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MAGNETIC SUSCEPTIBILITY AND GAMMA-RAY SPECTROMETRY ON DRILL CORE: LITHOTYPE CHARACTERIZATION AND 3D ORE MODELING OF THE MORRO DO PADRE NIOBIUM DEPOSIT, GOIÁS, BRAZIL

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ABSTRACT. The Morro do Padre niobium Deposit, in the Late-Cretaceous Catalão 2 alkaline-carbonatite complex, central Brazil, consists of stockworks of nelsonite and carbonatite dykes intruded into Precambrian phyllites, quartzites, and amphibolites. A gamma-ray spectrometry and magnetic susceptibility petrophysical survey was conducted on the cores of 73 drill holes in fresh-rock, producing a total of 1295 geophysical samples. Nelsonite, the host rock of the niobium mineralization in the Morro do Padre Deposit, has a characteristic geophysical signature, with higher gamma-ray spectrometry counting rates and magnetic susceptibility values, compared to other rock types. The studied nelsonites may be divided into N1 and N2 types. N2 nelsonite is richer in K, U and Th than N1. Carbonatites are divided into magnetic (C1) and nonmagnetic (C2) varieties. The nonmagnetic carbonatites can be subdivided into C2a and C2b. The C2a carbonatite is richer in K, U and Th than C2b, which is consistent with the presence of apatite and/or monazite in the former. The geophysical 3D modeling has shown that the main mineralized body is elongated in the E-W direction. It is about 100 m wide and 300 m long with a maximum depth of approximately 850 m reached by drilling.

Keywords: 3D ore modeling, niobium ore, applied geophysics, alkaline rocks, nelsonite.

RESUMO. O depósito de nióbio do Morro do Padre no complexo carbonatítico alcalino de Catalão 2 do Cretáceo Superior, região central do Brasil, consiste em *stockworks* de nelsonito e diques de carbonatito intrudidos em filitos pré-cambrianos, quartzitos e anfibolitos. A pesquisa petrofísica de gamaespectrometria e de susceptibilidade magnética foi realizada em testemunhos de 73 furos de sondagem em rocha fresca, produzindo um total de 1.295 amostras. Nelsonito, a rocha hospedeira da mineralização de nióbio no depósito Morro do Padre, tem uma assinatura geofísica característica, com maiores taxas de radiação gamaespectrométrica e maiores valores de susceptibilidade magnética em comparação com outros tipos de rochas. Os nelsonitos estudados podem ser divididos em N1 e N2. O nelsonito N2 é mais rico em K, U e Th do que o N1. Carbonatitos são divididos em magnéticos (C1) e não magnéticos (C2). Os carbonatitos não magnéticos podem ser subdivididos em C2a e C2b. O carbonatito C2a é mais rico em K, U e Th do que o C2b, o que é consistente com a presença de apatita e/ou monazita na composição minerológica. O modelamento 3D revela um corpo principal de nelsonito mineralizado, alongado segundo a direção E-W. Este é cerca de 100 m de largura e 300 m de comprimento, com uma profundidade máxima de 850 m.

Palavras-chave: modelamento 3D de minério, minério de nióbio, geofísica aplicada, rochas alcalinas, nelsonito.

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INTRODUCTION

Approximately 90% of the world Nb production comes from the Araxá (about 70%) and Catalão 1 and 2 carbonatite complexes, belonging to the Late-Cretaceous Alto Paranaíba Igneous Province, in central Brazil (Brod et al., 2004).

Although alkaline-carbonatite deposits are characterized by high geophysical contrasts with their host rocks, providing an excellent opportunity for detailed magnetic and gamma-ray spectrometric assessment, the in situ study of the petrophysical properties of their individual rock types is rather rare in mineral exploration.

This study focuses on the petrophysical properties of different alkaline rock types and their relationships with chemical and petrographic properties. The aim is to identify geophysical criteria to distinguish different classes of carbonatite and nelsonite and to provide a 3D geophysical modeling of the ore body.

