Geophysical analysis applied to mineral exploration in the region of Morro do Pilar, eastern part of Southern Serra do Espinhaço – Minas Gerais, Brazil

Maristella Moreira Santos* (IFMG/Campus Congonhas) and Maria Sílvia Carvalho Barbosa (DEGEO/UFOP).

Abstract

This study aims to evaluate the mineral potential in the region of Morro do Pilar, eastern part of Southern Serra do Espinhaço, MG-Brazil, through qualitative and quantitative analysis of the Magnetometric and Radiometric Methods, integrated with geological data. Quantitative analysis was performed from the 2D inversion method (Euler Deconvolution) of the magnetometric data, which systematized, allowed to observe the geometry of the ore bodies in depth, using a 3D model. It was delimited potential areas in iron, platinum and gold ore, associated with itabirite, serpentinites and of hydrothermal origin, respectively. Based on the results obtained, a drilling project may be proposed in the area.

Introduction

In the early 20th century, the presence of outcropping or shallow mineral deposits became increasingly scarce, leading to the development of geophysical methods, mainly the magnetometry and radiometry, which aid the mapping of subsurface deposits.

On this basis, the study area was chosen (Fig. 1). It is located on the eastern part of Southern Serra do Espinhaço, Minas Gerais, Brazil. The region has a great potential for iron, gold, platinum mineralization, among others and, despite the great potential, non-outcropping ore bodies have not been described in the literature yet. Thus, from magnetometry and radiometry data, it was possible to identify the signature of the geophysical response that the ore bodies have and, through the use of the Euler Deconvolution of the potential method in question, obtain the distribution and geometry of bodies in depth, in this way, contributing to the region's mineral research studies.

Geological background

The study area covers the Conceição do Mato Dentro (Guimaraes *et al*. 1996) and Serro (Knauer & Grossi Sad 1996) Sheets, belonging to the “Espinhaço Project”.

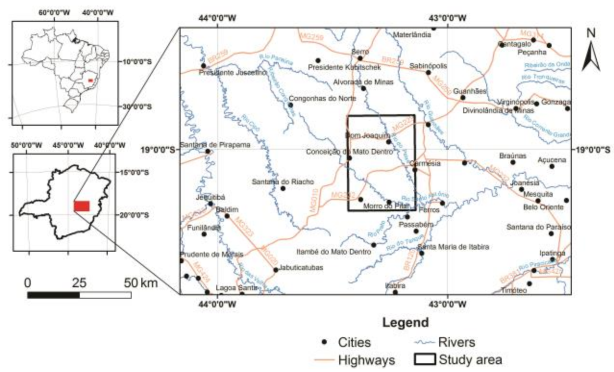

Fig. 1 – Localization map of the study area.

Litho-stratigraphic Units in the area are arranged roughly according to tracks of north-south direction, caused by a system of thrust faults with mass movements towards the west, which put the units in tectonic contact among themselves (Guimaraes *et al.* 1996).

The following units outcrop in the region (Fig. 2): the Gouveia Complex, from Archean age, includes gneissic rocks and granitoids of granitic to granodioritic trend (e.g., Pflug & Carvalho 1964); the Guanhães Group (Grossi Sad *et al*. 1989), from Archean to Paleoproterozoic age, is represented by their Middle (banded iron formations) and Superior (banded gneisses with amphibolites, quartzites, metaultramafics and banded iron formation intercalations) formations; the Rio Mata Cavalo Metavolcanic-sedimentary Sequence, also from Archean to Paleoproterozoic age, is represented by metaultramafics with iron, quartzites and phyllites formations (e.g., Dossin 1985); the Costa Sena Group, probably related to the Early Proterozoic, is composed of muscovite-quartz schist (Fogaça *et al*. 1984); the Serro Group, probably from the Early Proterozoic, occurs in the form of large tectonic slivers of metaultramafic rocks, interspersed with quartz schist, fine quartzite and banded iron formation (Renger 1972); the Zagaia Unit, also probably from the Early Proterozoic age, is predominantly metasedimentary, both chemistry, with banded iron formation and metachert, as clastic, with varied types of quartzites (Assis 1982); the Serra da Serpentina Group, probably from the Early Proterozoic age, presents quartzitic, schist, itabiritic and phyllitic units (e.g., Dossin 1985); the Espinhaço Supergroup (Almeida & Hasui 1984), from the Middle Proterozoic, is represented mainly by the Sopa-Brumadinho Formation (Guinda Group), localized band of metavolcanic and acid metasubvolcanic rocks of the Conceição do Mato Dentro Metaigneous Suite are also recognized. The Sopa-Brumadinho

