The Use of Airborne Magnetics in Hydrogeology: An Example from Northeast Brazil

*Oderson Souza, REFO/CPRM & IG/UNICAMP
Adalene M. Silva, LGA/UnB
Anne McCafferty, CICT/USGS
Mônica Perrotta, DISERE/CPRM

This paper was prepared for presentation during the 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Abstract

The use of airborne geophysics in hydrogeology or environmental issues is neglected in Brazil, whereas in other countries it takes part in governmental actions. The first airborne survey aimed to hydrology in Brazil has provided considerable knowledge about methods and their variances to enhance features of interest more adequately. We discuss the role of some of traditional filtering techniques and propose other processes to map a desired hydrogeological feature. In this context, the use of a matching filter to separate shallow-seated structures and domains, followed by vertical derivatives were found suitable to map fractures and dykes. The horizontal gradient maps were more adequate to map boundaries related to geomagnetic units. A spatial analysis in geographic information system is also important, where the geophysical products can be integrated and re-evaluated with other kind of data, such as digital terrain model, litho-structural, hydrological and satellite images as the most commonly available.

Introduction

There are in literature many applications of filtering techniques applied to rock and structural mapping aiming geologic maps and ore prospecting. A summary of the most commonly used techniques and applications are found in Milligan and Gun (1997), Silva (1997), and Grauch and Johnston (2002). Fewer works were produced for hydrogeological applications and usually they rely on low-pass filters to locate basement topography and bedrock depth in sedimentary basins (Pine and Minty, 2005) and the high-pass filters that enhance shallow-source anomalies as faults, well-casings, dykes, (Street et al. 2002, Paine and Minty, 2005).

In Brazil, few authors applied airborne geophysical data to hydrological issues, and most of the works come from academic researches. Mandrucci et al. (2003) used the analytic signal algorithms (Nabighian, M.N., 1972). The author integrated the phase of analytic signal of magnetic data with satellite spectral data from Enhanced Thematic Mapper sensor-ETM+ to help the distinction of regional morphostructural domains. Silva (2005) made use of the amplitude of analytic signal to map geomagnetic domains and major magnetic gradient trends that were incorporated in the structural map extracted from digital terrain models and ETM+ data.

In this paper we discuss the role of the processing techniques for airborne geophysical data in hydrogeologic prospecting. Also we present a study case in Irauçuba region, State of Ceará, where several geologic, hydrogeologic and geophysical data sets were available. The possibility to work with airborne surveys of different resolution provided enough liberty to test other filtering techniques to address hydrogeological issues at diverse crustal segments and circumstances.

Standard Processing for Airborne Geophysical Data

Basically, after the data correction due to acquisition along flight line and sensor errors, commonly called micro-leveling, the magnetic data undergo to these filtering steps:

a) Data subtraction from the geomagnetic reference field (IGRF or DGRF) to extract only the residual/local magnetic anomaly;

b) Gridding of the data with an adequate cell size to the goal. Due to acquisition character of flight-lines the minimum curvature and the Bi-grid interpolation methods are the most used;

c) Application of analytic signal algorithms (amplitude and phase) deals the derivatives of a magnetic field in three orientations (x,y,z) to calculate the amplitude and phase of that field. It has the advantage to be independent of the direction of the magnetization vector, which means that all bodies with the same geometry have the same analytic signal. In this case, reduction-to-the-pole transformation is not required. The amplitude is desirable to locate edges of wide bodies or centers of narrow bodies/gradient trends, while the phase is useful to estimate dipping of sources. The half-widths of the analytic signal peaks can be linearly related to depths if the sources of the peaks are vertical magnetic contacts (Gunn, 1997);

d) Reduction to the magnetic north pole-RTP to correct for the distortion of anomaly position and shape due to surveys carried out over low-magnetic latitude (which is the case in most part of Brazil). Commercial algorithms that deal with this kind of algorithms generally promote artifacts to the gridded data, so some authors prefer to interpret over the analytic signal image, without performing RTP reduction;