GEOLOGICAL SETTING

The Alto Paranaíba igneous province is a NW-trending concentration of Late-Cretaceous alkaline igneous rocks, intruding Neoproterozoic metasedimentary rocks of the Brasília Fold Belt, between the southwest border of the Archaean São Francisco craton and the northeast border of the Phanerozoic Paraná basin (Gibson et al., 1995).

The province (Fig. 1) contains numerous kamafugitic (subordinately kimberlitic and lamproitic) sub-volcanic intrusions, kamafugitic lavas and pyroclastics (Mata da Corda Group), and large carbonatite-bearing plutonic complexes. The latter comprise Catalão 1 and Catalão 2, in Goiás State, and Serra Negra, Salitre, Araxá and Tapira, in Minas Gerais State. These complexes contain niobium, phosphate, titanium, REE, and vermiculite deposits, although only niobium (Araxá, Catalão 1 and 2) and phosphate (Tapira, Araxá, Catalão 1) are currently mined (Brod et al., 2004; Ribeiro, 2008).

The Alto Paranaíba Province carbonatite-bearing complexes evolve through fractional crystallization, liquid immiscibility, and metasomatism, resulting in a wide diversity of lithotypes and mineralizations with intricate contact relationships (Brod, 1999; Grasso, 2010; Palmieri et al., 2011; Barbosa et al., 2012; Brod et al., 2013; Gomide et al., 2013; Ribeiro et al., 2014). Similarly to other complexes in the province, Catalão 2 is a multiphase intrusion. It occupies a NE-SW elongated area with reentrant W and E borders, indicating the presence of multiple intrusions, as suggested by Machado Junior (1991). The southern part of the complex is unexposed at the present erosion level, sitting underneath a cover of fenitized country rock, which probably represents the roof of an alkaline intrusion. Stockworks of carbonatite and mineralized nelsonite intrude this southern area, and host the primary niobium mineralization, occurring in two main areas: the Boa Vista Mine, to the West, and the Morro do Padre Deposit, to the East (Palmieri et al., 2011).

The alkaline rocks at Morro do Padre consist mainly of nelsonite (the main pyrochlore host) and carbonatite intrusions, with subordinate phlogopite picrite, pyroxenite, metasomatic phlogopitite and fenite (Palmieri et al., 2011).

Nelsonites and carbonatites intrude as parallel and braided thin dike zones rather than single bodies. Nelsonites occur as stockworks of E-W oriented dykes, which splay upward along fractures. They consist of fine- to medium- grained carbonate, magnetite, apatite, tetra-ferriphlogopite, and pyrochlore (Palmieri et al., 2011).

The carbonatites have a considerable textural and mineralogical range, and occur as stockworks of dykes with variable thickness and, rarely, as plugs. Two generations of carbonatite are recognized in this deposit. The first is an almost pure, medium to coarse-grained carbonatite that crosscuts the fenite country rocks. The second is associated with the nelsonites, forming pockets within nelsonite dykes, and may be rich in apatite or magnetite and tetra-ferriphlogopite.

The Precambrian wall rocks for the primary Nb deposit are mostly fenitized and their mineralogy depends largely on the protolith. The main metasomatic mineral in fenites, formed from phyllites and quartzites, is K-feldspar, whereas tetra-ferriphlogopite is the main metasomatic phase in fenitized amphibolites.

METHODOLOGICAL APPROACH

Gamma-ray spectrometry

The alkaline-carbonatite deposits are characterized by positive magnetic, uranium and thorium anomalies, often near the center of the complex, surrounded by potassium-enriched fenites. These properties provide an excellent level of detail in the magnetic and gamma-ray spectrometric assessment by regional surveys, as well as for in situ measurements on drill cores. Similarly to the geophysical responses, the singular chemical compositions of alkaline rocks, carbonatites and the associated mineral deposits result in very strong geochemical contrasts between them and the country rocks. Therefore, geophysical and geochemical methods are widely used in mineral exploration to detect these bodies and control the concentration and quality of the ore during the mining (Gunn & Dentith, 1997; Abram et al., 2009).

