Paleoproterozoic magmatism of Vila Riozinho, Tapajós Gold Province, Amazonian craton, Brazil. **Precambrian Research**, v. 119, issues 1-4, p. 189-223, Dec. 2002. DOI: https://doi.org/10.1016/S0301-9268(02)00123-7

LAMARÃO, C. N.; DALL'AGNOL, R.; PIMENTEL, M. M. Nd isotopic composition of Paleoproterozoic volcanic rocks of Vila Riozinho: implications for the crustal evolution of the Tapajós Gold Province, Amazon Craton. **Journal of South American Earth Sciences**, v. 18, issues 3-4, p. 277-292, 2005. DOI: https://doi.org/10.1016/j.jsames.2004.11.005

LAUX, J. H.; PIMENTEL, M. M.; DANTAS, E. L.; ARMSTRONG, R.; JUNGES, S. L. Two neoproterozoic crustal accretion events in the Brasília belt, central Brazil. **Journal of South American Earth Sciences**, v. 18, issue 2, p. 183-198, 2005. DOI: https://doi.org/10.1016/j.jsames.2004.09.003

LEMOS, R. L.; GASPAR, J. C. Magmatismo Kamafugítico em Maicuru e seu ambiente tectônico. In: CONGRESSO BRASILEIRO DE GEOLOGIA, 41., 2002, João Pessoa. **Anais** [...]. João Pessoa: SBG, 2002.

MACHADO, I. C. **Gurupi Gold Project:** Cipoeiro and Chega Tudo properties. Feasibility study. TechnoMine Services LLC, 2011. Available at: https://www.sedar.com/GetFile.do?lang=EN&docClass=24&issuerNo=00019963&issuerType=03&projectNo=01692707&docId=2812427. Accessed on: Dec. 18, 2019.

MACHADO, N.; LINDENMAYER, Z.; KROGH, T.H.; LINDENMAYER,Z.G.U-Pb geochronology of Archaean magmatism and basement reactivation in the Carajás area, Amazon shield, Brazil. **Precambrian Research**, v. 49, issues 3-4, p. 329-354, Feb. 1991. DOI: https://doi.org/10.1016/0301-9268(91)90040-H

MATOS, J. H. S. N. **Evolução metalogenética da Mina de Cobre Pedra Verde (CE)**. 2012. 107 p. Dissertação (Mestrado em Geologia e Recursos Naturais) – Instituto de Geociências, Universidade Estadual de Campinas, São Paulo, 2012.

MCCUAIG, T. C.; HRONSKY, J. M. A. The mineral system concept: the key to exploration targeting. *In*: KELLEY, K. D.; GOLDEN, H. C. **Building Exploration Capability for the 21st Century**. Littleton: Society of Economic Geologist, 2014. p. 153-175. (Special Publications of the Society of Economic Geologists, 18). DOI: https://doi.org/10.5382/SP.18.08

MCCUAIG, T. C.; BERESFORD, S.; HRONSKY, J. Translating the mineral systems approach into an effective exploration targeting system. **Ore Geology Reviews**, v. 38, issue 3, p. 128-138, nov. 2010. DOI: https://doi.org/10.1016/j.oregeorev.2010.05.008

MELO, A. F. F.; PINHEIRO, M. M.; LOBATO, T. A. **Projeto Cérbero I - Alfa**: relatório final. Belém: CPRM, 1985. 3 v.

JORGE JOÃO, X. S.; FRIZZO, S. J.; MARINHO, P. A. C.; CARVALHO, J. M. A.; SILVA NETO, C. S.; SOUZA, A. N.; GUIMARÃES, L. R. **Projeto Sudoeste do Amapá:** relatório final: texto – parte I. Belém: CPRM, 1978. v.1-a, 224 p.

MORETO, C.P.N.; MONTEIRO, L.V.S.; XAVIER, R.P.; CREASER, R. A.; DUFRANE, A.; TASSINARI, C. G.; SATO, K.; KEMP, A.; AMARAL, W. S. Neoarchean and Paleoproterozoic Iron Oxide-Copper-Gold Events at the Sossego Deposit, Carajás Province, Brazil: Re-Os and U-Pb Geochronological Evidence.**Economic Geology**, v. 110, n. 3, p.809-835, 2015. DOI: https://doi.org/10.2113/econgeo.110.3.809

MOSHER, Z. G. (2013). **Technical report and resource estimate on the Cachoeira property, State of Pará, Brazil**. Vancouver: Tetra Tech, 2013. Available at: http://brazilresources.com/_resources/tech_report_oct_2013.pdf. Accessed in: 4 May, 2016.