e) The calculus of the horizontal gradient (Cordell and Grauch, 1985) of the magnetic potential is a standard technique to detect edges of gradient trends and bodies boundaries. However, the contact must be located over the maxima of the gradient, because the assumptions that steep boundaries between large bodies are represented by steep gradients of the magnetic field. Finding the maxima is then efficiently done with the curve-fitting approach of Blakely and Simpson (1986).The local curvature of the function can also be computed to get strike information that can be used in joining together the maxima (Phillips et al., 2006 in Pilkington, 2007);

f) Vertical derivatives enhance edges of large bodies or gradient trends. The process enhances high frequencies relative to low frequencies, which in turn resolves the effects of adjacent anomalies (Milligan and Gun, 1997). Higher-order derivatives can be extracted, where the former is the vertical gradient of the later order, to gradually eliminate low-wavelength regional effects but compromising with noise creation;

Proposed Processing Techniques

We propose changes in the standard procedure. Basically the magnetic data is separated in two classes of data, one with signature of deep-seated magnetic sources and those which represent shallow sources. When prospecting for groundwater in crystalline domains of semi-arid regions, the use of magnetic data related to sources deeper than 300 m may not be necessary. This precaution avoids misleading interpretation regarding structures not related to the level of groundwater occurrence for human supply. Whereas in crystalline domains partially covered by sedimentary rocks, the use of both deep and shallow magnetic source data is applicable to delineated boundaries between the different hydrogeologic domains as well as structures that act as hydraulic conductors or barriers. The first procedures of micro-levelling and enhancement of residual/local anomalies are equal to standard processing, then:

a) Reduction to the north magnetic pole is desirable so the interpreter can proceed to the following steps. An adequate and stable filter to use in data that come from low magnetic latitudes is found in Phillips (1997, 2007). An azimutal filter applied in the direction of magnetic field declination significatively reduces noise creation.

b) In general, magnetic anomaly fields are produced by sources spanning a range within the Earth crust, and the separation of these sources helps to understand the structural framework that is important for groundwater flow in a study-area and to eliminate those not important. A matched filtering algorithm (Syberg, 1972) can differentiate the depth to the top of magnetic anomalies. The technique uses frequency-domain filters to design wavelength filters based on the segmentation of the power-spectrum of the magnetic data, according simple magnetic source models. The results are groups of anomalies of long-wavelength related to deep-seated sources (hundred to thousands of meters in depth). Also it is possible to enhance groups of short-wavelength anomalies that comprise shallow magnetic sources (tens to hundred of meters), where generally, groundwater in crystalline domains are found;

c) With the shallow-source filtered data, the application of vertical and horizontal derivatives will enhance gradients trends related to brittle structures and rocks boundaries and small-scale grabens. If the data was acquired with flight-lines of few tens of meters, the contact between small basins and fresh basement or pipelines might be detectable;

d) The Terracing algorithm (Cordell and McCafferty, 1989) is another option to enhance tectonic boundaries originated by steep dipping structures, like shear zone. The terracing function tries to approximate a potential field function in to a step-like function (terrace). The premise is that the local curvature of the potential field may be represented by uniform domains, followed by abrupt domains. Souza Filho et al. (2007) used this as one of the data set to build a GIS-based groundwater favorability model.

e) The deep-source filtered data may be filtered for the horizontal gradient to highlight ductile shear zones, major boundaries between geologic units, basin limits and not-exposed intrusions;

f) Where a regional (lower resolution) and a local (higher resolution) survey are available. It might be interesting to combine those in order to observe deep-seated magnetic sources that could not be possible with the restricted local survey. The process requires the extraction of deep-source data from the regional survey data, and subtracts them from the local data (residual anomaly data). Prior resampling of the regional data to the same cell-size of the local data is needed.

g) The transformation of the magnetic field values into magnetic potential (Baranov, 1957) is a procedure not always practiced in Brazil but recommended for those who wants to calculate magnetic gradients to locate edges and body sources (Cordell and Grauch, 1985; Debeglia et al., 2005);

Extraction of boundaries and gradient trends will be done by locating and joining the maxima points in the vertical derivative or horizontal gradient maps, according to functions in Blakely and Simpson (1986) for example. This processed information will take part in a SIG environment for posterior interpretations.

