

# PREDICTIVE GEOPHYSICAL MODEL FOR GOLD MINERALIZATION IN THE QUADRILÁTERO FERRÍFERO, BRAZIL: THE CASE OF CUIABÁ MINE

ADALENE MOREIRA SILVA<sup>1</sup>, ANNE MCCAFFERTY<sup>2</sup>, AUGUSTO CÉSAR BITTENCOURT PIRES<sup>1</sup>  
AND LUÍS CLÁUDIO RIBEIRO RODRIGUES<sup>3</sup>

**ABSTRACT** Geophysical and radiometric signatures of the immediate area around the Cuiabá Mine is determined using the probability ratio mapping technique, a new statistical approach to map favorable host geologic units and mineralized environments. Airborne magnetic, electromagnetic and radiometric data collected as part of the Rio das Velhas Project were processed to characterize the geophysical and radiometric signatures at the well-known Cuiabá deposit. Areas with similar signatures to that of Cuiabá were then located in the survey area to delineate possible unknown deposits and occurrences related to carbonate-sulfide-greenstone-hosted mineralization. This approach allows for an objective exploration strategy to link geological and geophysical information over large survey areas. The results of this modeling procedure infer areas of exposed and subsurface Cuiabá-type BIF that are important to gold exploration in the area and require ground follow-up studies.

**Keywords:** Quadrilátero Ferrífero, Rio das Velhas Greenstone Belt, Cuiabá Mine, Cuiabá-type BIF, mineralized environments.

**INTRODUCTION** The Cuiabá Mine, one of the largest gold mines in Brazil, is hosted by carbonate-sulfide banded iron formation and is the major gold producer in the Quadrilátero Ferrífero (Fig. 1). The deposit produces 540 000 tones of ore per year with an average grade of 8 g/t Au and silver as by-product. The cut-off grade is 4.0 g/t gold and proven gold reserves exceed 180 tones of gold (Ribeiro Rodrigues 1998).

Banded iron formations (BIF) are by far the most important hosts of the economically viable gold mineralization in the Rio das Velhas Greenstone Belt. BIFs have contributed 99% of the total gold production, and are associated with different styles of mineralization. The banded iron formations also have different geological and physical properties that can be divided in three types: oxide, carbonate-sulphide (Cuiabá-type BIF), and ankerite/ferroan dolomite, quartz and plagioclase (*Lapa Seca-type BIF*) types (Ribeiro Rodrigues 1998, Silva 1999). The Cuiabá-type BIF consists of alternating sulfide layers, light quartz-carbonate layers and dark quartz-carbonate layers varying in thickness from a few millimeters up to one meter (Ribeiro-Rodrigues *et al.* 1994).

In the Quadrilátero Ferrífero, many exploration surveys have been conducted based on old prospects, surface geological and geochemical mapping. These efforts were the primary tools responsible for many gold discoveries. Limited outcrops and a thick weathered soil profile have been a problem to find new deposits in this region (Ladeira 1980, Pinto 1996, Silva 1999). However, recent technologies have allowed emphasis to be placed on the use of geophysical surveying followed by incorporation of various data layers into an expert system and GIS (geographic information system) (Silva 1999).

A new approach called probability ratio mapping (Lee *et al. in press*) is used in this study to allow for digital integration of several geospatial data layers to determine if there exists a characteristic signature over the area immediately surrounding the Cuiabá deposit. Additionally, the method is used as a way to evaluate the geophysical and radiometric signatures of the geologic host to the Cuiabá deposit.

**GEOLOGIC OVERVIEW** The QF is situated in the southern portion of the São Francisco Craton and is composed of Archean granite-gneissic terrains (GGTs); Archean Greenstone Belt (Rio das Velhas Supergroup); Paleoproterozoic (Minas Supergroup and Itacolomi Group) and Paleoproterozoic-Mesoproterozoic (Espinhaço Supergroup) supracrustal units (Cordani *et al.* 1980, Chemale Jr. *et al.* 1994) (Fig. 1).

The supracrustal units, Minas and Rio das Velhas Supergroups, surround and are surrounded by granite-gneiss domes and namely: Bação, Caeté, Bonfim, Belo Horizonte and Santa Rita. These domes consist of polydeformed gneiss, metatonalites to metagranites, amphibolites, meta-ultramafic rocks, as well as pegmatites formed in amphibolite facies conditions during the Archean and in the Transamazonian Eras (Cordani *et al.* 1980). The contact with adjacent supracrustal units is tectonic.