Formation is represented by the Rio Preto (micaceous quartzites and schists, being individualized major phosphate levels) and the Itambé do Mato Dentro (pure and ferruginous quartzites) Units. The Guinda Group is still represented by the Itapanhoacanga Formation (fine to medium quartzites with important horizons of banded iron formation, not being rare bodies of polimitic metaconglomerate and hematitic phyllites), acid intrusive bodies from the Middle Proterozoic age, usually show mylonitic contacts with the surrounding rocks; metadiabases and amphibolites, from the Late and/or Middle Proterozoic age, are identified individually as well as diabase intrusions dated from the Cretaceous (Grossi Sad *et al*. 1990).

The mineral resource of major importance in this region is iron ore, whose main deposits are located in the Serpentina and Escadinha Hills, near Conceição do Mato Dentro and Morro do Pilar. In the area close to Morro do Pilar, it is described the occurrence of platinum, palladium and gold, associated with alluvium, colluvium and veins that traverse quartzites and serpentinites (Guimarães et al. 1996).

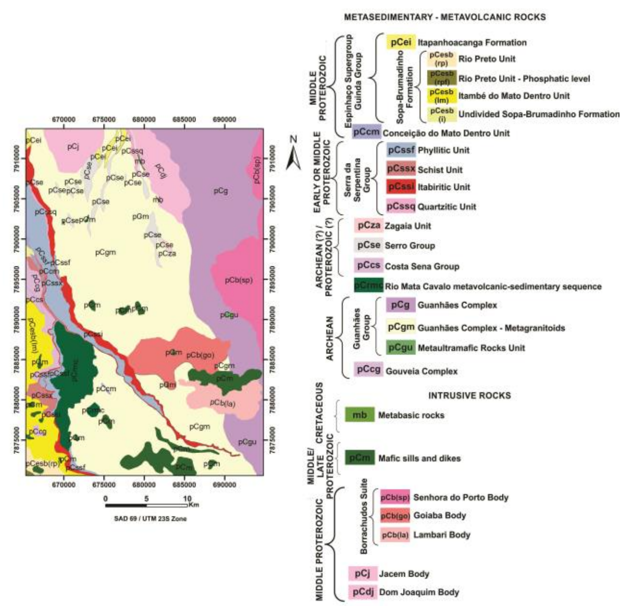

Fig. 2 – Geological map of the study area (modified from Guimarães *et al*. 1996 and Knauer & Grossi Sad 1996).

Method

In this work, we used the aeromagnetometrics and aerorradiometrics databases, provided by CODEMIG. The study area is covered by the survey Area 3 – Morro do Pilar – Serro – Guanhães, from the Aerogeophysical Survey Program of Minas Gerais, conducted in 2001 by LASA Engenharia e Prospecções S.A.

The data were processed for the generation of various thematic maps used in this study (Fig. 3). The file that contains the data is an ASCII type and was imported to the OASIS MONTAJ 7.0.1 program (GEOSOFT system), being converted into a database with .gdb extension. Through WINXY routine of the program, data were cut out to cover just the study area.

For the confection of images, the data were interpolated in a regular grid of 300m by the minimum curvature method. Then, magnetometric (Anomalous Magnetic Field; Analytic Signal; Vertical Derivative; Residual Field; Horizontal Derivatives in X and in Y; Vertical Derivative of Analytic Signal; Upward Continuation) and radiometric (K, Th, U channels and Total Count; Th/K, U/K, U/Th ratios; Ternary Image; F Parameter) thematic maps were generated.

Using the "ArcGis program (version 9.3) ", georeferenced maps were integrated into the geological data in GIS environment, in order to make the qualitative interpretation of the data. The geological database used for integration with the geophysics is referred to the Espinhaço Project (1996), a partnership between CODEMIG and the Instituto de Geociências, UFMG, in agreement with SEME/COMIG. The association has resulted in the availability of data in GIS format of the geological map, in original scale 1: 100000, in 2012.