Data Integration in SIG Environment

Integration with remote sensing images, digital terrain models and litho-structural maps are powerful sources to visualize surface structure framework, morphology, and drainage pattern.

The **I**ntensity-**H**ue-**S**aturation-IHS transformation is an option of a fast integration of airborne geophysical products and satellite images. To define hydrological potential regions Mandrucci et al. (2003) combined: **I** the ETM+ image; **H** as the phase of analytic signal; **S** a constant DN of 70, so that the airborne information (magnetic domains and dipping direction) is provided by color variations, the textural, landscape-drainage information is given by the ETM+ image and with a constant saturation. Ruy et al. (2006) and Carneiro et al. (2007) refer to color-composition of geophysical maps to be integrated with satellite spectral images and radar. Algorithms of IHS transformation and other colors enhancements are available in commonly commercial softwares of image processing.

Spatial modeling of multiple-source data helps the characterization of areas with geophysical, structural, and spectral signatures that are associated with a hydrogeological parameter (well production, water salinity, aquifer mapping…). Statistical techniques vary in the number of required parameters. The Probability Ratio-PR (Lee et al., 2000) and the Weights of Evidence (Bonham-Carter et al., 1989) are knowledge-driven methods, where the user has prior information about parameters of interest.

Study Case

In this item, some of the techniques described earlier are presented that illustrate the advantages and drawbacks about their use in hydrogeologic prospecting. Most of the filtering techniques are available in Phillips (1997, 2007) and in commercial softwares.

The study area of Juá is located in the south-western part of Irauçuba municipality, in the State of Ceará (Figure 1). The area is part of the semi-arid of Northeast Brazil and comprises migmatites, paragneisses, marbles and amphibole-gneisses of Precambrian age. The only alluvium deposit is located at the main river, with thickness of less than 2 m and width between 10 m to 40 m.

At Irauçuba, there are two airborne surveys of different resolution. The regional survey (Lasa, 1978) comprises the magnetic and radiometric methods, with north-south flight-lines spaced 500 m and east-west control-lines of 20,000 m apart. The sampling interval was 1 s, which is equivalent to 1 reading each 55 m. The magnetometer sensor was mounted on a stinger of an Islander aircraft, flighying at 150 m above ground.

The higher (local) helicopter survey (Lasa, 2001, PROASNE, 2009) was carried out at the Juá area, with the magnetic and electromagnetic methods. The survey covered a region of 120 km^2, where flight lines were oriented east-west with 100 m apart, while the control-lines were spaced 500 m and oriented north-south. The magnetic sensor acquired data every 0.1 s, providing 1 reading every 4 m. The sensor was carried inside a bird, 30 m high.

Both regional and local data were corrected for random noise and flight acquisition errors. Then, they were subtracted from the IGRF to enhance the residual anomalies. With the minimum curvature method were applied to the regional data to generate grids of 250 m cell-size, while the grid of local anomalies had a cell-size of 25 m.

All data were reduced to the magnetic north pole with the algorithms available in Phillips (1997). We tested other algorithms of reduction to the pole, as wells as several azimuth filters but noises remained along the magnetic declination orientation (Figure 2 a,b).The matching filter algorithm was applied to the regional residual data to extract deep magnetic sources located at 2000 m depth. From this latter map, WNW-ESE trends of low magnetization cross-cut geomagnetic units of NE-SW orientation.

The application of matching filter to the map of local anomalies provided two depths of magnetic sources: the middle depth anomalies (from 20 to 200 m depth) and the shallow source anomalies (from 20 to 60 m depth).

To improve location of edges of magnetic sources associated with geologic units and structures, the middle source magnetic grid was converted to map of magnetic potential. The magnetic potential were then, calculated its horizontal gradient and the maxima gradient peaks. The horizontal gradient of the middle-source provided information about related geologic units, N-S and ENE-WSW foliation trends and cross-cutting (brittle?) structures.