The Rio das Velhas Supergroup (RVSG – 3.0-2.7 Ga) is divided in two groups. The first, Nova Lima Group (NLG) comprises a lower

ultramafic unit, an intermediate felsic-mafic unit and a clastic-mafic-felsic unit (Ladeira 1980). These are overlain by metasedimentary rocks of the Maquiné Group.

## THE CUIABÁ MINE: GENERAL CHARACTERISTICS, DEFORMATION PATTERN, AND FEATURES OF GENETIC SIGNIFICANCE

**Geology of the Deposit** The lithological sequence of the Cuiabá Mine encompasses metavolcanic and metasedimentary rocks of the Nova Lima Group, which forms the lower part of the Rio das Velhas Greenstone Belt sequence (Vial 1988). The structure of the deposit is dominated by a large-scale, closed, south-east (30-40°) plunging tubular fold (Vieira 1992, Ribeiro-Rodrigues *et al.* 1996b, 1998, Toledo 1997). The locally gold bearing Cuiabá-Banded Iron-Formation (BIF), varying in thickness from 6 to 15 m, lies between lower mafic metavolcanic rocks (andesites) intercalated with discrete bands of carbonaceous schists and metapelites in the footwall, and carbonaceous phyllite and schist,

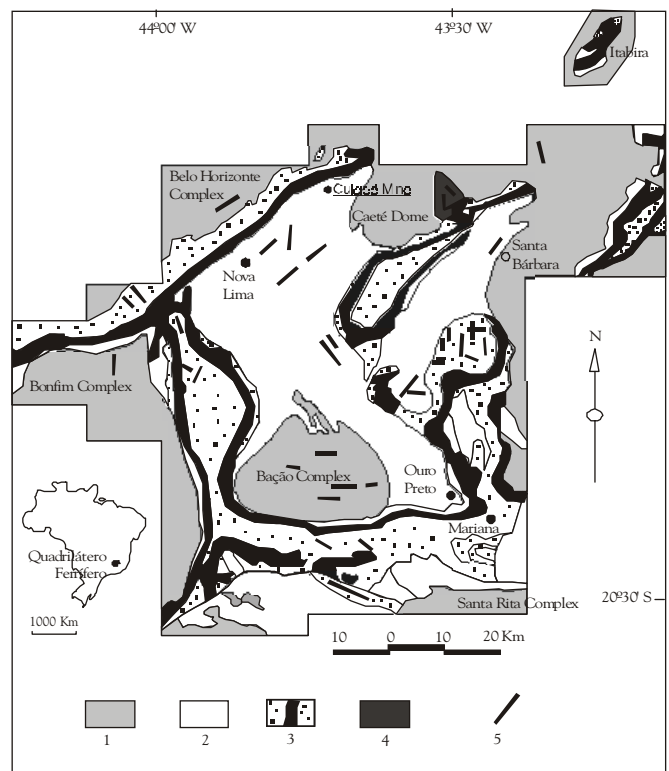


Figure 1-Geological sketch of Quadrilátero Ferrífero (Modified from Dorr 1969). 1-Granite-gneiss terrains, 2-Rio das Velhas Supergroup, 3-Minas Supergroup, 4-Espinhaço Supergroup, 5-Mafic dykes swarms.

1 Laboratório de Geofísica Aplicada, Instituto de Geociências, Universidade de Brasília, Brasília, DF, Brazil, 70910-900 (adalene@unb.br)  
2 United States Geological Survey, Box 25046, Mail Stop 964, Denver Federal Center, Denver, CO, USA, 80225 (anne@usgs.gov)  
3 Departamento de Geologia, Universidade Federal de Ouro Preto, MG, Brazil, 35400-000 (lcr@gold.com.br)

upper mafic metavolcanic rocks (basalts), metapelites and metavolcanoclastic rocks in the hanging wall. The Cuiabá-type BIF represents one single (up to 15 m thick) horizon of Algoma-type, carbonaceous-facies BIF and/or ferruginous chert. The rocks exhibit pronounced compositional banding, characterized by alternating, dark carbon-stained, carbonate-quartz bands with translucent, quartz-carbonate and chert bands (Ribeiro Rodrigues 1998).