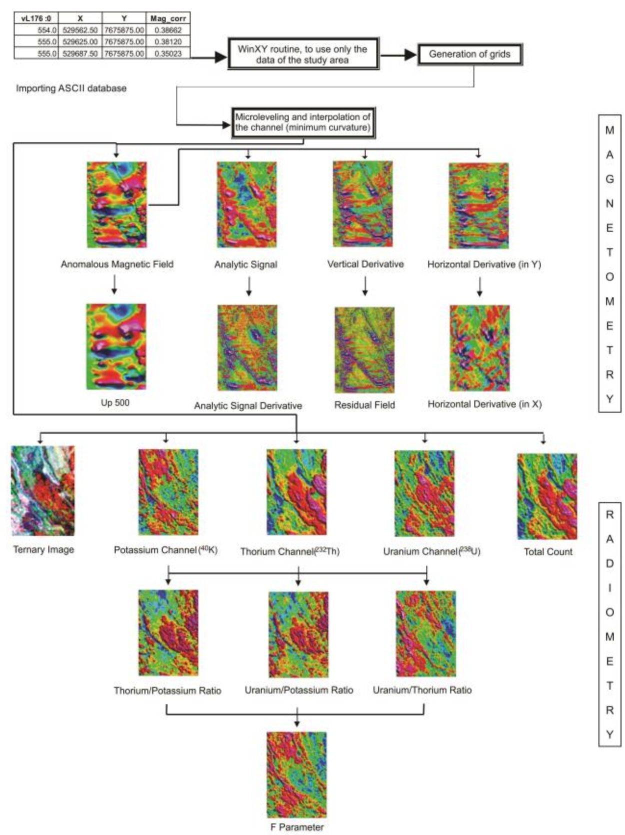

Fig. 3 – Flowcharts of the aeromagnetometric and aeroradiometric data processing steps of the study area.

With the use of a free version of Euler program (version 1.00), from the School of Geosciences – University of Witwatersrand, it was processed the Euler Deconvolution (2D) of magnetometric profiles equidistant and EW direction, aiming at the quantitative interpretation of magnetometric data, that integrated with geological data (by bibliography), making it possible to visualize, in depth, the structural conditioning of magnetic sources associated with possible mineralization of the study area (through a 3D model produced in ArcScene program). Hence, areas of high mineral potential were delimited, contributing in this way to the mineral research studies in the region.

Results and discussion

Magnetometry

The analysis of the magnetization of the rocks of the study area was based on the observation of the wavelength and amplitude of the anomalies. We used the Analytical Signal thematic map to delimit the anomalies, because this product transforms mathematically dipole in monopole anomalies, thus facilitating the interpretation. In this way, three different magnetic domains were identified, named, here, magnetofacies, associated with the magnetic anomalies of high, intermediate and low amplitudes (Fig. 4A). The Magnetofacies 1 represents high magnetic amplitudes and is associated with the rocks of the Serra da Serpentina Group (itabirite, phyllite, schist, quartzite); with amphibolite and gneiss from the Rio Mata Cavalo Metavolcanic-sedimentary Sequence; with mica quartzite, banded iron formation, metaconglomerate, hematite phyllite and felsic metavulcanic of the Itapanhoacanga Formation; and with schist, chloritite, amphibolite, quartzite, serpentinite of the Serra Group. The Magnetofacies 2 presents moderate magnetic relief (intermediate amplitude anomalies) and is associated with granite of the Jacém Body; the biotite-(hornblende) granite, orthogneiss, granitic augen gneiss and biotite granite of the Senhora do Porto, Goiaba and Lambari Bodies; mafic dikes and sills, the schist, quartzite and phosphatic level of the Rio Preto Unit; and granitoid of the Dom Joaquim Body. Low amplitudes are individualized in Magnetofacies 3, being related to schist, granite, gneiss, quartzite, banded iron formation and mafic metavolcanic rock of the Costa Sena Group, and quartzite, phyllite and metaconglomerate of the Itambé do Mato Dentro Unit. The granitoids of the Guanhães Complex present low to high magnetization, possessing, therefore, variations in terms of magnetic anomalies, arising from his compositional variation.

Figure 4B shows the magnetofacies map overlapping the geological map of the study region.

The magnetic lineaments (Fig. 5) were delimited on the Analytic Signal map and present main structuring in the directions EW and NW-SE, being intercepted by lineaments of NE-SW direction, that represent the Brasiliano Event (last tectonic-metamorphic event that affected the region). Because the lineaments of EW direction are less evident in radiometric maps, it can be said that they are possibly older than the NW-SE lineaments.