The map of the 1st-vertical derivative were calculated from the shallow-source anomaly map and provided better definition of gradient trends related to NW-SE, WNW-ESE brittle structures (Figure 3a), specially when displayed as color-shaded grids with different orientations in false-illumination.

Spatial Models in Hydrogeology

The magnetic data do not measure the presence or absence of water directly. However, they have the ability to enhance and map geologic features that can be used to identify probable water-bearing structures and lithologies in crystalline rocks. Two situations illustrate the usefulness of airborne geophysics to map favorable hydrogeological conditions in the crystalline domain:

a) Magnetic anomaly gradients refer to boundaries between geomagnetic units or define shear zones. Negative gradients of magnetic anomalies may be related to brittle tectonic discontinuities;

b) Structural lineaments interpreted from remote sensing techniques may be correlated to any of the above geophysical features and they are important for groundwater storage and flow.

An example of spatial modeling is given below where the trends of positive and negative gradients were compared with the classes of well yield according to the Probability Ratio-PR technique. The trends were extracted as separated vector layers, then proximity zones of 50 m aside were applied to the vectors and rearranged in azimuth classes. Latter they were transformed to raster coverage of 25 m cell-size.

The hydrogeological parameter of study is well-yield classes (m^3/h, Table 1). Juá area has 20 wells uniformly distributed however, those most productive are located in the southwest portion.

The Probability Ratio (Lee *et al*., 2000) and the Weights of Evidences (Bonham-Carter et al., 1989) methods uses a ratio of probabilities to describe the statistical likelihood for a class of evidential layers having some spatial association with a given prototype area.

Table 1: Well-yield classes for Juá region and correspondent number of pixels. Colors refer to the same classification of wells in Figure 1.

Yield Class (Q) and Range (m^3/h)	Water-Wells within Class	Pixels (25 m cell-size) within Class
Class 1 ($Q < 0.3$)	3	154
Class 2 ($0.3 < Q < 1$)	9	426
Class 3 ($1 < Q < 2$)	3	149
Class 4 ($Q > 2$)	5	232

The evidential layers (or test classes) are the geophysical gradient trends, and the prototype areas are the proximity zone of wells within four yield classes (Equation 1).

$$\mathrm{Pr}_{\mathrm{Weights}} = \frac{(\mathrm{Pixels}_{\mathrm{overlap}} / \mathrm{Pixel}_{\mathrm{evid}})}{(\mathrm{Pixels}_{\mathrm{yield\ class}} / \mathrm{Pixels}_{\mathrm{study\ area}})}, \qquad \text{Equation 1}$$

Where, $\mathrm{Pixels}_{\mathrm{overlap}}$ is the area overlap between an evidential layer and a prototype yield class.

Results

Favorable areas for groundwater occurrence were found prospective along a WNW-ESE structure (Figure 3b) and in few other places to the south and west of the area. An example of how to display the spatial association of the magnetic gradient trends and their map location is given by Figure 4.

It was found that three of the most productive wells were located in a WNW-ESE structural trend that is non-magnetic and electrically conductive at the surface. Field observations discovered that it is a brittle shear zone, filled by granite that cuts the paraderived gneisses and migmatites. The shear zone has undergone successively reactivations since the end of Neoproterozoic, where fracturing accumulation is more than 100 per square meter. The non-magnetic property of the structure is given by the predomination of quartz and k-feldspar in the granite matrix (Figure 3b). The structure is of regional importance because it is also seen in the deep-source filtered magnetic grid. Its conductive character is given by water accumulation and clay veneer that fill the only alluvium in the area. Although there is a reservoir 50 m from the wells (Figure 1), Silva et al. (2001) argues that only the closest well is directly influenced by this reservoir.

Conclusions

The filtering techniques cited in this study case better enhanced features of hydrogeologic interest. For regional survey data, it is recommended to use a matching filter prior to the high-pass filtering techniques or horizontal derivatives to exclude the anomalies related to deep-seated structures, and therefore, not-related to the level of groundwater occurrence in crystalline domain. The ASA algorithm, although very useful in mineral prospecting, it is not of great advantage because gradient trend information (probable related fractures) and definition is lost.