**Gold mineralization** Three styles of gold mineralization can be identified in the Cuiabá Mine: (1) the main mineralization is **stratabound** and hosted by sulfide-rich BIF/chert. Subordinate types of mineralization are **shear-related**, (2) **mafic- or sediment-hosted** represented by disseminated sulfides, and/or (3) **quartz veins** occurring in bedding-parallel shear zones within metavolcanics or metasediments (Ribeiro Rodrigues 1998).

**BIF-HOSTED MINERALIZATION** Economic-grade gold mineralization is associated mainly with six ore shoots, ranging in thickness from 1 to 6 m, contained within the Cuiabá-type BIF horizon. The orebodies consist of alternating sulfide layers, light quartz-carbonate layers and dark quartz-carbonate layers varying in thickness from a few millimeters up to one meter (Ribeiro-Rodrigues *et al.* 1994). Typical mineralogy of the unmineralized Cuiabá-type BIF includes siderite, ankerite, quartz and minor amounts of calcite and carbonaceous matter. The orebodies represent mineralized segments of the Cuiabá-type BIF (> 4 ppm Au) which grade laterally into lower-grade or barren BIF. The ore shoots consist of alternating sulfide, light quartz-carbonate, dark carbonate-quartz and chert layers, varying in thickness from a few millimeters up to one meter. Pyrite is the predominant sulfide (> 90 vol.%), and other sulfide phases are pyrrhotite, arsenopyrite, chalcopyrite, sphalerite and galena. Gold is fine-grained (< 60 µm) and occurs as inclusions, in fractures and along grain boundaries of pyrite. Silver contents in gold grains vary from 8 to 24 wt.% (Ribeiro-Rodrigues *et al.* 1997).

The genesis of the gold mineralization at Cuiabá is controversially discussed, involving syngenetic versus epigenetic models. The stratiform nature of the mineralization suggests a syngenetic concentration of gold during seafloor deposition of sulfide-facies BIF (e.g., Ladeira 1980). However, the results of detailed textural and structural study of the Cuiabá orebodies (Ribeiro-Rodrigues 1998) do not favor this model. According to this author, an epigenetic origin for gold mineralization is clearly indicated by: (1) the selective and pervasive replacement of carbonate layers by sulfides. The mineralized portions of the Cuiabá-type BIF are the result of post-sedimentary sulfidation, forming large replacement orebodies. The extensive replacement has imparted a pseudo-syn-sedimentary pattern to the gold ores, which show alternating sulfide layers and primary quartz-carbonate and chert bands; (2) the structural control of the ore shoots which are parallel to the D<sub>1</sub>-phase mineral-stretching lineation (Ribeiro-Rodrigues 1998).

**DATA SETS** A variety of regional data sets from Rio das Velhas Greenstone Belt have been registered and analyzed using a geographic information system (GIS). The data sets include the Rio das Velhas Project geological map and Rio das Velhas airborne geophysical survey data (airborne magnetic, radiometrics, frequency domain electromagnetics). The data sets were variously processed to prepare them for the probability ratio analysis. Data layers include a reduced-to-pole magnetic anomaly map, horizontal gradient of the reduced-to-pole magnetic anomaly, a terrace-conductivity map from the 4175 Hz resistivity data, and a potassium concentration map. Detailed descriptions of the processing steps taken to produce layers for the probability ratio analysis are described in Silva (1999).

**OVERVIEW OF THE PROBABILITY RATIO MAPPING TECHNIQUE** In general, the probability ratio method determines a numerical value that describes the strength of a spatial association between a training area and a test class within a predictive layer. Values resulting from the analysis are called probability ratios or weights and describe the statistical likelihood that a particular layer will predict the location of a given training region. Weights greater than 1 indicate a positive association between the test class and the training region; a value less than 1 suggests a negative association; and a value equal to one implies a random association. For example, a weight of 12 for a

class implies that class is 12 times more likely to be found within the reference area than in any other (non-reference) area in the study. The mathematical basis for the probability ratio technique is well described in Lee *et al.* (in press).

For this study, classes within the airborne geophysical and radiometric data are defined as predictive layers and tested against training areas defined by the Cuiabá Mine environment and the Mestre Caetano Formation. Probability ratios are calculated to determine whether or not there exists a characteristic signature over the mineralized environment and geologic host with a known high potential for gold mineralization. We infer areas mapped outside the training areas share the same geophysical and radiometric signatures and would be likely candidates for gold mineralization.