The sources of natural gamma radiation are based on the high-energy radioactivity. Potassium (^{40}K), Uranium (^{238}U) and Thorium (^{232}Th) are the only naturally occurring elements with radioisotopes that produce gamma rays of sufficient energy and

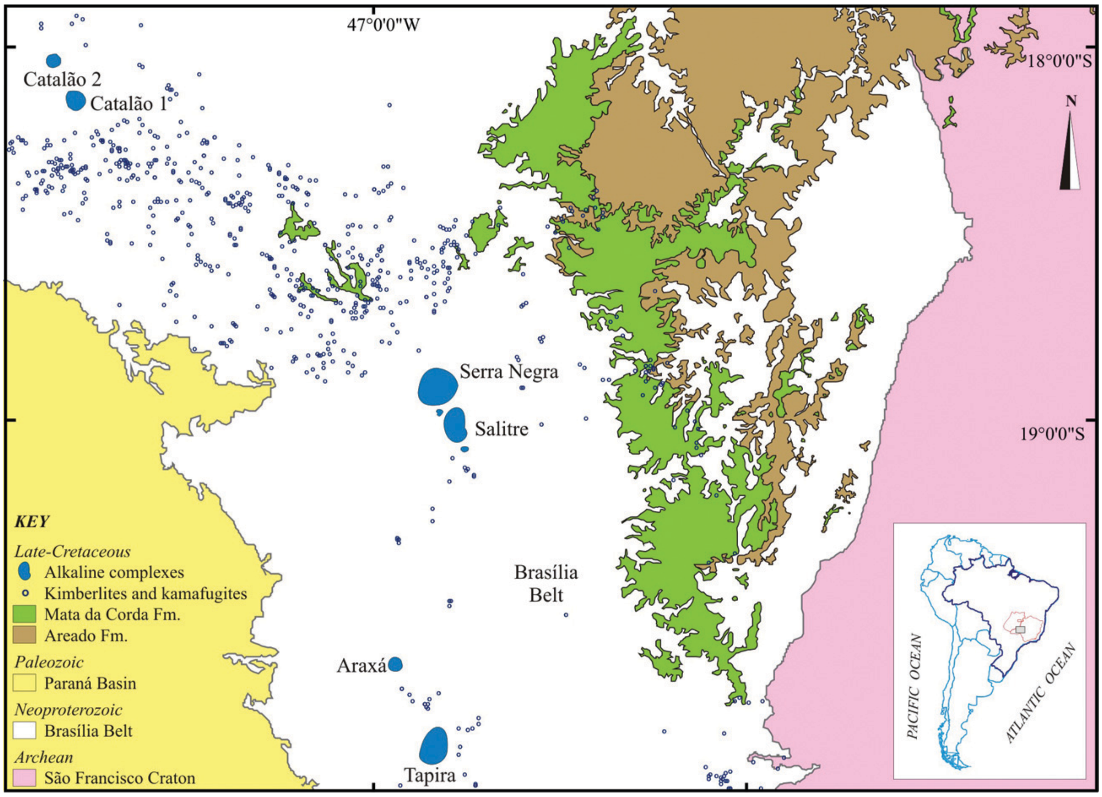

Figure 1 – Geological map of the Alto Paranaíba Igneous Province, showing the large alkaline-carbonatite complexes, numerous small kamafugite or kimberlite intrusions, and the Mata da Corda kamafugitic lavas and pyroclastics. Adapted from Oliveira et al. (2004).