NOGUEIRA,A.C. R.; TRUCKENBRODT, W.; PINHEIRO, R.V.L. Formação Águas Claras, Pré-Cambriano da Serra dos Carajás: redescrição e redefinição litoestratigráfica. **Boletim Museu Paraense Emílio Goeldi**, v. 7, p. 177-277,1995.

NYKÄNEN, V.; LAHTI, I.; NIIRANEN, T.; KORHONEN, K.Receiver Operating Characteristics (ROC) as validation tool for prospectivity models – a magmatic Ni-Cu case study from the Central Lapland greenstone belt, Northern Finland. **Ore Geology Reviews**, v. 71, p. 53-860, Dec. 2015. DOI: https://doi.org/10.1016/j.oregeorev.2014.09.007

OLIVEIRA, A. C. S.; LIRA, R. R. C (org.). **Geologia e recursos minerais da folha Rio Roosevelt - SC.20-X-B:** estado do Amazonas. Manaus: CPRM, 2019. Escala 1:250.000. (Programa Geologia do Brasil - PGB. Levantamento Geológicos Básicos do Brasil).

OLIVEIRA, C. G.; OLIVEIRA, F. B.; DELLA GIUSTINA, M. E. S.; MARQUES, G. M.; DANTAS, E. L.; PIMENTEL, M. M.; BÜHN, B. M. The Chapada Cu-Au deposit, Mara Rosa magmatic arc, Central Brazil: constraints on the metallogenesis of Neoproterozoic large porphyry-type deposit. **Ore Geology Reviews**, v. 72, part. 1, p. 1-21, 2016. DOI: https://doi.org/10.1016/j.oregeorev.2015.06.021

OLIVEIRA, C. M.; FONSECA, L. R.; OLIVEIRA, N. P. A laterita titanífera de Maraconaí (PA). *In*: CONGRESSO BRASILEIRO DE GEOLOGIA, 35., 6 - 13 nov. 1988, Belém. **Anais...** Belém: SBG-Núcleo Norte, 1988. 6 v., v. 1. p. 271-285.

PALHETA, E. S.; ABREU, F. A. M.; MOURA, C. A. V. Granitóides proterozóicos como marcadores da evolução geotectônica da região nordeste do Pará, Brasil. **Revista Brasileira de Geociências**, v. 39, n. 4, p. 647-657, 2009.

PARENTE, C. V.; BOTELHO, N. F.; SANTOS, R. V.; GARCIA, M. G. M.; OLIVEIRA, C. G.; VERISSIMO, C. U. V. Contexto geológico, tipológico e geoquímico isotópico das brechas hidrotermalizadas de ferro e cobre tipo-IOCG associadas à bacia eo-paleozoica Jaibaras, da Província Borborema, Brasil. *In*: FRANTZ, J. C.; MARQUES, J. C.; JOST, H. (ed.). **Contribuições à metalogenia do Brasil**. Porto Alegre: UFRGS, 2011. v. 1, p. 175-198.

PEREIRA, R.M. P.; ROSIÈRE, C. A.; SANTOS, J.O. S.; LOBATO, L.M.; FIGUEIREDO E SILVA R.C.; MCNAUGHTON, N.J. Unidade Caninana: sequência clástica paleoproterozoica revelada por datação U em zircões detríticos da Província Mineral Carajás. *In*: SIMPÓSIO DE GEOLOGIA DA AMAZÔNIA, 11., 2009, Manaus. **Anais**[...]. Manaus: SBG, 2009.