Comparing vertical derivatives and horizontal gradient amplitude, the latter is more useful to delineate trends related to shallow structures, whereas the former technique is suitable to map boundaries of geomagnetic units but it becomes difficult to extract trends related to fractures of local importance if the survey is of regional character.

The cited spatial modeling techniques may be applied to other sources of data such as structural lineaments, slope direction, radiometric count or electromagnetic conductance. That way, for each class of data it was found their spatial association with a hydrogeologic parameter. A groundwater potential map can be drawn and tested with wells not used to build the model.

At last, there is not a definitive procedure. The interpreter must try among the available filtering techniques but having in mind the kind and scale of structures that are present in the study-area.

Acknowledgments

The authors thank CAPES Program for the Doctorate Scholarship, BEX: 3688/05-4 and the support of CPRM, IG/UNICAMP, USGS and IG/UnB to develop this work.

References

Baranov, V., 1957, A New Method for the Interpretation of Aeromagnetic Maps: Pseudogravimetric Anomalies. *Geophysics*, 22:359-383.

Blakely, R.J., and Simpson, R.W., 1986, Approximating Edges of Source Bodies from Magnetic or Gravity Anomalies. Geophysics, v. 51:1494-1498.

Carneiro, C.C., Crósta, A.P., Silva, A.M., Pinheiro, R.V.L., 2007, Integração de Imagens SAR, DEM e Magnetométricas no Mapeamento Geológico e Estrutural da Área Centro-Oeste do Sistema Transcorrente Carajás (PA). In: Rosa-Costa, L.T.da; Klein, E.L.; Viglio, E.P. (Org.). Contribuições à Geologia da Amazônia. 1ª ed. Belém: Sociedade Brasileira de Geologia - Núcleo Norte, 2007, v. 5, p. 63-74.

Cordell, L.; Grauch, V.J.S., 1985, Mapping Basement Magnetization Zones from Aeromagnetic Data in the San Juan Basin, New Mexico. In: HINZE, W.J., ed., The utility of regional gravity and magnetic maps. Society of Exploration Geophysicists, p. 181-197.

Cordell, L.; McCafferty, A. E., 1989, A Terracing Operator for Physical Property Mapping with Potential Field Data. Geophysics, v. 54, n. 17, p. 621-634.

Debeglia, N., Martelet, G., Perrin, J., Truffert, C., Ledru, P, Tourlière, B., 2005, Semi-automated Structural Analysis of High Resolution Magnetic and Gamma-Ray Spectrometry Airborne Surveys. Journal of Applied Geophysics, v. 58, p. 13– 28.

Grauch, V.J.S., Johnston, C.A., 2002, Gradient Window Method: A Simple Way to Separate Regional from Local Horizontal Gradients in Gridded Potential-Field Data: 2002 Technical Program Expanded Abstracts, 72nd Annual Meeting, Society of Exploration Geophysicists, p. 762-765.

Gunn, P.J., 1997, Quantitative Methods for Interpreting Aeromagnetic Data: A Subjective Review. AGSO, Journal of Australian Geology and Geophysics, v. 17, n. 2, p. 105-113.

Lasa Engenharia e Prospecções S.A., 1978, Projeto Aerogeofísico Itatira, Empresas Nucleares Brasileiras S.A.- NUCLEBRÁS, 3 volumes (Subáreas A, B e C), texto e anexos, Rio de Janeiro.

Lasa Engenharia e Prospecções S/A, 2001, Projeto Aerogeofísico Água Subterrânea no Nordeste do Brasil, Blocos Juá (CE), Samambaia (PE) e Serrinha (RN). Relatório final do Levantamento e Processamento dos Dados Magnetométricos e Eletromagnetométricos e Seleção das Anomalias Eletromagnéticas. Cooperação Canadá-Brasil, 3 volumes, 3 CD-Rom. Available at http://proasne.net/Relatorio.pdf.

