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INDEX AND PROBABILITY MAPS OF OCCURRENCE OF IRON ORE DEPOSITS: A PROPOSED GEOPHYSICAL APPROACH DEVELOPED IN CURRAL NOVO DO PIAUÍ (PI) STATE – BRAZIL

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ABSTRACT. This article shows the results of the development of a procedure called TC-ASA index which is based on the contrast of magnetic and radiometric properties between host rocks and the mineralization, being interpreted as the probability of occurrence and defining ambience where iron formation to occur. It consists in subtracting the values of total count (TC) from the analytic signal (ASA), which are products of gammaspectrometry and magnetic methods, respectively. This index was applied to the actual data referring to the iron formations of Curral Novo do Piauí, where the main mineral is magnetite, thus characterized by high magnetic susceptibility and often associated with metabasic rocks. These rocks often present low concentration of radioactive elements, enabling the identification of geological environment with potential for occurrence of iron ore. The use of this procedure allowed for the reduction of the exploration area, providing a fast target selection for geological mapping, geochemistry and ground geophysics. In addition, it supplies with important elements that will assist mining companies in setting strategic priorities.

Keywords: iron ore exploration, probability of occurrence maps, gammaspectrometry, magnetometry.

RESUMO. Este trabalho mostra os resultados do desenvolvimento de um procedimento aqui denominado Índice TC-ASA que tem por base o contraste de propriedades magnéticas e radiométricas entre as rochas encaixantes e a mineralização, sendo interpretado como probabilidade de ocorrência e delimitando ambiências propícias a ocorrências de formações ferríferas. Tal procedimento consiste na subtração dos valores de contagem total (CT) dos valores do sinal analítico (ASA), que são produtos dos métodos geofísicos gamaespectrométrico e magnetométrico, respectivamente. Este índice foi aplicado a dados reais coletados nas formações ferríferas de Curral Novo do Piauí, cujo principal mineral é a magnetita, caracterizada pela suscetibilidade alta e frequentemente associada à metabásicas. Estas rochas normalmente têm baixa concentração de elementos radioativos, possibilitando a identificação de ambiências geológicas potenciais para ocorrência deste tipo de minério. A utilização deste procedimento permitiu a diminuição da área de pesquisa em estudo de reconaissance proporcionando uma rápida seleção de alvos para mapeamento geológico, geoquímica e geofísica terrestre. Além disto, proporciona elementos importantes que auxiliam as empresas de exploração mineral na definição de suas prioridades estratégicas.

Palavras-chave: prospecção de minério de ferro, mapas de probabilidade de ocorrência, gamaespectrometria, magnetometria.

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INTRODUCTION

The use of geophysical methods during exploration phase has presented interesting results. In general, when using these tools, the integrated analysis of the resulting products provide the exploration companies with important elements for defining priorities and strategies. This article describes the development of a procedure, supported by two geophysical methods: gamma-ray spectrometry and magnetometry, in order to outline the favorable environments for the occurrence of iron formations. This methodology proposes the adoption of a quantitative index, resulting from the subtraction of the total count, a gammaspectrometry product, from the analytic signal, a magnetometry product. Based on this proposal, gammaspectrometric and magnetometric data from iron deposits existing in Curral Novo do Piauí area were examined and used for formulating the proposed index, since these deposits present characteristic geophysical patterns, likely to suggest the occurrence of iron ore mineralization (Sato et al., 2011). The studied area is denominated Massapê-Manga Velha (Fig. 1), situated in the southeastern portion of the state of Piauí (PI), comprising the towns of Curral Novo do Piauí and Simões, where Brasil Exploração Mineral S.A. – BEMISA contracted an airborne survey and carries out field works.

Geology of the study area

The geology of the study area is inserted in the of the Granjeiro Complex that may be subdivided into two main lithologic domains: the volcano-sedimentary succession and the TTG granitoids domain, which represent the oldest rocks existing in that region (Fig. 2).

In a general way, the iron formations are made up by mixed iron formations that are most often preserved. The iron oxide present in these rocks is magnetite, grading about 30 to 40% of Fe content, being the main lithotype with economic interest in the studied area.

In spite of the regional context be predominantly composed of acid rocks (granitic gneisses and syenogranites), the iron formation bodies (high magnetic susceptibility) are associated with amphibolitized and biotitized metabasics underwent of metamorphic effects, articulated with acid domains with a wide area spectrum.