PHILLIPS, G.N.; POWELL, R. Formation of gold deposits: a metamorphic devolatilization model. **Journal of Metamorphic Geology**, 28, issue 6, p. 686-718, Aug. 2010. https://doi.org/10.1111/j.1525-1314.2010.00887.x

PIMENTEL, M. M.; FUCK, R. A. Neoproterozoic crustal accretion in central Brazil. **Geology**, v. 20, n. 4, p. 375-379, 1992. DOI: https://doi.org/10.1130/0091-7613(1992)020<0375:NCAICB>2.3.CO;2

PIMENTEL, M. M.; FUCK, R. A.; BOTELHO, N. F. Granites and the geodynamic history of the neoproterozoic Brasília belt, Central Brazil: a review. **Lithos**, v. 46, issue 3, p. 463-384, Mar. 1999. DOI: https://doi.org/10.1016/S0024-4937(98)00078-4

PIRES, A. C.B. Identificação geofísica de áreas de alteração hidrotermal, Crixás-Guarinos, Goiás. **Revista Brasileira de Geociências**, v. 25, n. 1, p. 61-68, 1995. Available at: http://www.ppegeo.igc.usp.br/index.php/rbg/article/view/11501/0

POLLARD, P.J.; TAYLOR, R.J.; PETERS, L.; MATOS, F.; FREITAS, C.; SABOIA, L.; HUHN, S. 40Ar-39Ar datingofArcheaniron oxide Cu-AuandPaleoproterozoic granite-relatedCu-Audeposits in the Carajás Mineral Province, Brazil: implications for geneticmodels. **Mineralium Deposita**, v. 54, issue3, p. 329-346, Mar. 2019. DOI: https://doi.org/10.1007/s00126-018-0809-1.

PRADO, E. M. G.; BERGAMI, G. N.; SILVA, L. C.; RODRIGUES, T. R.; GUERRA, G. I. T.; SOUZA, A. A.S; CAMPOS, L. D. New Cu-Pb occurrence in gossan and hydrothermal breccias in the Nova Brasilândia Group, Rondônia State, Brazil: preliminary results, perspectives and interpretations. **Technical Report**, Brasília, n. 7, Jun. 2016.

PRADO, F. S.; MENDONÇA, J. C. G. S.; MORAIS, J. B. A.; MEDEIROS, M. F.; ASSUNÇÃO, P. R.; ANDRADE, V. A.; MEDEIROS, R. P. **Projeto Martinópole**: relatório final. Recife: CPRM. 1979. v. 1.

PRADO, F. S.; SCHEID, C.; SILVA, S. M. P.; MEDEIROS, M. F.; MELO, F. **Projeto Uruoca**: relatório preliminar de pesquisa de cobre, chumbo e zinco nos municípios de Uruoca, Martinópole, Marco e Senador Sá: Estado do Ceará. Fortaleza: CPRM, 1981. v. 1. Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/5633

RIDLEY, J. R. (ed.). **Gold transporting hydrothermal fluids in the Earth's crust**. London: Geological Society of London, 2014. p. 121-145. (Special Publications, 402). DOI: https://doi.org/10.1144/SP402

RIZZOTTO, G. J.; SANTOS, J. O. S.; HARTMANN, L. A.; TOHVER, E.; PIMENTEL, M. M.; MCNAUGHTON, N. J . The Mesoproterozoic Guaporé suture in the SW Amazonian Craton: Geotectonic implications based on field geology, zircon geochronology and Nd-Sr isotope geochemistry. **Journal of South American Earth Sciences**, v. 48, p. 271-295, Dec. 2013. DOI: http://dx.doi.org/10.1016/j.jsames.2013.10.001.

ROSA-COSTA, L. T. D., CHAVES, C. L., SILVA, C. M. G. D., CAMPOS, L. D., ABRANTES, B. K. C., TAVARES, F. M., & LAGO, A. L. **Área de relevante interesse mineral:** reserva nacional do cobre e Associados-RENCA. Belém: CPRM, 2017.

SALGADO, S. S.; CAXITO, F. A.; QUEIROGA, G. N.; CASTRO, M.P. Stratigraphy, petrography and tectonics of the manganese-bearing Buritirama Formation, Northern Carajás Domain, AmazonCraton. **Brazilian Journal of Geology**, v. 49, n.1, Apr. 2019. DOI: https://doi.org/10.1590/2317-4889201920180106.