Radiometry

The analysis of the radiometric domains (radiofacies) was done on the basis of the values presented in the thorium (^{232}Th), uranium (^{238}U) and potassium (^{40}K) channel maps, from which were interpreted three radiofacies, with

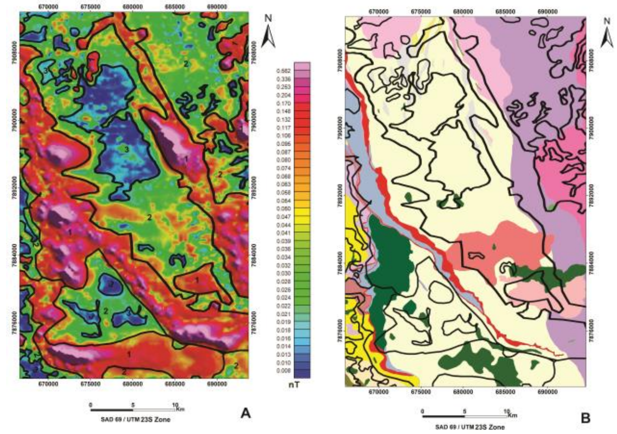

Fig. 4 – Magnetofacies overlapping image of the Analytical Signal (A) and the geological map of the study area (B – see Fig. 2 caption).

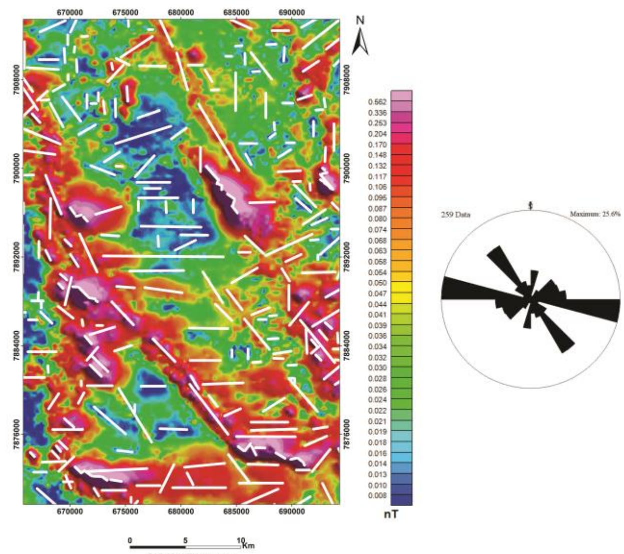

Fig. 5 – Magnetic lineaments (white) delimited from the Analytical Signal map and rose diagram of lineaments.

similar signatures of gamma radiometry, classified according to the variation of the K, U and Th radioelements concentration (Fig. 6A). Each radioelement was classified qualitatively according to their relative concentration in low, medium and high.

The Radiofacies A, where concentrations of U and Th are relatively high and K concentration is low, corresponds to the biotite-(hornblende) granite, orthogneiss, granitic augen gneiss, biotite granite of the Lambari, Goiaba and Senhora do Porto Bodies, besides being related to granite, metarhyolite of the Conceição do Mato Dentro Unit, and schist, granite, gneiss, banded iron formation, quartzite, mafic metavolcanic rock of the Costa Sena Group. The Radiofacies B, in which K, U and Th intermediate concentration is observed, relates to the mafic dikes and sills, the muscovite schist, quartzite of the Serra da Serpentina Group; granitoid, gneiss of the Gouveia Complex; chloritite, amphibolite, quartzite, schist, serpentinite of the Serro Group; and granite of the Jacém

Body. The Radiofacies C, of relatively low U and Th concentrations and high K concentration, is associated with itabirite, phyllite and fine quartzite of the Serra da Serpentina Group; schist and quartzite of the Rio Preto Unit; quartzite, phyllite and metaconglomerate of the Itambé do Mato Dentro Unit; amphibolite and gneiss of the Rio Mata Cavalo Metavolcanic-sedimentary Sequence; mica quartzite, banded iron formation, metaconglomerate, hematite phyllite and felsic metavolcanic of the Itapanhoacanga Formation; granitoid of the Dom Joaquim Body; and phosphatic level of the Rio Preto Unit. The granitoids of the Guanhães Complex present low to high concentrations of K, U and Th, since in these units occur greater variation in the composition of the rocks. Figure 6B shows the radiofacies map overlapping the geological map of the study area.