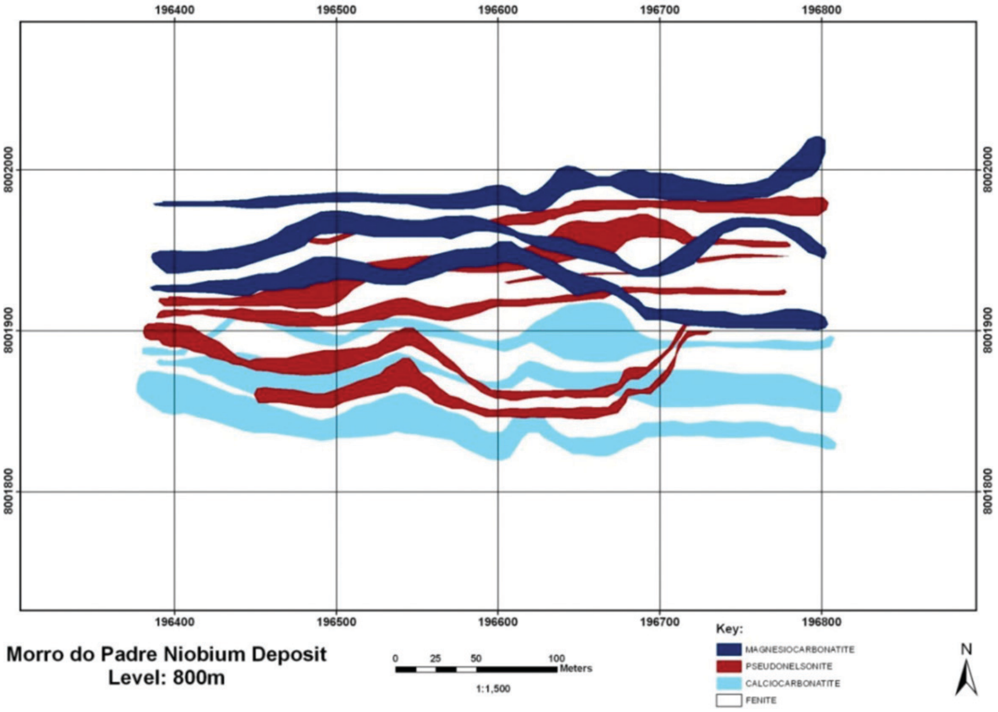

Figure 2 – Geological map of the Morro do Padre Deposit, interpreted from drill cores corresponding to the altitude level of 800 m (Palmieri et al., 2011).

intensity to be measured in geophysical surveys. Average crustal abundances are K = 2%, U = 2.7 ppm, Th = 12 ppm (Dickson & Scott, 1997; Minty, 1997).

^{40}K is the only radioactive isotope of K that decays by electron capture to ^{40}Ar. This is followed by the emission of a single gamma-ray photon with energy of 1.46 MeV. The gamma-ray flux from ^{40}K may be used to estimate the total amount of K present since the ^{40}K isotope occurs as a fixed proportion of total K in the environment. The spectra recorded at each site are processed with the instrument calibration parameters providing an estimate of the contents of K (%). The major hosts of K in rocks are potassic feldspars and micas. Consequently, K content is relatively high in felsic rocks such as granites, but low in mafic rocks such as basalts and very low in dunites and peridotites (Dickson & Scott, 1997; Minty, 1997).

Uranium and thorium themselves do not emit gamma-rays. Thus, it is necessary to rely on the gamma-ray emissions from their radioactive daughter isotopes ^{214}Bi and ^{208}Tl to estimate the concentrations of ^{238}U and ^{232}Th, respectively. The uranium and thorium windows are centered on the 1.76 MeV (U) and 2.61 MeV (Th) photo peaks (Wilford et al., 1997). Estimates of uranium and thorium concentrations are, therefore, indirect and usually reported as "equivalent uranium (eU)" and "equivalent thorium (eTh)" assuming equilibrium conditions (Grasty et al., 1997; Minty, 1997; Gunn, 1998; IAEA, 2003).

U appears as U^{4+} in igneous rocks and has crystal-chemical properties close to Th^{4+} and the Light Rare Earth Elements ($LREE^{3+}$). This explains the coherent geochemistry of U, Th and LREE in igneous rocks (Bea, 1999). These elements are present in accessory minerals such as zircon, monazite, apatite, allanite, titanite, and pyrochlore, most of which are weather-resistant and may become concentrated in the weathering cover. As U becomes mobile under supergene conditions, a large variety of U^{6+} minerals may form. This explains the variety of minerals found in uranium deposits, including silicates, phosphates, carbonates, sulfates, vanadates, molybdates, niobates, tantalates and titanates (Bea, 1999). Th is a constituent of the accessory minerals zircon, monazite, allanite, xenotime, apatite, and titanite, which are common in igneous and metamorphic rocks (Dickson & Scott, 1997; IAEA, 2003).