**THE CUIABÁ PREDICTIVE MODEL** Predictive layers against which the training areas are tested are defined based on the following geologic and geophysical rationales: **a)** the mapped Mestre Caetano Formation, which is host to the Cuiabá deposit, is used as a training area to predict other favorable host areas for carbonate-sulfide BIF-hosted-gold mineralization; **b)** the location of Cuiabá and its associated mineralization is known and used as a training area for the geophysical and radiometric data; **c)** the reduced-to-pole magnetic anomaly data map positive magnetization domains associated with Cuiabá-type **d)** boundaries of magnetization sources mapped from the horizontal gradient of the reduced-to-pole map the important known structures that are main controls of the Archean-greenstone-hosted gold deposits and **e)** conductivity domains map and **f)** the potassium data map areas of potassic enrichment attributed to hydrothermal alteration related to the gold mineralization.

**Cuiabá model construction** Training areas with circular buffers around the Cuiabá Mine location (radius of 500-, 1000-, and 2000-meters) were constructed to determine zones of influence with geologic, metallogenic, and geophysical meaning. The various buffer sizes were individually evaluated to define an optimum buffer-radius that yielded maximum contrast to map the Cuiabá-mineralized environment. Buffers of 1-km and 2-km yielded poor results in the form of low probability ratios. The poor results are inferred to reflect more variable physical and radiometric properties farther from the actual deposit. One explanation for the variability is that the geological setting surrounding the mines is highly variable due to a combination of local processes such as hydrothermal alteration, deformation and lithological succession, compared to more regional lithologic homogeneity away from the immediate deposit environment that is unaffected by local mineralizing processes. A second explanation may be in variable thickness and size of the banded iron formation host that would yield different geophysical and radiometric signatures from deposit to deposit.

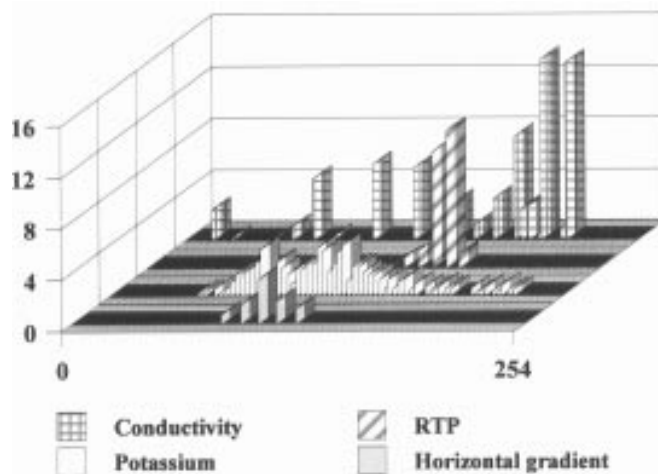


Figure 2-Probability ratios for reduced-to-pole magnetic data, conductivity data from 4175 Hz resistivity, and potassium data for a 500-m radius area around Cuiabá. Height of the bar shows the strength of the spatial association between the predictive layer and the mine environment. The larger the probability ratio, the greater the association between the Cuiabá deposit environment and the geophysical or radiometric data layer.

The optimum distance was interpreted to be 500-m (Silva 1999) and was selected not only for geologic but also due to geophysical constraints. Data from the airborne survey in this study were collected along flight lines spaced 250 meters apart. At a maximum, five flight lines could cross the 500-meter radius test area, which provides the minimum resolution in defining a spatial feature in the geophysical data.

Prior to modeling, all data were rescaled to values between 1 and 255 using a histogram equalization transformation also called uniform distribution stretching. This transformation modifies the values so the greatest contrast enhancement occurs in the data range with the most values. This technique tends to bring out more detail in areas with more frequently occurring data serving to emphasize subtle features (Silva 1999). Predictive layers tested against the 500-m radius area around Cuiabá include the rescaled reduced-to-pole magnetic anomaly data, the horizontal gradient of reduced-to-pole, conductivity data calculated from the 4175-Hz resistivity, and potassium data. Fig. 2 shows a chart of the probability ratio results for the various predictive layers. The x-axis shows relative levels of magnetization, rtp horizontal gradient, conductivity, and potassium classes from low to high. The y-axis defines the probability ratio value for a particular class. Fig. 2 shows where in the geophysical and radiometric data there is significance to the mine environment around Cuiabá.