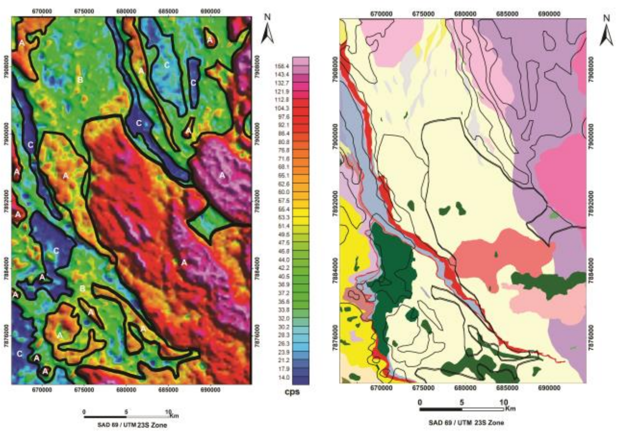

Fig. 6 – Radiofacies overlapping the Th channel map (A) and the geological map of the study area (B – see Fig. 2 caption).

The main radiometric structural features were characterized from the Th channel map. The analysis of this structure shows the predominance of lineaments with NW-SE direction, and lineaments of NS, EW and NE-SW direction subordinates (Fig. 7). Such structures are more superficial than the interpreted magnetic data, being related to structural weakness zones, where contrasts of radioelements values occur.

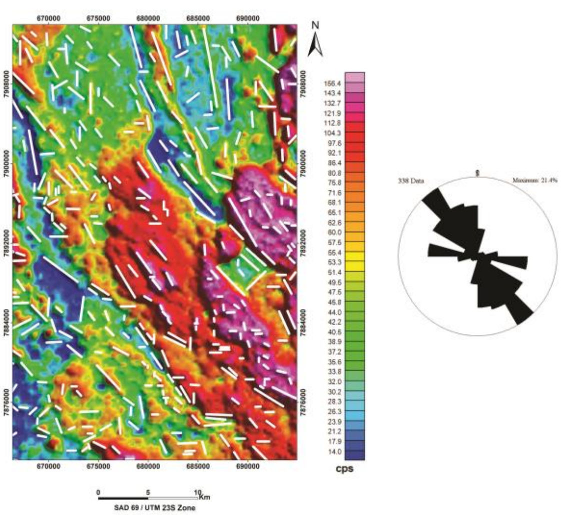

Fig. 7 – Radiometric lineaments (white) interpreted from Th channel map and the rose diagram of lineaments.

Euler Deconvolution

In order to perform the inversion of the data collected, whose main purpose is estimate the depth of the sources which cause the magnetic anomalies, we used the Euler Deconvolution method, for it provides fast solutions in profiles. A total of 15 magnetic profiles (Analytical Signal) of EW direction, 30km long and 3km equidistant were performed (Fig. 8B).

So as to obtain the inversion of the data in all profiles, we used the Euler 2D software (free program), with the following parameters: structural index equal to 1.0 (physical model – monopole; geological model – contact), window size equal to 11 and maximum depth ranging between 1500 and 5000m (Fig. 8A).

The analysis of the in-depth profiles allows us to interpret a series of folds and faults arranged laterally, beyond the presence of shear zones with orientation about NS and NW-SE.

Based on the data obtained, it was possible, through the krigging method in the ArcScene program, to create a 3D interpolation (Fig. 9), on which are displayed the deep structures, as well as their inclination and extension.

Doing the analysis of the 3D model in Figure 9, it is possible to conclude that four distinct anomalies reach higher depths, being related to low frequency magnetic anomalies (high wavelength).

It is important to note that the anomalies associated with high magnetic amplitude (ferromagnetic minerals) correspond to areas conducive to mining, showing high frequency and, therefore, relatively minor depths.

The model generated here, integrated with geological data (by bibliography), allowed to delimit areas of high mineral potential.

Mineral potential

In order to delimit areas with high mineral potential, database of areas required for mining and mining concession of the DNPM (SIGMINE, 2012 – Fig. 10A and Fig. 11) was used. Geophysical and, secondarily, geological characteristics of those areas were defined and new areas with mineral potential were sought.

In the study area, mineral potential of iron, platinum (Fig. 10A) and gold (Fig. 11) ore were delimited.