Carbonatite and nelsonite in the Morro do Padre Deposit contain apatite, monazite and pyrochlore and, therefore, may be correlated with the gamma-ray responses.

Magnetic Susceptibility

The magnetic properties of ferromagnetic rocks are usually dominated by magnetite, reflecting the presence of ferric iron exceeding the amount that can be readily incorporated into the major and varietal minerals. Consequently, basic and ultrabasic rocks generally have the highest susceptibilities, acid igneous and metamorphic rocks have intermediate to low values, and sedimentary rocks have very small susceptibilities. Pyrrhotite and ilmenite also produce positive magnetic anomalies in geophysical surveys (Clark et al., 1992; Reynolds, 1997; Carvalho, 1999; Sheriff, 1999).

The magnetic susceptibility (μ) represents a relationship between magnetic flux density B and magnetizing force H ($B = \mu H$). Although susceptibility is dimensionless, it can be normalized to obtain a numerical value compatible with the SI (Reynolds, 1997).

This parameter is an extremely important property of rocks and essential to magnetic exploration methods. Geomagnetic methods are widely used to define stratigraphic horizons, geologic structures, and specific lithotypes that can be mineralised or not (Carvalho, 1999). In this study, magnetic susceptibility is used to map Nb mineralization domains directly on drill cores, since the Nb mineral ore, pyrochlore, is strongly associated with magnetite in the deposit.

METHODS

A hand-held 256-channel Exploranium gamma ray spectrometer (GR-320 with a 0.35 l NaI (Tl) detector) was used to measure the natural concentrations of potassium, uranium and thorium at the sampling sites. A reference isotopic source avoids shifts in the spectral alignment of the instrument. The measured spectra recorded at each site were processed with the instrument calibration parameters providing the contents of potassium, uranium and thorium (Exploranium, 2007).

A total of 1295 samples from 73 drill holes (see Fig. 3 for the location of drilling sites), with total drilling length of 2638 m, were used. The measurements were made every 2.5 m directly on the drill cores, for consistency with the geochemical samples from Mineração Catalão Ltda. However, it should be noted that the geochemical analyses represent the full 2.5 m interval, whereas our geophysical measurements represent punctual, regularly spaced samples.

The sampling procedure followed these steps:

a) Each sample was placed in a wooden cleaned drill core box;

b) The detector was placed directly on the sample surface to avoid gamma-ray signal loss.