The basic rocks associated with the mineralization show an opposite and quite distinct behavior when the radiometric channels (U, Th or K), and even the total count channel are analyzed, in order to identify and separate the lithologic domains of the basic from the acid rocks. This is due to the fact that acid rocks usually contain a larger amount of radioactive minerals content compared to the basic rocks. Considering this characteristic it is foreseeable a strong contrast of the magnetic and radiometric proprieties.

Iron formations and other iron occurrences observed in the surroundings of the study area show as a common characteristic their association with the lithic components of Granjeiro Complex. According to Santos (1996) the Granjeiro Complex contains two diachronic lithostratigraphic associations with the following array and peculiarities: an older set of supracrustal rocks, composed of amphibolitized metamafics, foliated mafic and felsic tuffs, metacherts, iron formations, paragneisses, calcisilicates, paraderived quartzites and schists; presence of volcano-sedimentary components and inclusion of chemical exhalative horizons pointing out for processes developed in an oceanic crust environment; one unit composed of granodioritic to tonalitic orthogneisses with U-Pb SHRIMP 2.54 Ga age (Silva et al., 1997). These interpretations related with the supracrustals and the orthogneisses indicate rock ages ranging between 2.65-2.55 Ga, suggesting that the Granjeiro Complex represents a greenstone belt remnant.

Sato et al. (2012) determined U/Pb ages in zircon crystals from metabasic rocks indicating ages of $2{,}121\pm19$ Ma for the rock formation and also interpreted as the minimum age for the iron formations and ages of 572 ± 24 Ma for the metamorphism. For tonalite-gneiss basement were determined ages of 2319 ± 19 Ma for the igneous protolith and 677 ± 94 Ma for the metamorphic overgrowths on the zircon crystals, indicating a new interval between 2.31 Ga and 2.65 Ga for the rocks of Granjeiro Complex.

Studies carried out in the prospect (Dias & Silva, 2009; Costa, 2010) brought new data concerning the petrography and geochemistry which, according to the authors, indicate the presence of two types of iron formation in the same deposit suggesting, therefore, a mixed hypogenic/supergenic model for the iron ore generation at the Curral Novo do Piauí district.

MATERIALS AND METHODS

The data were used correspond to those from an aeromagnetic and gammaspectrometric database collected during the survey carried out for a BEMISA's Project called Planalto Piauí, comprising the municipalities of Simões, Curral Novo do Piauí, Araripina and Betânia do Piauí, finalized in January of 2009 (Microsurvey, 2009).

The airborne geophysical survey was performed by using a Caravan Aircraft flying, with nominal flight altitude of 100 m and average speed of 280 km/h, with flight line spacing of 300 m and tie lines 3000 m apart. The magnetometer sampled every 0.1 s and

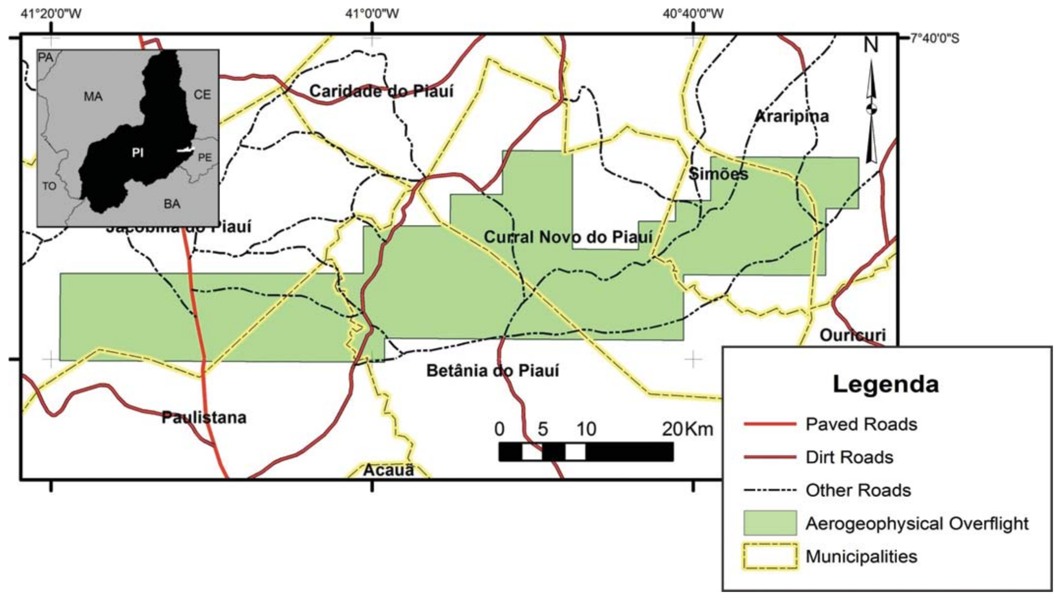

Figure 1 – Location map of the studied area, at the locality of Massapê-Manga Velha (working site).