For geophysical analysis of areas with potential for iron and platinum ore, the Analytic Signal Derivative map was consulted, considering that high-amplitude anomalies surrounded by lower anomalies (Fig. 10B) result from outcrop or shallow bodies, whereas for potential areas in gold ore, the radiometric map of F parameter was analyzed. This map consists of the joint analysis between the radioelement K and the U/Th ratio (Fig. 11). In the F parameter thematic map, it can be inferred through their higher values, areas of hydrothermalism (one of the possible origins of gold).

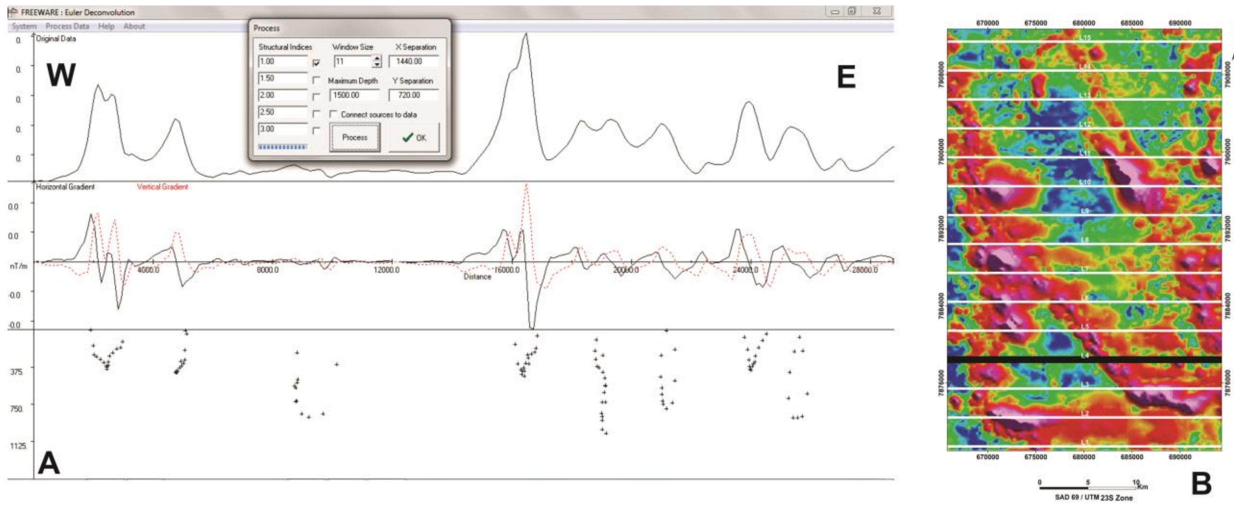

Fig. 8 – Deconvolution profile generated in Euler 2D software (A) and location of profiles performed, the profile presented (B) is highlighted in black.

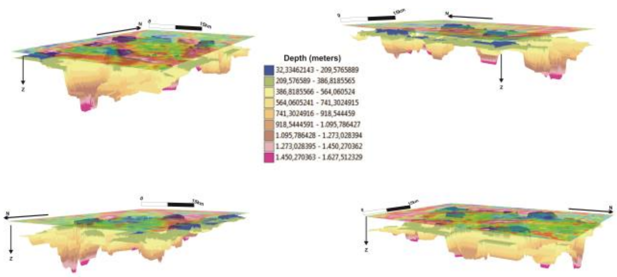

Fig. 9 – 3D visualization of the structures of the study area in depth (four perspectives).

The areas required for mining and mining concession of iron ore are on the Itabiritic Unit of the Serra da Serpentina Group, whose geophysical feature shows that the ore is outcropping or shallow.

On this basis, features similar to those found in areas already required were sought, in order to obtain new potential areas for iron ore. As we can see in Figure 10A, geophysical responses similar to those found previously can be noticed in the northeastern portion of the area, being these, however, on the rocks of Guanhães Group, that, in addition to banded gneisses with intercalations of amphibolite, quartzite and metaultramafic rocks, is also represented by banded iron formations (Grossi Sad *et al.* 1989). The radiometric response to iron ore (outcropping to shallow) is displayed in the ternary image, where we can see that the relative concentrations of U, Th, and K are the same for this ore (Fig. 10 c).