Mandrucci, V.; Araújo, C.C.de; Taioli, F., 2003, Sensoriamento Remoto, Aerogeofísica e Geoprocessamento Aplicados ao Estudo de Aquífero Fraturado em Terreno Cristalino, Leste do Estado de São Paulo. In: Revista Brasileira de Geociências, v. 33 (suplemento), p. 43-52.

Millingan, P.R., Gunn, P.J., 1997, Enhancement and Presentation of Airborne Geophysical Data. ASGO Journal of Australian Geology and Geophysics, 17(2):63-75.

Nabighian, M.N., 1972. The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Its properties and use for automated anomaly interpretation. Geophysics 37, 507–517.

Phillips, J.D., 1997, Potential-Field Geophysical Software for the PC, version 2.2: U.S. Geological Survey Open-File Report 97-725, 34 p, 1997.

Phillips, J.D., 2007, Geosoft eXecutables (GX's) Developed by the U.S. Geological Survey, version 2.0, with Notes on GX Development from Fortran code: U.S. Geological Survey Open-File Report 2007-1355.

Phillips, J.D., Hansen, R.O., Blakely, R.J., 2006, The Use of Curvature in Potential-Field Interpretation. Australian Earth Sciences Convention 2006. Expanded Abstracts CD, Melbourne.

Pilkington, M., 2007, Locating Geologic Contacts with Magnitude Transforms of Magnetic Data. 2007. Journal of Applied Geophysics, V.63 (2):80-89.

Paine, J.G., Minty, B.R.S., 2005, Airborne Hydrogeophysics. In: Rubin Y and Hubbard SS (ed) Hydrogeophysics, Chapter 11. Eds. Springer. The Netherlands, p.333-357.

PROASNE, 2007, Northeast Brazil Groundwater Project. Web page of the cooperation between the Geological Surveys of Brazil and Canada. Available at http://PROASNE.net, cited 31st Oct. 2007.

Ruy, A.C., Silva, A.M., Toledo, C.L.B., Souza Filho, C.R.de, 2006, Uso De Dados Aerogeofísicos de Alta Densidade para Mapeamento Geológico em Terrenos Altamente Intemperizados: O Estudo De Caso Da Região de Cláudio, Porção Sul Do Cráton São Francisco. Revista Brasileira de Geofísica, v. 24, n. 4, p. 535-546.

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. Universidade de Brasília. Tese de Doutorado.

Silva, O.A.da, 2005, Análise de dados aerogeofísicos aplicada à exploração e ao gerenciamento de recursos hídricos subterrâneos. Tese de Doutorado Instituto de Geociências, Universidade Federal da Bahia, 88 p.

Silva C.M.S.V., Vasconcelos M.B., Santiago M.M.F., 2001, Recarga e datação de poços no cristalino (Recharge and dating of drilled wells in the crystalline domain). In: IV Simpósio de Hidrogeologia do Nordeste, 2001, Recife. Anais do IV Simpósio de Hidrogeologia do Nordeste. : ABAS (ed.). São Paulo. p. 8-14.

Souza Filho O.A.de, McCaffertty A.E., Silva A.M., Perrotta M.M., 2007, Ground-Water Potential: a predictive model from airborne geophysical, radiometric, and remote sensing data, Ceará, Brazil. In: Simpósio Brasileiro de Sensoriamento Remoto (SBSR), 13., 2007, Florianópolis. Anais...São José dos Campos: INPE, 2007, p. 3593-3595. CD-ROM. ISBN 978-85-17-00031-7.

Street, G.J.; Pracillio, G.; Anderson-Mayes, A., 2002, Interpretation of Geophysical Data for Salt Hazard Identification and Catchment Management in Southwest Western Australia. Exploration Geophysics, v.33, p. 65-72.

Syberg, F.J.R., 1972, A Fourier Method for the Regional-Residual Problem of Potential Fields: Geophysical Prospecting, V.20, P.47-75. In: Phillips, J.D., 1997, Potential-Field Geophysical Software for the PC, version 2.2: U.S. Geological Survey Open-File Report 97-725, 34 P.