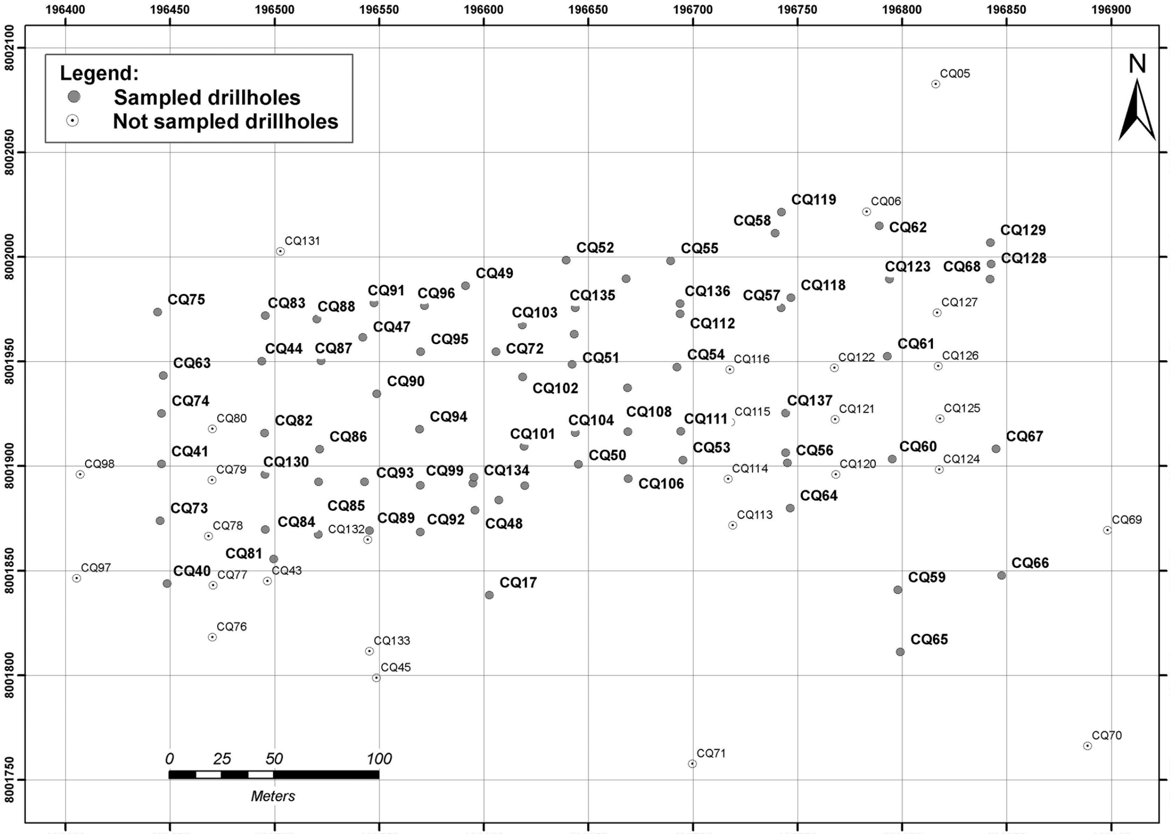

Figure 3 – Drill hole location map of the Morro do Padre Nb Deposit, showing the drillings used in this work (black dots).

Lovborg & Mose (1987) argue that measurement times depend on the radiation environment and the type, location and geometry of radioactive sources. They derived equations to determine the counting time for K, U, and Th with 10% error for various ratios of K, U and Th. For 350 cm^3, with NaI (TI) detector, 2 and 6-minute sampling times are considered reasonable for highly and low radioactivity rocks, respectively. In this study we adopted a 5-min sampling time for all gamma-ray measurements.

Gamma ray field measurements yield a number of counts N, registered in a particular energy window (K, U and Th) for a counting time, $t = 5$ min. These can be converted to a count rate, $n = N/t$ (cpm). Then, the recorded count rate is correlated to the concentrations of the radioelements by a built-in algorithm (IAEA, 2003). The gamma ray calibration is essential when different gamma-ray surveys are being compared. In this work count per minute (cpm) data were used because they are less influenced by deviations from the theoretical model during the gamma calibration process.

Magnetic susceptibility was measured with a Hand-Held Conductivity & Magnetic Susceptibility Meter DDD MPP-EM2S + Multi Parameter Probe from GDD Instrumentation Inc.

Three readings were taken for each sample for magnetic susceptibility measurements. The probe was initialized every minute or before each reading, moved away from any conductive or magnetic material and pointed to the air to decrease the instrumental drift.

In situ gamma-ray measurements represent a larger sample volume than in situ magnetic susceptibility measurements, but given the large (2.5 m) sample spacing and the highly variable characteristics of the ore, both data were registered in the database as measured in the same location.

Data processing

The statistical multivariate analysis of magnetic and gamma-ray spectrometric data was used to identify the samples with similar geophysical signature and good correlation with the mapped geology (Pires & Harthill, 1989; Pires, 1990). However, units mapped as relatively homogeneous on geological maps often exhibit significant variation in geophysical data and, consequently, in other physical properties (e.g. magnetic susceptibility and conductivity) (IAEA, 2003).

In this context, the similarity matrix technique K-means unsupervised classification (Davis, 2002) was used to define the best correlation of geophysical data with the mapped rock types in the Morro do Padre Deposit. Basic statistical analysis, including calculation of averages, standard deviations, variances, as well as F and t tests and scatter plots analyses were also carried out to characterize different classes.

The K-means algorithm divides n samples into k centroids. The procedure classifies a given data set into a certain number of clusters (assumed k clusters) fixed a priori. A similarity matrix is calculated and each sample is then allocated to the corresponding nearest centroid using the Euclidean distance method. So, for each cluster a new center is computed by averaging the feature vectors of all samples assigned to it. The process of assigning samples and recomputing centers is repeated for a specified number of iterations. The process is terminated when all samples are allocated in clusters and the convergence criterion is met. Therefore, new averages are calculated until all samples have been classified, reaching the smallest possible error (Davis, 2002).