Platinum occurrences have been described in the study region (e.g., Guimarães 1959), these being associated with alluvium, colluvium and veins, also containing magnetite and ilmenite (minerals responsible for positive magnetic anomalies), traversing quartzitic rocks (shear zones in the Itambé do Mato Dentro Unit) and serpentinites of the Rio Mata Cavalo Unit (primary occurrences). In fact, the areas required for platinum ore (Fig. 10A) are on such units, whose geophysical responses indicate that the ore body is outcropping or shallow. In this way, new potential areas for platinum ore, which feature the same geophysical features of the areas

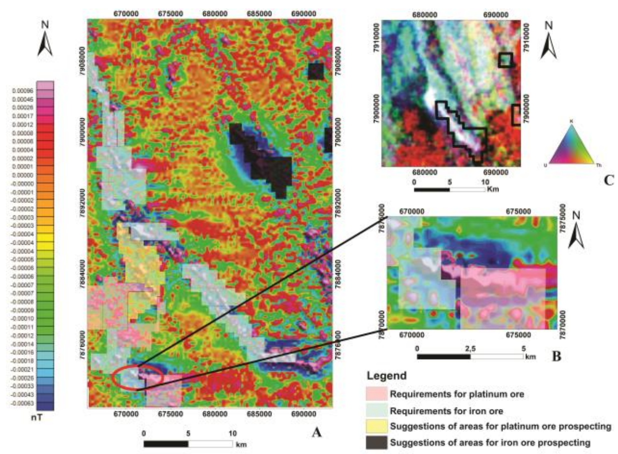

Fig. 10 – Suggestions of potential areas for iron and platinum ore, next to the areas required for such ores, superimposed on the magnetometric map of Analytic Signal Derivative (A), highlighting the geophysical feature that suggests the presence of outcropping or shallow ore (B) and the radiometric response similar to that of iron ore in ternary image (C).

required and that are located on the Rio Mata Cavalo Unit, were delineated.

Analyzing Figure 11 (radiometric map of F parameter), it is possible to perceive that the areas required for gold ore lie over regions of high anomalies (the ^{40}K, the ^{238}U and ^{232}Th are the main constituents of hydrothermal solutions – Adams & Gasparini 1970), alongside the lineaments, which allow percolation of fluids and, consequently, the enrichment of gold. Hence, it is possible to delimit potential areas for gold ore near those areas already required and that have geophysical features similar to those of such areas.

It is important to note that the remaining potential minerals such as chromium, aluminium and aquamarine, have not been delimited since it was not provided a conclusive geophysical response, although the individual analysis of the three variables considered (geology, mining requirements and concessions and geophysics) indicate potential areas.

From the bounded areas with high mineral potential in iron, platinum and gold, the plotting was done in depth preview of the bodies that have generated magnetic anomalies, and thus, making it possible to generate a drilling project in the area. For example, for iron ore, a drill hole located at 686457m W and 7894984m S coordinates would have an extension of not more than 200m (Fig. 12).

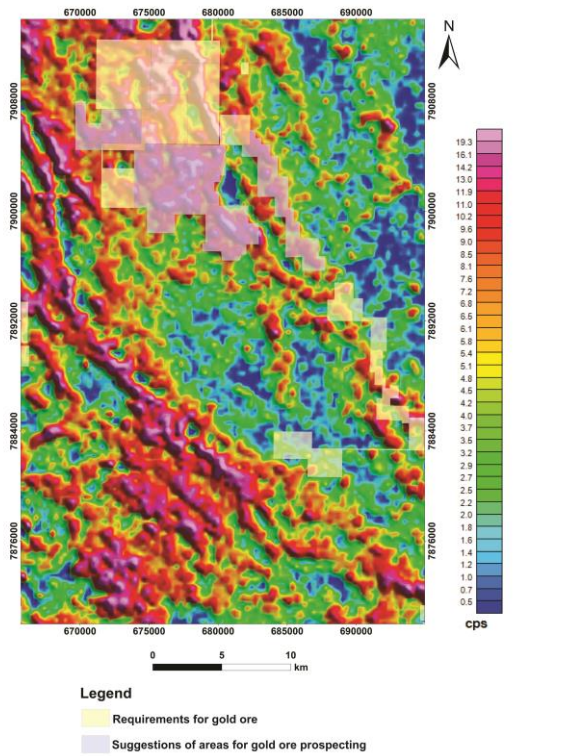

Fig. 11 – Suggestions of potential areas for gold ore, next to the areas required for such ore, overlapping the radiometric map of F parameter.

Conclusions

The effectiveness of geophysics in mineral exploration, especially in areas with hidden targets, and the aid of this tool in the geological mapping, can be evidenced. The system developed in this work, through 3D visualization, allows the proposition of a drilling project in a given region, enabling time and expenses savings on elimination of areas without economic interest, thus contributing to the mineral prospecting.