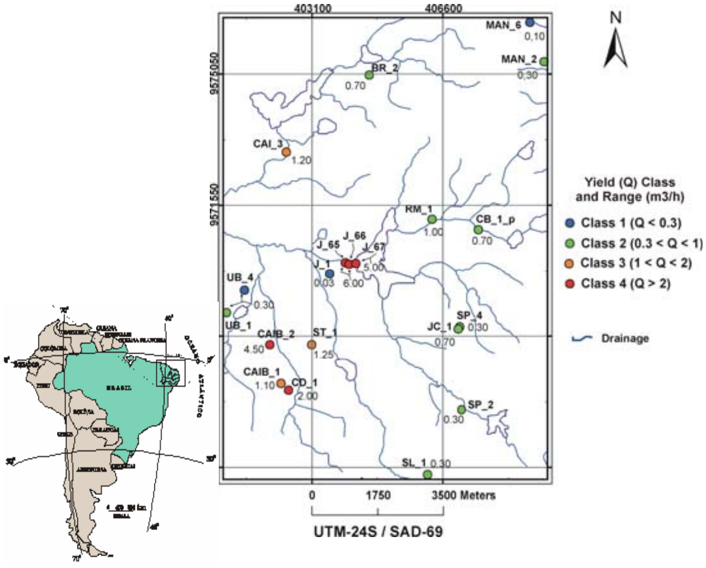


Figure 1: Location of Juá region in Northeast Brazil and the location of wells classified by yield (m^3/h).