RESULTS AND DISCUSSION

Nelsonite

The primary (fresh rock) Niobium mineralization in the Morro do Padre Deposit consists mainly of pyrochlore-rich nelsonites (Palmieri et al., 2011). Nelsonite is characterized by the highest counts of radioelements (K, U and Th), as well as higher Nb_2O_5, P_2O_5, Fe_2O_3 percentages and higher magnetic susceptibility than other rock types.

High concentrations of Nb_2O_5 are related to the presence of pyrochlore, P_2O_5 is mostly associated with apatite and/or monazite, whereas the radioelements are associated with apatite, monazite and pyrochlore, and total Fe_2O_3 with magnetite. Values of magnetic susceptibility in the nelsonites can be about 100 times greater than in the other rock types (see Fig. 4).

Figure 5 shows a detailed analysis of gamma-ray spectrometry and magnetic susceptibility together with chemical variables, in the CQ135 drill core. The profiles show lower magnetic susceptibility in the granular magnetite-poor carbonate domains, and high magnetic susceptibility in the region of the magnetite-rich nelsonite dykes. In the latter domain, even negative magnetic anomalies never reach zero values (Fig. 5). The positive gamma-ray spectrometry anomalies coincide with the magnetic ones and with increased Nb_2O_5 contents.

K-means unsupervised classification tests were employed to define different ore types. Two classes of nelsonite were defined. The first corresponds to slightly lower K, U and Th compared to the second (Table 1 and Fig. 6).

This result is consistent with the findings of Palmieri et al. (2011), who, using petrography, mineral chemistry, and whole-rock geochemistry, recognized two types of nelsonites. N1 is an apatite-rich rock formed by crystallization from a phosphate-oxide magma, and N2, a magnetite-rich rock that results from the accumulation of apatite, magnetite, pyrochlore and phlogopite on the walls of carbonatite dykes. Palmieri et al. (2011) classified N2 as pseudo nelsonite, since these rocks do not crystallize directly from phosphate-oxide magma.

Table 2 shows that P_2O_5 and Nb_2O_5 have statistically significant positive correlations with CT. The highest correlation of Nb_2O_5 is with Th, whereas P_2O_5 correlates best with K and U. K and U are highly correlated, but both elements show lower correlation with Th.

On the other hand, in N1, the correlations of P_2O_5 and Nb_2O_5 with the radioelements are much lower, and mostly not statistically significant. There are small positive correlations of Nb_2O_5 with Th and Fe_2O_3. Again, U and K are highly correlated, but the correlation of both elements with Th is much poorer.

Both classes 1 and 2 present positive correlation between CaO and P_2O_5, which relates to the abundance of apatite. The correlations described above suggest that U concentration is probably related to the content of apatite whereas Th may be related to pyrochlore abundance. The low, not statistically significant correlations between Th and P_2O_5, suggests that monazite does not play a significant role in controlling the gamma-ray results in the analyzed samples. K values are more difficult to explain. This element is probably related to variable phlogopite content, which is the main K-bearing mineral in the studied nelsonites, particularly in those of class 2. However, the reasons for the high K and U correlation and low SiO_2 correlation are not clear at the present stage.

Carbonatite

The profile of the CQ137 drill cores (Fig. 7) shows that CaO positive anomaly coincides with carbonatites. The shallow carbonatite intercept of the profile is associated with positive U and K anomalies, unlike the deep carbonatite intercept. The U and K anomalies are probably related with higher amounts of apatite, monazite and tetra-ferriphlogopite, suggesting that these minerals are more abundant in the shallow carbonatite.