ROSA-COSTA, L. T.; LAFON, J. M.; DELOR, C. Zircon geochronology and Sm-Nd isotopic study: further constraints for the Archean and Paleoproterozoic geodynamical evolution of the southeastern Guiana Shield, north of Amazonian Craton, Brazil. **Gondwana Research**, v. 10, n. 3-4, p. 277-300, Nov. 2006. DOI: https://doi.org/10.1016/j.gr.2006.02.012

ROSA-COSTA, L. T.; MONIÉ, P.; LAFON, J. M.; ARNAUD, N. O. 40Ar–39Ar geochronology across Archean and Paleoproterozoic terranes from southeastern Guiana Shield (north of Amazonian Craton, Brazil): evidence for contrasting cooling histories. **Journal of South American Earth Sciences**, v. 27, issues 2-3, p. 113-128, 2009. DOI: https://doi.org/10.1016/j.jsames.2008.08.010.

ROWLAND, J. V.; SIBSON, R.H. Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. **Geofluids**,v. 4, issues 4, p. 259-283, Nov. 2004. DOI: https://doi.org/10.1111/j.1468-8123.2004.00091.x

SAUNDERS, D. F.; TERRY, S. A.; THOMPSON, C.K. Test of national uranium resource evaluation gamma-ray spectral data in petroleum reconnaissance. **Geophysics**, v. 52, n. 11, p. 1547-1556,1987. DOI: https://doi.org/10.1190/1.1442271

SANTOS, J.O. S. Geotectônica dos Escudos das Guianas e Brasil Central. In: BIZZI, L.A.; SCHOBBENHAUS, C.; VIDOTTI, R.M.; GONÇALVES, J. H. (ed.). **Geologia, tectônica e recursos minerais do Brasil**: texto, mapas e SIG. Brasília: CPRM, 2003. cap. 4, p. 169-226.

SANTOS, J.O. S.; HARTMANN, L. A.; GAUDETTE, H. E.; GROVES, D. I.; MCNAUGHTON, N. J.; FLETCHER,I.R. A new understanding of the Provinces of the Amazon Craton based on Integration of Field Mapping and U-Pb and Sm-Nd Geochronology. **GondwanaResearch**, v. 3, n. 4, p. 453-488, Oct. 2000. DOI: https://doi.org/10.1016/S1342-937X(05)70755-3

SANTOS, J. O. S.; VAN BREEMEN, O. B.; GROVES, D. I.; HARTMANN, L. A.; ALMEIDA, M. E.; MCNAUGHTON, N. J.; FLETCHER, I. R. Timing and evolution of multiple Paleoproterozoic magmatic arcs in the Tapajós Domain, Amazon Craton: constraints from SHRIMP and TIMS zircon, baddeleyite and titanite U-Pb geochronology. **Precambrian Research**, v. 13, issues 1-2, p. 73-109, 2004. DOI: https://doi.org/10.1016/j.precamres.2004.01.002

SANTOS, T. J. S. **Evolução tectônica e geocronológica do extremo nordeste da Província Borborema**. 1999. Tese (Doutorado) – Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, São Paulo, 1999.

SAWATZKY, D. L.; RAINES, G. L.; BONHAM-CARTER, G. F.; LOONEY, C.G. **Spatial Data Modeller (SDM)**: ArcMAP 9.3 geoprocessing tools for spatial data modelling using weights of evidence, logistic regression, fuzzy logic and neural networks. 2009. Available at: http://arcscripts.esri.com/details.asp?dbid=15341.

SCANDOLARA, J. E. **Geologia e evolução do terreno Jamari, embasamento da faixa Sunsas, Aguapeí, centro-leste de Rondônia, sudoeste do craton Amazônico**. 2006. Tese (Doutorado) – Programa de Pós-Graduação em Geologia Regional Instituto de Geociências, Universidade de Brasília, Brasília, 2006.

SILLITOE, R. H.; HEDENQUIST, J. W. Linkages between volcanotectonic settings, ore-fluid compositions, and epithermal precious metal deposits.*In*:SIMMONS, S. F.; GRAHAM, I. **Volcanic, geothermal, and ore-forming fluids**: rulers and witnesses of processes within the earth. Littleton: Society of Economic Geologists, 2003. (Special Publications of the Society of Economic Geologists, v. 10). DOI:https://doi.org/10.5382/SP.10.16

SOUZA, J. O.; FRASCA, A. A. S.; OLIVEIRA, C. C. (org.). **Geologia e recursos minerais dafolha Alta Floresta**: relatório integrado. Brasília: CPRM, 2005. Escala 1:500.000. (Programa Levantamentos Geológicos Básicos do Brasil - PLGB; Projeto Província Mineral de Alta Floresta - Promin Alta Floresta).