Acknowledgments

The authors are grateful to CODEMIG for the transfer of aerogeophysical data used.

References

Adams J.A.S. & Gasparini P. 1970. Gamma-ray spectrometry of rocks, Elsevier Publ. Co., New York, 295 p.

Almeida F.F.M. & Hasui Y. 1984. O Pré-Cambriano do Brasil, Edgar Blücher, São Paulo, 378 p.

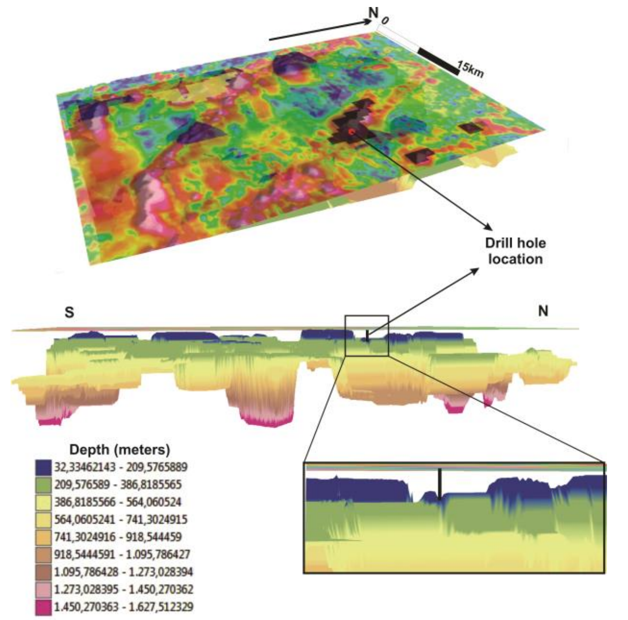

Fig. 12 – Drill hole for iron ore, whose estimated extension top is equal to 32 m and base 209m.

Assis L.C. 1982. Estratigrafia, tectônica e potencialidade mineral das unidades precambrianas da região do Serro-MG (Quadrícula de Mato Grosso). Tese de Mestrado, UnB, Brasília, 149 p.

Dossin T.M. 1985. Geologia e Geoquímica das Formações Ferríferas da Serra da Serpentina, Conceição do Mato Dentro - MG. Tese de Mestrado, Universidade de Brasília, 140 p.

Fogaça A.C.C., Schöll W.V. 1984. Estratigrafia e tectônica das rochas arqueanas e proterozóicas da região de Guinda e Gouveia (MG). Anais, 33º Congr. Bras. Geologgia, Soc. Bras. Geologia, Rio de Janeiro, p. 2638-2653.

Grossi Sad J.H., Magalhães J.M.M., Carelos, P.M. 1989. Geologia do Distrito de Guanhães, Minas Gerais. Belo Horizonte, DOCEGEO- GEOSOL, Relatório Interno, 252 p.

Grossi Sad J.H., Chiodi Filho C., Santos J.F., Magalhães J.M.M., Carelos P.M. 1990. Duas "suites" graníticas do bordo sudeste do Craton São Francisco, em Minas Gerais: Petroquímica e Potencial Metalogenético. Anais, 36º Cong. Bras. Geologia, Natal, 4:1836-1841.

Guimarães D. 1959. Notas à margem de "O Palládio e a Platina no Brasil", de E. Hussak. Rio de Janeiro, DNPM/ DFPM, Boletim 106, p. 81-99.

Guimarães M.L.V., Mourão M.A.A., Grossi Sad J.H. 1996. Mapa geológico da Folha Conceição do Mato Dentro, Minas Gerais, Brasil. Escala 1:100.000. Projeto Espinhaço (Convênio Comig/UFMG).

Knauer L.G., Grossi-Sad J.H. 1996. Mapa geológico da Folha Conceição do Mato Dentro, Minas Gerais, Brasil. Escala 1:100.000. Projeto Espinhaço (Convênio Comig/UFMG).

Pflug R. & Carvalho R.T. 1964. A evolução estrutural da região de Gouveia, Serra do Espinhaço, Minas Gerais. Rio de Janeiro, DNPM/ DFPM, Boletim 213, p. 1-37.

Renger F. 1972. As rochas ultramáficas da Serra do Espinhaço, Minas Gerais. Rev. Bras. Geociências, p. 151-160.