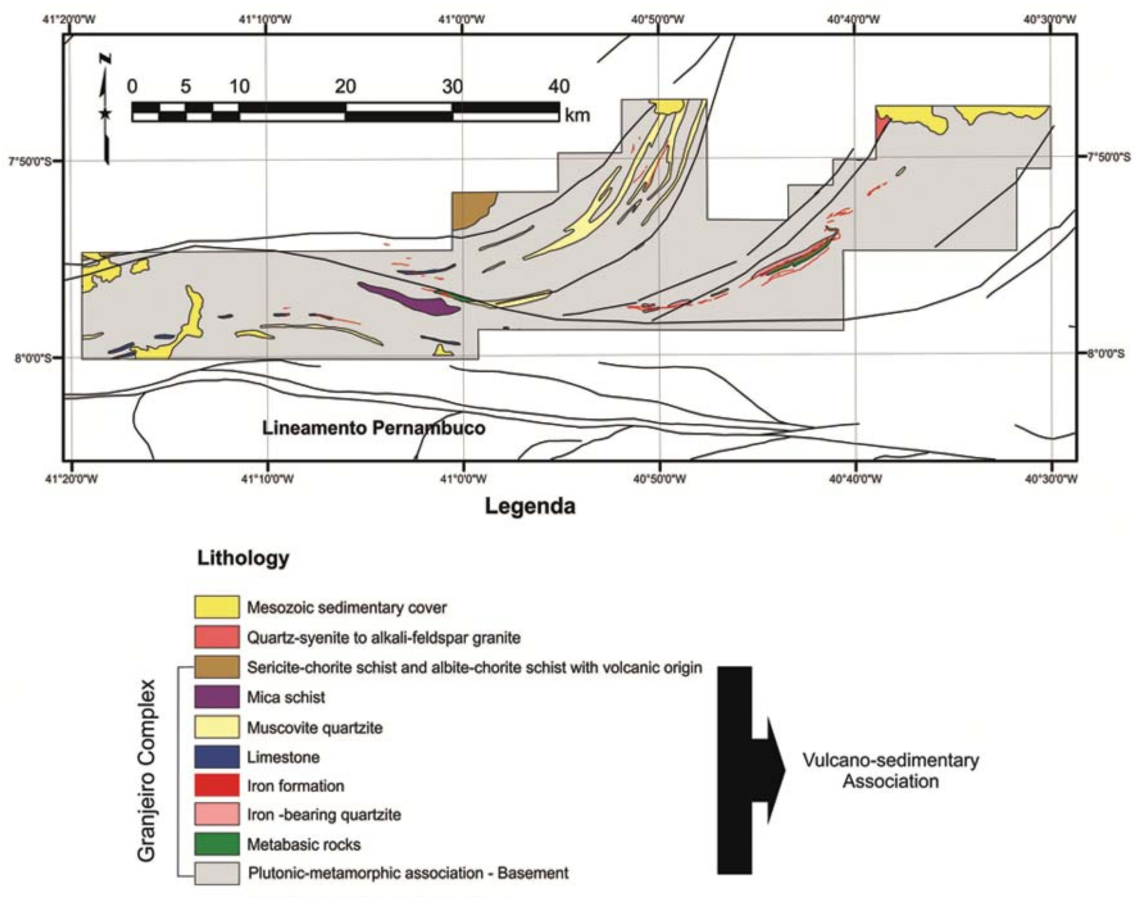

Figure 2 – Geologic Map of the studied area. Adapted from Ribeiro & Vasconcelos (1991).

the radiometric channels every second. In terms of space the survey with those characteristics made possible magnetometer readings at every 8-10 m over the lines. A total of 4.291,55 linear km were surveyed in the North-South direction with East-West direction for tie lines.

The magnetometer sensor was a Geometrics G-822A-type, 0.003 nT sensitivity, within the range of 20.000 to 100.000 nT and sensor noise below 0.02 nT. The spectrometer was of the RSX 500-type, with the radiometric information captured by 1,024 channels. The line positioning was delivered in local UTM projection, in the 24 South zone, SAD 69 datum and GRS 1967 reference ellipsoid. Due to the airborne survey resolution the work scale is 1:30,000.