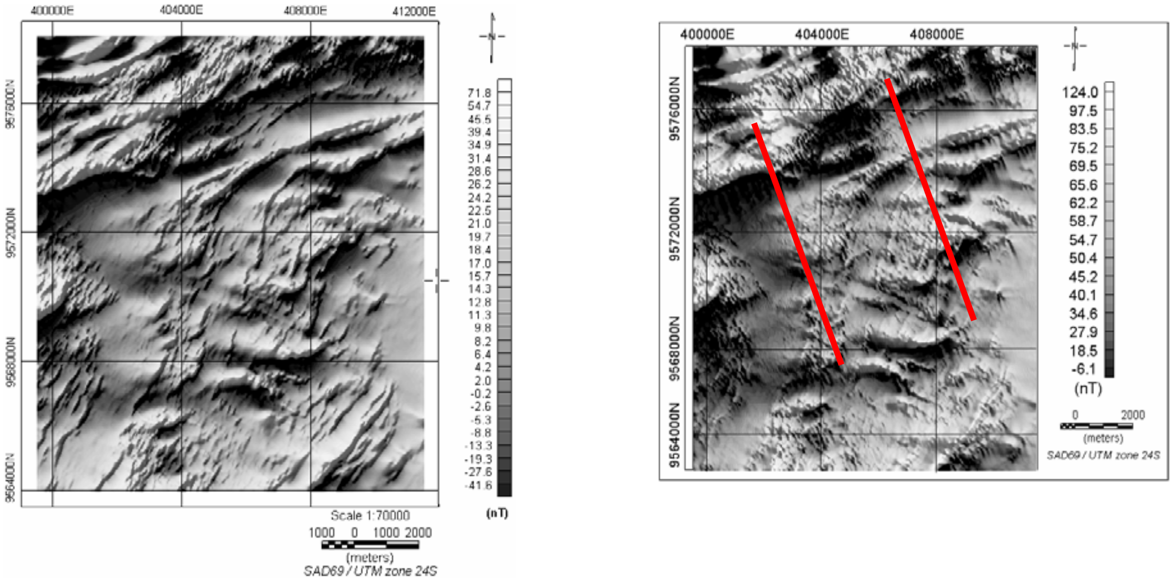
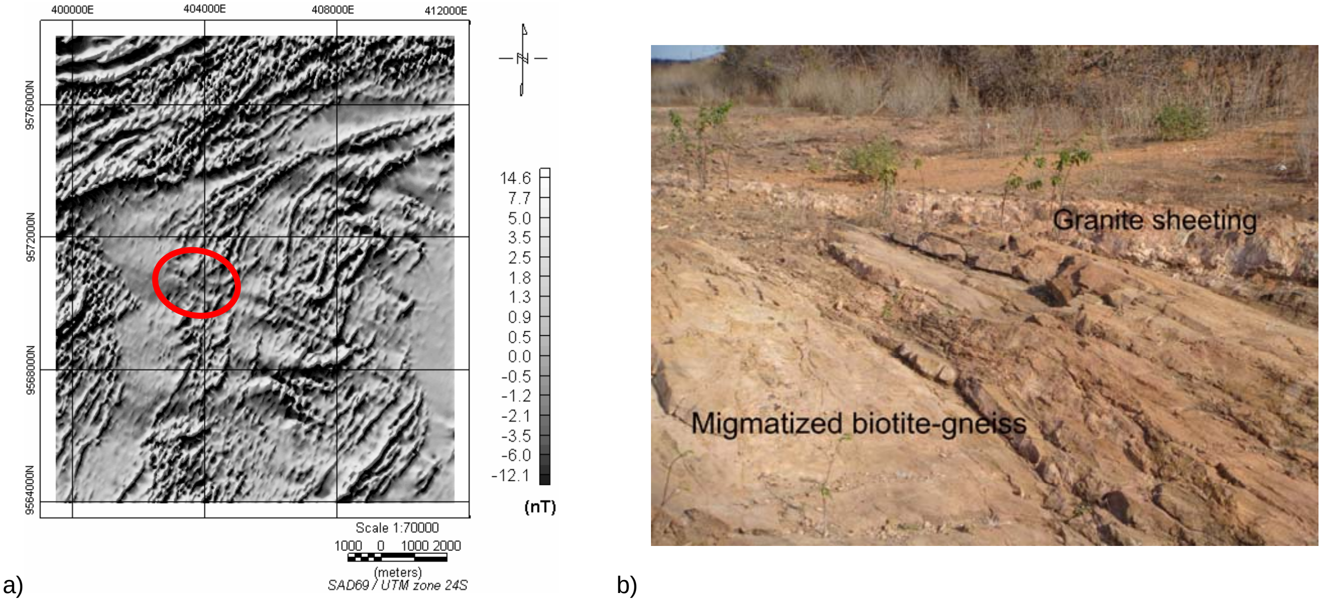


Figure 2: Comparison of reductions to magnetic north pole filters applied on Juá magnetic residual field grid: a) good result using Phillips (1997) algorithm; b) bad result using commercial algorithm. Red traces mark artifacts with direction parallel to the geomagnetic declination were generated.



a) b)

Figure 3: a) First vertical derivative algorithm applied to Juá magnetic data matched filtered to enhance magnetic sources between 20 e 60 m depth; b) outcrop on top of WNW-ESE gradient trend displayed as red circle in the map that comprises a brittle shear zone with granite sheeting of East-West direction that cuts migmatized biotite-gneiss.

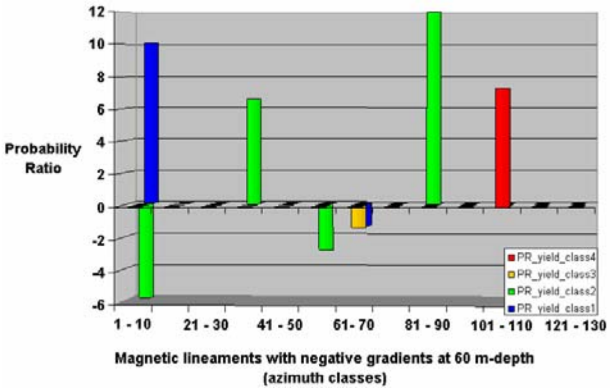


Figure 4: Graphic display of weights of probability ratio for each azimuth class of magnetic trend associated with locations of yield-well classes in Juá area.