SQUIRE, R. J.; MILLER, J. M. Synchronous compression and extension in East Gondwana: tectonic controls on world-class gold deposits at 440 Ma. **Geology**, v. 31, n. 12, p. 1073-1076, 2003. DOI: https://doi.org/10.1130/G19710.1

TALLARICO, F.H. B.; FIGUEIREDO, B. R.; GROVES, D. I.;KOSITCIN, N.; MCNAUGHTON, N. J.; FLETCHER, I. R.; REGO, J.L. Geology and SHRIMP U–Pb Geochronology of the Igarapé Bahia Deposit, Carajás Copper–Gold Belt, Brazil: an Archean (2.57 Ga) example of iron–oxide Cu–Au–(U–REE) mineralization. **Economic Geology**, v. 100, n. 1, p. 7-28,2005. DOI: https://doi.org/10.2113/100.1.0007

TAVARES,F.M. **Evolução geotectônica do nordeste da Província Carajás**. 2015. Tese (Doutorado) – Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2015.

TAVARES, F.M.; OLIVEIRA, J.K.M.; PAULA, R.R.; COSTA, I.S.L.; PRADO, E.B.S. O Cinturão Norte do Cobre da Província Mineral de Carajás: épocas metalogenéticas de controles críticos das mineralizações. *In*: SIMPÓSIO DE GEOLOGIA DA AMAZÔNIA15., 2017, Belém. **Anais** [...]. Belém:SBG,2017.

TAVARES, F. M.; TROUW,R. A. J.; SILVA, C. M. G.; JUSTO; A. P., OLIVEIRA, J. K. M. The multistage tectonic evolution of the northeastern Carajás Province, Amazonian Craton, Brazil: revealing complex structural patterns. **Journal of South American Earth Sciences**, v. 88, p. 238-252, Dec. 2018. DOI:https://doi.org/10.1016/j.jsames.2018.08.024

VASQUEZ, M. L.; RICCI, P. S. F.; KLEIN, E. L. Granitóides pós-colisionais da porção leste da Província Tapajós. *In*: KLEIN, E. L.; VASQUEZ, M. L.; ROSA-COSTA, L. T. (ed.). **Contribuições à geologia da Amazônia**. Belém: SBG, 2002. v. 3, p. 67-84.

VASQUEZ, M. L.; CHAVES, C. L.; MOURA, E. L.; OLIVEIRA, J. K. M. **Geologia e recursos minerais das folhas São Domingos, SB.21-Z-A-II e Jardim do Ouro, SB.21-Z-A-III**: estado do Pará. Belém: CPRM, 2017. 305 p. Escala 1:100.000.