DATA PROCESSING

Radiometric Data

The RPS (radiometric processing system) package, part of the Geosoft®-Oasis Montaj 7.0 (IAEA, 2003), was the tool used for processing the data. Such processing comprehends corrections such as of dead time, parallax and random errors, removal of radon background and estimate of the Skyshine coefficients among others, as sketched in Chart 1.

Chart 1 – Schematic representation of the radiometric and magnetic processing.

Coordinates	
Projection	UTM Zone 24S
Datum	SAD 69
Ellipsoid	GRS 1967
Local Datum	SAD 69 (IBGE, Brazil)
Magnetic data	
Lag correction	
Diurnal correction	
Levelling and microlevelling	
IGRF correction (2005 model recalculated to survey date)	
Radiometric data	
Lag correction	
Dead time correction	
Removal of cosmic and aircraft background	
Removal of random's background and estimate of skyshine coefficients	
Removal of compton effect	
Altitude correction	
Converted into radio-elements concentration	
Microlevelled	

Subsequently the radiometric data were converted into concentration: Thorium and Uranium radio-elements concentration – into parts per million (ppm); potassium into percentage (%); and Total Count (Fig. 4) into cps (counts per second).

The minimum curvature algorithm (Briggs, 1974) was used as interpolator over a regular grid with 75 $\times$ 75 m cell-size. Finally, all data were microleveled using Butterworth filters and directional cosines for better visualization. The use of this technique was necessary to remove low-amplitude remnant noise (Microsurvey, 2009).

Magnetometric Data

The magnetic data processing begins with lag and diurnal variation's corrections, Chart 1, followed by leveling using tie lines, transversals, and subsequently microleveling. The Butterworth filters and direction cosines were used to remove remanent low-amplitude noises.

The last procedure was the IGRF correction. Upon correction, all data were interpolated with the bidirectional algorithm using a regular cell (Microsurvey, 2009).

For locating the magnetic sources and their boundaries, the analytic signal filter was applied to data (Fig. 5) based on Geosoft®-Oasis Montaj 7.0 software.

Nabighian (1972, 1974) introduced the concept of analytic signal for magnetic interpretation. Roest et al. (1992) demonstrated that the analytic signal amplitude – ASA (absolute value) is expressed by the addition of the first derivatives of the real components in the x and y directions and in the imaginary component in the z direction:

$$|A(x,y)| = \sqrt{\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2 + \left(\frac{dT}{dz}\right)^2} \quad (1)$$

where:
$|A(x,y)| =$ Analytic signal amplitude;
$T =$ magnetic field observed in (x,y).

Solution of the analytic signal will be a function that shows the boundaries of the body or the geologic feature using magnetic data (Nabighian, 1972; Keating & Pilkington, 1990; Roest et al., 1992; Hsu et al., 1996).

Generation and development process of the TC-ASA index

The process for generation of the TC-ASA index and the maps of probability of occurrence may generically be summarized in seven stages of data processing (Fig. 3).