A final predictive model for the Cuiabá mineralized environment was generated using an approach that sums probability ratios of various predictive layers at each cell location. This is called a sum-of-weights approach. This approach has been successfully used to generate predictive models for regional studies in geologic units and other deposits in the Rio das Velhas Greenstone Belt (Silva 1999),

Montana (Lee *et al.* in press) and mineral resource study in southeast Alaska (McCafferty *et al.* in press).

Co-registered pixels were added to create composites of multiple layers of geophysical and radiometric information. Only those pixels with probability ratios greater than 2 were considered for incorporation into final models. Additionally, each pixel present in final models that incorporated more than one evidential layer represents a either sum of probability ratios between multiple data layers or null values. For this reason, the minimum weight for any predictive model is 4 ( $2 + 2$ ). For example, for pixels where there is a probability ratio for conductivity but not for magnetization, these pixels are assigned a null value.

**The Cuiabá Model** Fig. 3 shows carbonate-sulfide -BIF-hosted gold predictive model based on the area around the Cuiabá Mine. This map shows areas with similar geophysical and potassic signatures as that around Cuiabá. Areas in gray scale show levels of probability ratios with values from 12 (light gray) to 32 (black). These areas define a combination of classes in the magnetization, conductivity and potassium data that is 12 to 32 times more likely to occur over the region around Cuiabá Mine than another area in the study area. The few areas mapped outside Cuiabá Mine have similar physical properties as that of the mineralized environment found at Cuiabá. We would infer that these areas may be favorable for gold mineralization.

Detail of the signature around Cuiabá Mine point out few candidates that are interpreted to have the potential to contain similar mineralization as that found at Cuiabá, the largest mine operation at present (Fig. 4). The principal potential target of this model (labeled **Potential target A** on Fig. 4) occurs outside of the Mestre Caetano Formation.