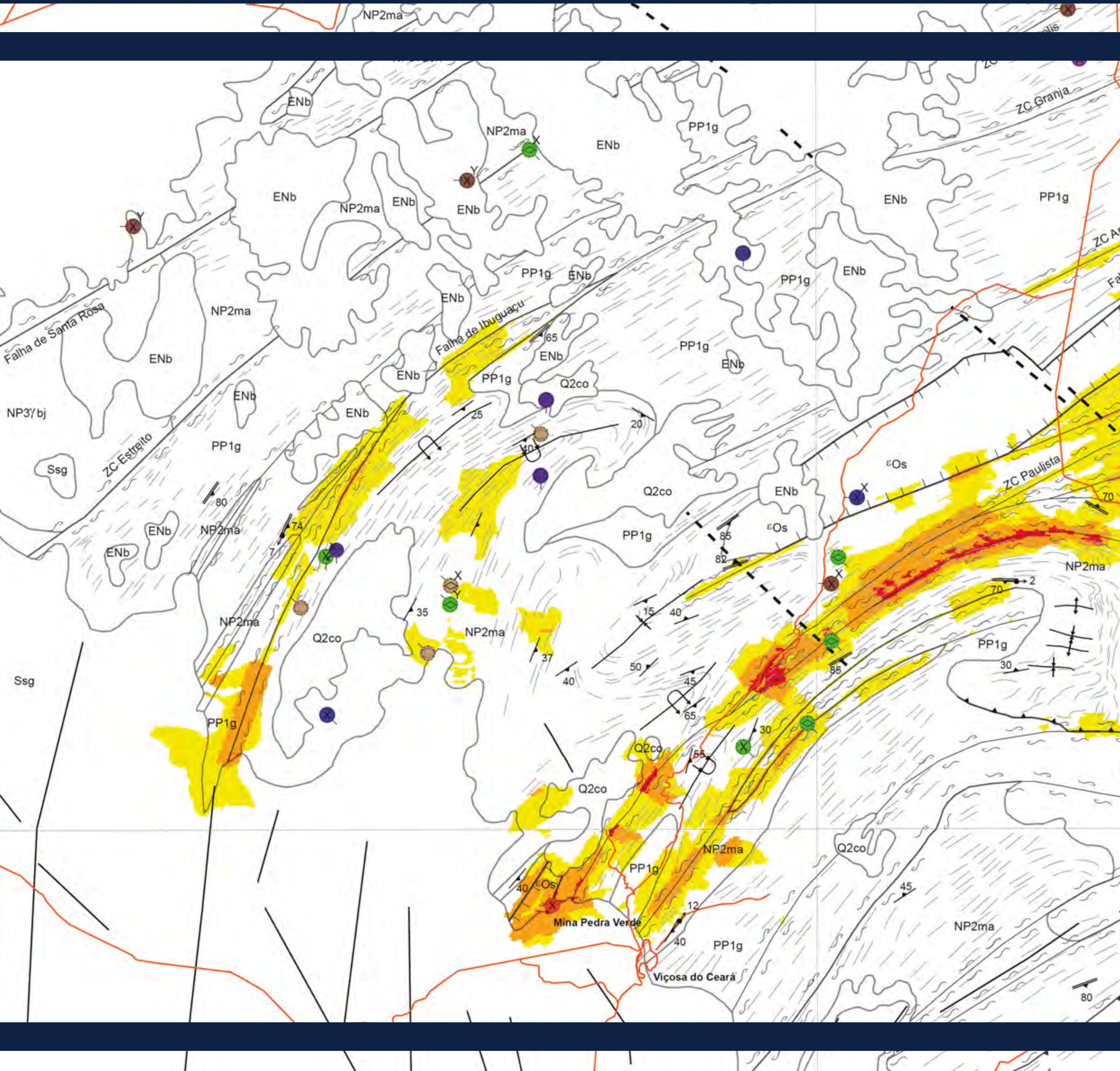
WYBORN, L. A. I.; HEINRICH, C. A.; JAQUES, A. L. Australian Proterozoic mineral systems: essential ingredients and mappable criteria. *In:* AUSLMM ANNUAL CONFERENCE, 1994, Darwin. **Conference proceedings**. Parkville: Australasian Institute of Mining and Metallurgy, 1994. p. 109-115.

XAVIER, R. P.; MONTEIRO, L.V. S.; MORETO, C.P. N.; PESTILHO, A.L. S.; MELO, G.H. C.; SILVA, M.A.D.; AIRES, B.; RIBEIRO, C.; SILVA, F.H.F. The iron oxide copper-gold system of the Carajás Mineral Province, Brazil. *In:* HEDENQUIST, J. W.; HARRIS, M.; CAMUS, F. **Geology and genesis of major copper deposits and districts of the world**: a tribute to Richard H. Sillitoe. Littleton: Society of Economic Geologists, 2012. (Special Publications of The Society of Economic Geologists, v. 16). DOI:https://doi.org/10.5382/SP.16.17

ZHANG, N.; ZHOU, K. Mineral prospectivity mapping with weights of evidence and fuzzy logic methods. **Journal of Intelligent & Fuzzy Systems**, v. 29, n. 6, p. 2639-2651, 2015. DOI: https://doi.org/10.3233/IFS-151967.

GEOLOGICAL SURVEY OF BRAZIL
CPRM

ISBN:
978-85-7499-582-0 (print)
978-85-7499-582-3 (pdf)



www.cprm.gov.br

geosgb.cprm.gov.br

This publication can be downloaded free of charge from www.cprm.gov.br