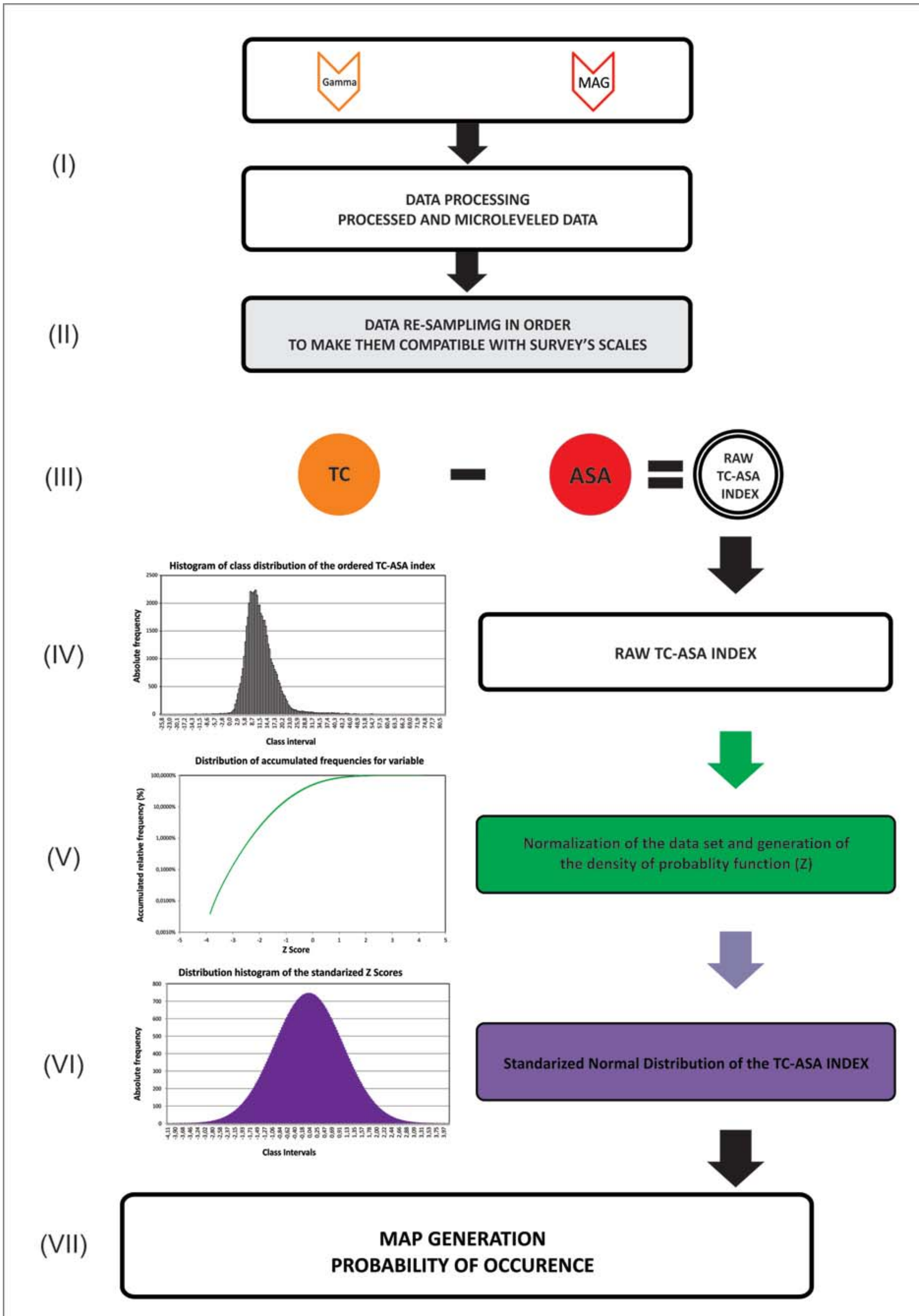

Figure 3 – Synthesis of the data modeling process for obtaining the probability of occurrence maps.

Geophysical data processing (Fig. 3.I) was characterized by the traditional data processing beginning with the classic techniques for leveling the magnetometric and gammaspectrometric data.

Data are-sampling (Fig. 3.II), beginning with the processed data, and generation of leveled products appropriate to the interpretation of the gammaspectrometric database, was utilized for the accomplishment of the magnetometric data re-sampling which were surveyed with a wider spatial resolution in relation to the gammaspectrometric data over a grid of the total magnetic field (CMT). Following this procedure a grid of the analytic signal amplitude (ASA) was generated using filters that are part of the Geosoft®-Oasis Montaj 7.0.

The TC-ASA index (Fig. 3.III) is generated with the subtraction of the Total Count (TC) values from the Analytic Signal (ASA) values. This procedure was carried out according to description of the geologic environments proposed in Sato (2011). Locally, such geologic environments are those favorable for the occurrence of magnetite rich iron formations. From the geophysical point of view they may be described as lows in the total count channel, which are customarily representative of metabasic rocks associated with iron mineralization – usually with low concentration of radioactive elements and described as highs in relation to the analytic signal. These highs are representing iron formations. Here some comments are to be made about the limitations of the method as a function of the studied variables, in other words, the investigation of the TC variable is limited to only some few centimeters of subsurface, being this limitation inherent of the gammaspectrometric method, while the magnetometry, and consequently its derived products, investigate greater depths.

The dataset normalization (Fig. 3.IV)

In this step the dataset was normalized from the generation of a cumulative frequency curve, in other words, the TC-ASA index dataset was ordered from the lowest to the highest and subsequently the ratio $1/n$ was calculated, where n is the dataset's amount of the data and the cumulative frequency curve was finally found. For those values obtained for the data's cumulative frequency it was accomplished the calculation of the inverse function Z of the normal distribution, and then values for the Z scores were obtained for each sample from the construction of a function that returns the Z score value with an associate p probability.