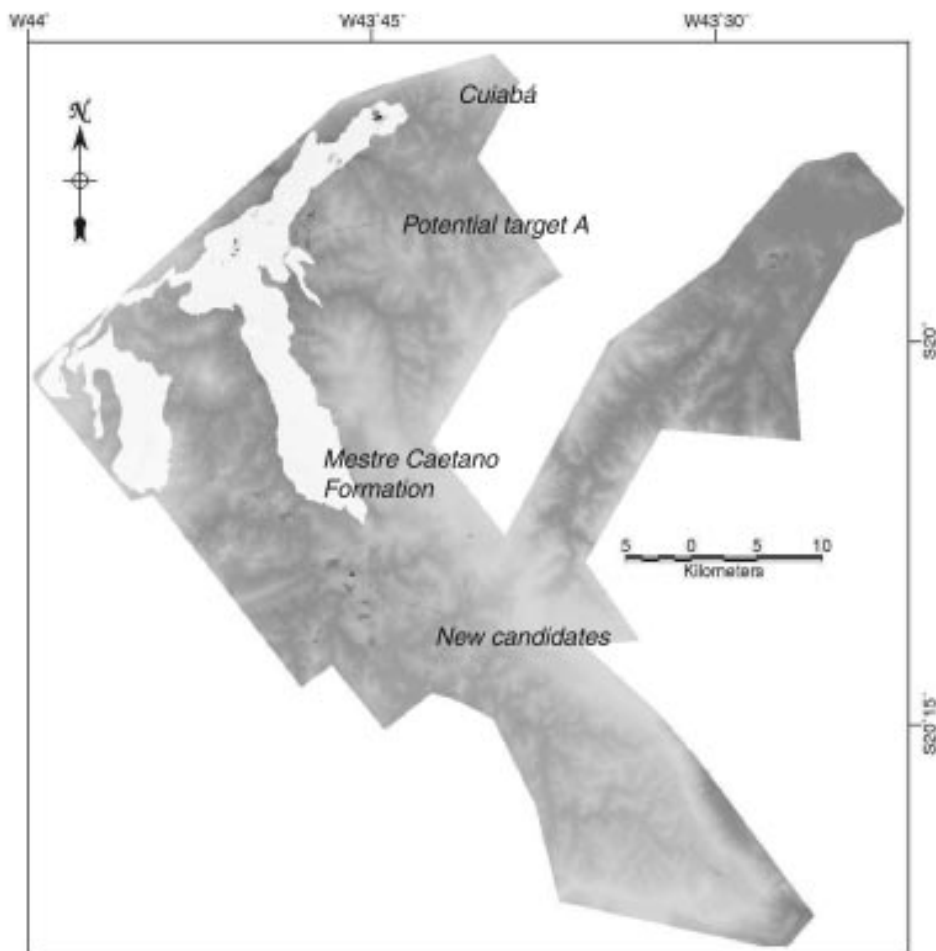


Figure 3-Predictive geophysical model for the Cuiabá-type BIF, based on magnetization, horizontal gradient of reduced-to-pole data, conductivity, and potassium data around Cuiabá Mine. White polygons are mapped host rock (Mestre Caetano Formation). Areas in greyscale show results of probability ratio mapping technique with weights from 12 (light gray) to 32 (black). These areas define a strong association of magnetization, conductivity and potassium that is 12 to 32 times more likely to occur over the region around Cuiabá Mine than another area in the study area. The few areas mapped outside Cuiabá Mine have similar physical and radiometric properties as that found at Cuiabá.

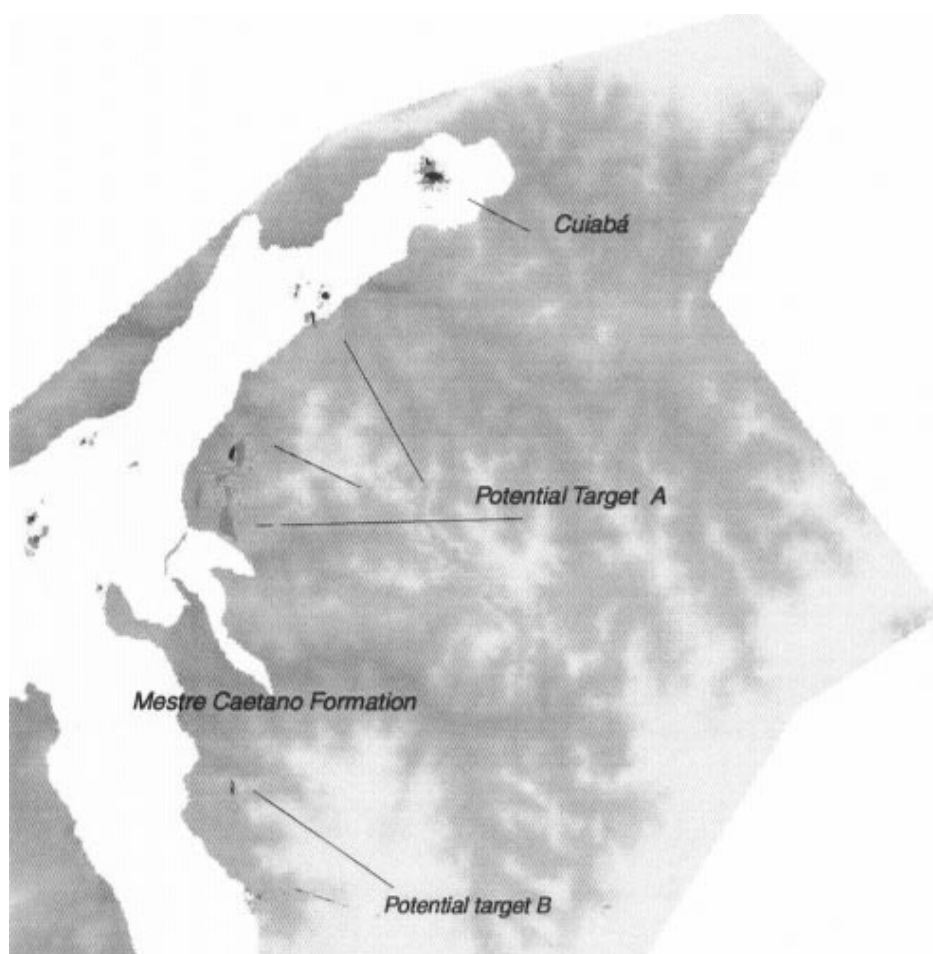


Figure 4-Detail of geophysical signature around Cuiabá Mine. There are few candidates that share the same physical and potassic signatures as the mineralized environment around Cuiabá.