The cumulative frequency curve of the normalized distribution (Fig. 3.V) was generated from the data transformation and with the interpretation possibility according to a standard normal curve, enabling the data interpretation based on the area calculation under a normal curve and its interpretation in terms of probability. This study particularly brings into focus the outliers with negative values within the normal curve since they indicate the geologic environment that are more favorable for occurrence of iron formation.

By using the standardized normal distribution of the TC-ASA index (Fig. 3.VI), and the transformation of the normal curve's data into a cumulative frequency curve, it is possible direct interpretation in terms of probability of occurrence of potential environments for magnetite rich iron formations. Actually, in the context of the cumulative frequency curve, the outliers with some interest are indicated by the lower possibilities of occurrence and this fact is corrected by the subtraction of 1 from the dataset for inverting the probability of occurrence, and properly indicating the environments presenting better probability of occurrence of iron formations. For the accomplishment of this transformation it was generated a function that returns the accumulated values of a standard normal distribution (with average 0 and standard deviation 1) to all normalized dataset. This function was generated from the accumulate probability density function, and subsequently these values were subtracted from 1 seeking the identification and enhancement of the negative outliers that indicate the most favorable geological environments.

The procedures used for delimitating the anomalies for the identification of the environments with possible anomalies, probable anomalies, and the threshold and background outlining were carried out based on an adaptation of the method proposed by Hawkes & Webbs (1962). In such a way that the background, defined as an interval, is characterized by the upper limit of the fluctuations of the analyzed variable. Particularly for this case, the variable named probability of occurrence was defined from the average, thus, the composition range of the background varying from zero to the data average, which is equal to 50%, being this aspect the difference of the methodology proposed herein.

Upon the background definition it was possible to outline the corresponding threshold. The interval of possible anomalies corresponds to the values in the threshold interval plus a standard deviation. In the same way, the interval of probable anomalies is equal to the threshold interval plus a standard deviation up to the highest value of the dataset.

This adaptation became necessary because, in practice, the procedures used during this work proved to be more efficient and suitable for the areas defined as exploratory targets, in spite of being less conservative than the proposals submitted with the original work. The further step was the definition of the background and threshold intervals, possible and probable anomalies for the area covered by the airborne geophysical survey.

During the following stage the maps of probability of occurrence were generated (Fig. 3.VII) by using data interpolation process based on the minimum curvature method (Briggs, 1974).

RESULTS AND DISCUSSION

The TC-ASA index is the product of a direct subtraction of the total count values (cps) from the analytic signal values (nT/m), shown in Figures 4 and 5, respectively.

The generation of a probability of occurrence associated with each one of the sampled point of the airborne geophysical survey enabled the indication of an average probability of occurrence for any polygon within the surveyed area (e.g.an area where a claim has been submitted).

The probabilistic variable interpreted in the light of a methodological adjustment, proposed by Hawkes & Webb (1962), for anomaly discrimination has also allowed the discrimination of anomalous environment in terms of probability of occurrence of favorable geological environments for occurrence of iron formations as presented in Figure 6.