## References

- Chemale Jr. F., Rosière C.A., Endo I. 1994. Tectonic Evolution Of The Quadrilátero Ferrífero, Mg, Brazil. *Precambrian Research*, **65**:25-54.
- Cordani U.G., Kawashita K., Mueller G., Quade H., Reimer V., Roeser H.P., 1980. Interpretação tectônica e petrológica de dados geocronológicos do embasamento do bordo sudeste do Quadrilátero Ferrífero, Minas Gerais. *Anais da Academia Brasileira De Ciências*, **52**:785-799.
- Dorr J.V.N. 1969. Physiographic, Stratigraphic, And Structural Development Of The Quadrilátero Ferrífero, Minas Gerais. *U.S.G.S. Paper*, **641-A**:1-110.
- Hildenbrand J.D. & Perez Da Gama M.F. 1993. *Levantamento aero- magnetométrico, gamaespectrométrico e eletromagnético. Projeto Rio Das Velhas*. Relatório final, V1, Texto técnico, Prospec S/A, 47 p.
- Ladeira E.A. 1980. *Metallogenesis Of Gold At The Morro Velho Mine, And In Nova Lima District, Quadrilátero Ferrífero, Minas Gerais, Brazil*. University of Western Ontario, Ph. D. Thesis, 272p.
- Lee G.K., McCafferty A.E., Alminas H.V., Bankey V., Elliot J.E., Frishman D., Knepper D.H.Jr., Kulik D.M., Marsh S.P., Phillips J.D., Pitkin J.A., Smith S.M., Stoesser D.B., Tysdal R.G., Van Gosen B. *Geoenvironmental assessment of Montana: United States Geological Survey Digital Data Series DDS-x*. in press.
- McCafferty A.E., Smith B.D., Sole T.C., Karl S., Taylor C.D. Predictive geophysical models for select geologic units and mineralized environments, Kuprenof and Zarembo Islands, Southeast Alaska: *United States Geological Survey Professional Paper* PP-x, in press.
- Pinto P.C. 1996. Introdução. *Projeto Rio Das Velhas. Mapa geológico integrado. Escala: 1:100.000. Texto Explicativo*. Programa De Estudos Mineiros. Convênio DNPM-CPRM. DNPM-Secretaria De Minas e Energia-Ministério de Minas e Energia, 1-10.
- Ribeiro-Rodrigues L.C. 1998. *Gold Mineralization In Archaean Banded Iron Formation, Quadrilátero Ferrífero, Minas Gerais, Brazil - The Cuiabá Mine*. Rwth Aachen, Germany, Aachener Geowissenschaftliche, Ph. D. Thesis, 262p.
- Ribeiro-Rodrigues L.C., Friedrich G., Oliveira C.G. 1996b. Gold mineralization in archaean banded iron formations in Brazil. In: 30<sup>th</sup> International Geological Congress, Beijing, 1996. *Extend Abstracts* ... 3:756.
- Silva A.M. 1999. *Integração de dados geológicos e geofísicos utilizando-se uma nova técnica estatística para seleção de alvos para exploração mineral, aplicada ao Greenstone Belt Rio das Velhas, Quadrilátero Ferrífero*. Instituto de Geociências, Universidade de Brasília, Ph.D. Thesis, 195p.
- Silva A.M., McCafferty A.E., Pires A.C.B. 1999. A new approach to map host rock for gold exploration in the Rio Das Velhas Greenstone Belt, Quadrilátero Ferrífero, Minas Gerais, Brazil. *International Congress of the Brazilian Geophysical Society*, 6, *Proceedings*, CD-ROM
- Toledo C.L.B. 1997. *Controle estrutural da mineralização aurífera na mina de Cuiabá, setor noroeste do Greenstone Belt Rio das Velhas, Quadrilátero Ferrífero*. Universidade Estadual de Campinas, M.Sc. Thesis, 166p.
- Vial D.S. 1988a. Mina de ouro de Cuiabá, Quadrilátero Ferrífero, Minas Gerais. In: C. Schobenhäus & C.E.S. Coelho (eds.) *Principais depósitos minerais do Brasil, metais básicos não ferrosos, ouro e alumínio*, **V.3**: 413-419.
- Vieira F.W.R. 1991a Textures and processes of hydrothermal alteration and mineralization in the Nova Lima Group, Minas Gerais, Brazil. In: E.A. Ladeira (ed.) *Brazil GOLD'91*, AA Balkema, Rotterdam, 319-325.
- Vieira F.W.R. 1992. *Geologia da Mina de Cuiabá, níveis 03 e 04. Mineração Morro Velho Ltda.*, Relatório Interno, 23 p.

Contribution IGC-090

Received February 28, 2000

Accepted for publication May 25, 2000