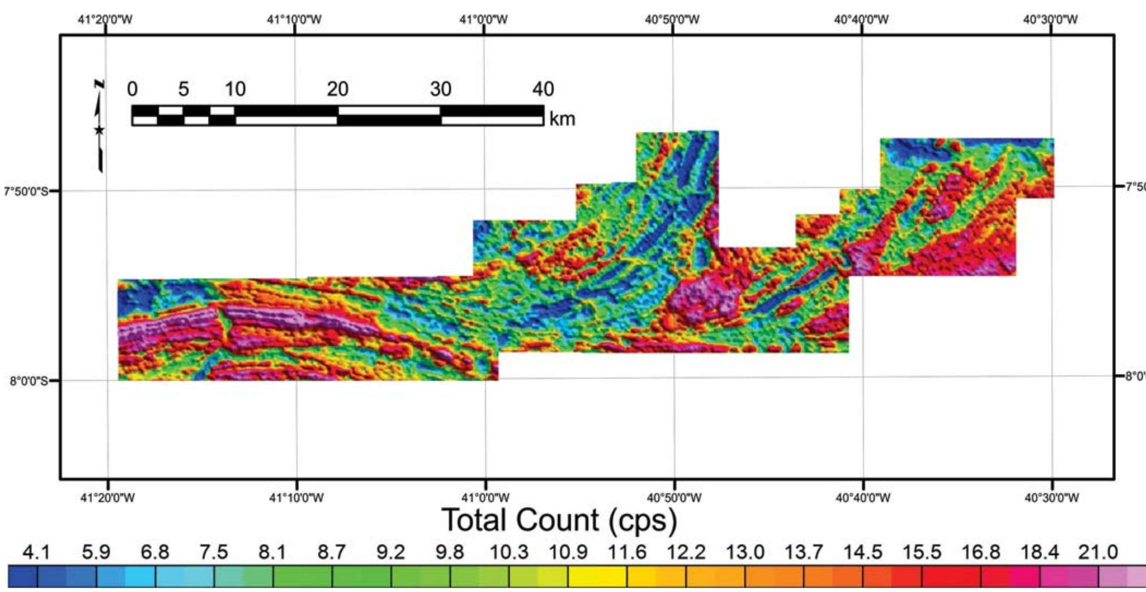

Figure 4 – Total count (cps) map.

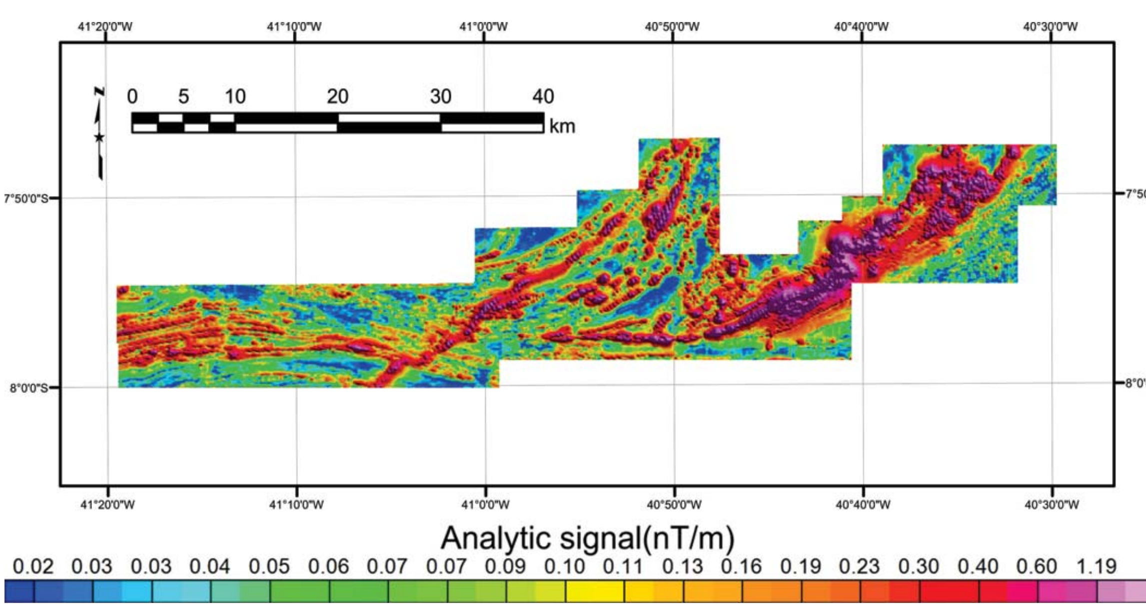

Figure 5 – Map with analytic signal in nT/m.

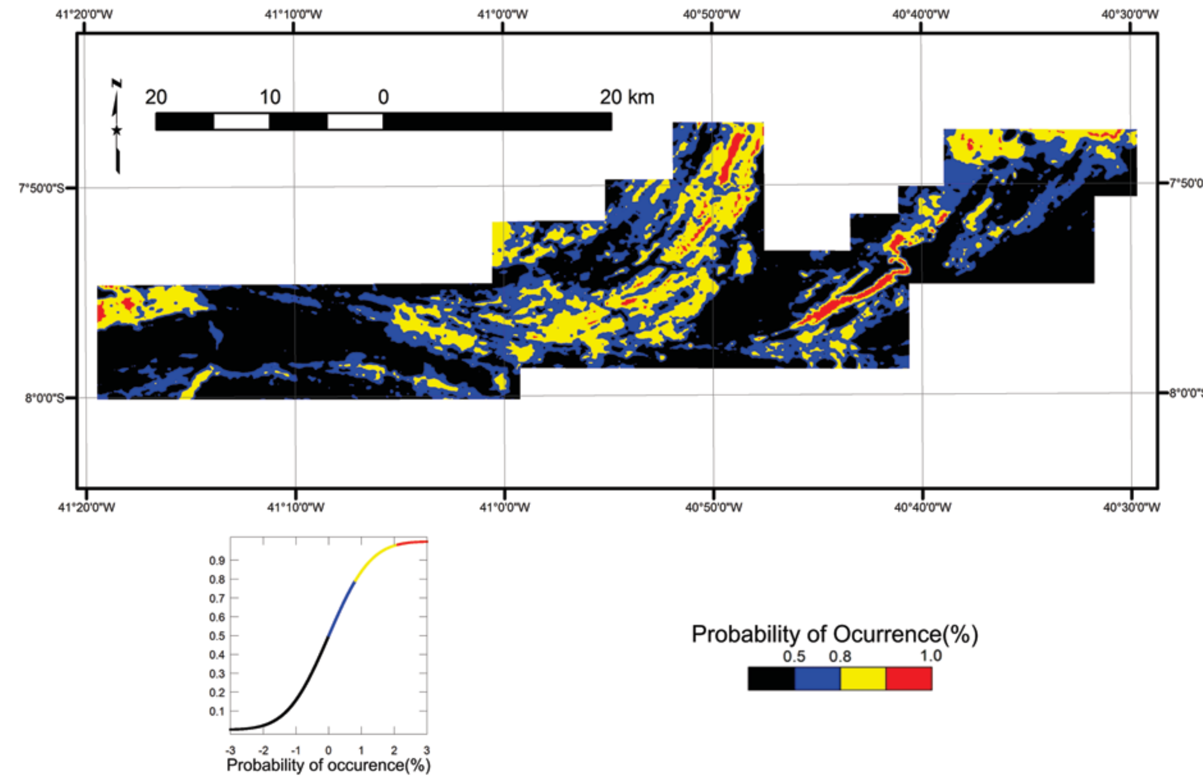

Figure 6 – Map of probability of occurrence of potential geologic environments for the occurrence of iron formations with magnetite.

As a result of the analysis of the data it was possible to prepare a classification of the favorable environments for the occurrence of iron formation and a comparison of its contents with regional and detailed geologic mapping that was prepared by BEMISA's geologists (Fig. 2).

The anomalous environments mapping was carried out based on the classification defined and shown in Table 1. Subsequently the area calculations were accomplished for each one of the classified environments, enabling the evaluation of the efficiency of the proposed method, in terms of its capacity to reduce the size of the exploration areas by taking into consideration that the most expensive phase, and consequently higher risks, is those associated with the initial exploration phases. Consequently, an expressive reduction of the areas to be investigated

Table 1 – Delimited classes for verifying areas with potential for occurrences of iron formations with magnetite, and areas, in sq. km and percentages, indicating the area reduction where prospecting and exploration will be carried out.

Class	Type	INTERVALS			AREA (km^2)	AREA (%)
0	NO POTENCIAL	0,00	-	50,30	487.202,0	42,83
1	LOW POTENCIAL Thereshold +1 Standard Deviation	50,31	-	76,10	551.503,0	48,48
2	POSSIBLE ANOMALY Medium Potencial	76,11	-	98,20	94.124,0	8,27
3	PROBABLE ANOMALY Potencial environment for occurence of iron formation with magnetite	98,21	-	100,00	4.746,0	0,42
SUM					**1.137.575,0**	**100**

will significantly reduce the cost of mineral exploration trough an efficient selection of exploratory targets for detailed field work. This results in a planned investment based on prioritizing targets with best probability of anomalous occurrences of iron formations, as shown in Table 1.

CONCLUSIONS

The proposed method allows to carry out the exploration surveys in a quantitative way, by using data collected during the airborne geophysical (magnetometric and gammaspectrometric) surveys.

A reduction of the survey area is achieved when the proposed methodology is applied, allowing a fast target selection for geological mapping, geochemistry and ground geophysics services. For this study area an immediate reduction of 42.83% was produced after applying the aforementioned methodology. Only 8.27% of the airborne surveyed area was indicated for investigation of possible anomalies and 0.42% of the total area for probable anomalies. The most expressive iron formation bodies are located within the areas of probable anomalies that were outlined from the map of probability of iron occurrence.

The geological mapping identified and confirmed iron formations with minor expression in geologic environments outlined by the map of probability of occurrence, as shown in Figure 6.

Therefore, this methodology may provide a significant cost reduction during the reconnaissance phase, minimizing risks and providing a direct selection of the priority targets for assessment, valuation of targets and exploratory drilling.

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