K-means unsupervised classification tests also defined two carbonatite types: the first, magnetic carbonatites (30 samples) and the second, nonmagnetic carbonatites (765 samples). The

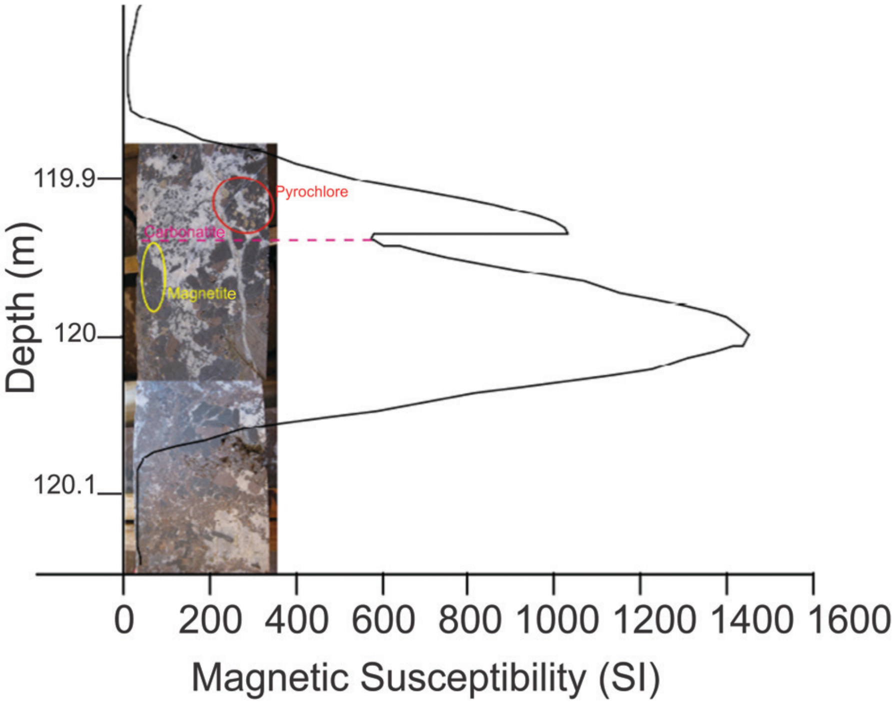

Figure 4 – Geophysical log of a CQ96 drill core section showing the decrease of the magnetic susceptibility anomaly due to the presence of carbonatite pockets in the nelsonite dike. The small light brown crystals, in the circled area, are pyrochlore; the white areas are apatite + carbonate, and the dark gray to black grains are magnetite.

Table 1 – Statistics (average ± standard deviation) of N1 and N2 nelsonite classes.

Nelsonite classes	CT	K	U	Th	% (total Nelsonite)
N1	231.75±7.08	29.31±0.71	18.49±0.59	17.62±0.81	40.82
N2	259.97±18.48	31.56±1.47	20.12±1.14	20.78±2.38	59.18

nonmagnetic carbonatites were additionally classified in two families: C2a) 238 samples or 36.99% of type 2 carbonatites; and, C2b) 482 samples or 63.01% of type 2 carbonatites.

Figure 8, Tables 3 and 4 show that the C2b class has slightly higher radioelements concentration than C2a. Geochemistry data show that C2b rocks are Nb_2O_5, P_2O_5, TiO_2 and Fe_2O_3 enriched, and that these chemical constituents correlate positively with U and Th. These results suggest the presence of pyrochlore, apatite and/or monazite, and magnetite in the carbonatite, particularly those of the C2b class.

Other rocks

Mean and standard deviation for the measured variables in other rock types are given in Table 5.

Geophysical data were inefficient to distinguish fenites and carbonatites due to similar radioelements contents (see Tables 4 and 5). Phlogopitite, picrite and pyroxenite occur only as minor rock types in the Morro do Padre Deposit (Table 5). The results of K-means unsupervised classification tests employed to define these lithotypes could not discriminate them based on gamma-rays responses. Therefore, these rocks were not included in further statistical analysis.

Mathematical Modeling of the Deposit

A multiple linear regression of the estimated concentrations is useful for removing the effects of geological process and the gross systematic changes in radioelement concentration within an interpreted unit (e.g. Pires, 1995; Wellman, 1998; Pires et al., 2010).

In this work, linear regression was used to obtain a linear equation to indirectly estimate Nb_2O_5 grades in drill cores, allowing us to constrain geophysically an envelope of high niobium concentrations in the Morro do Padre Deposit.

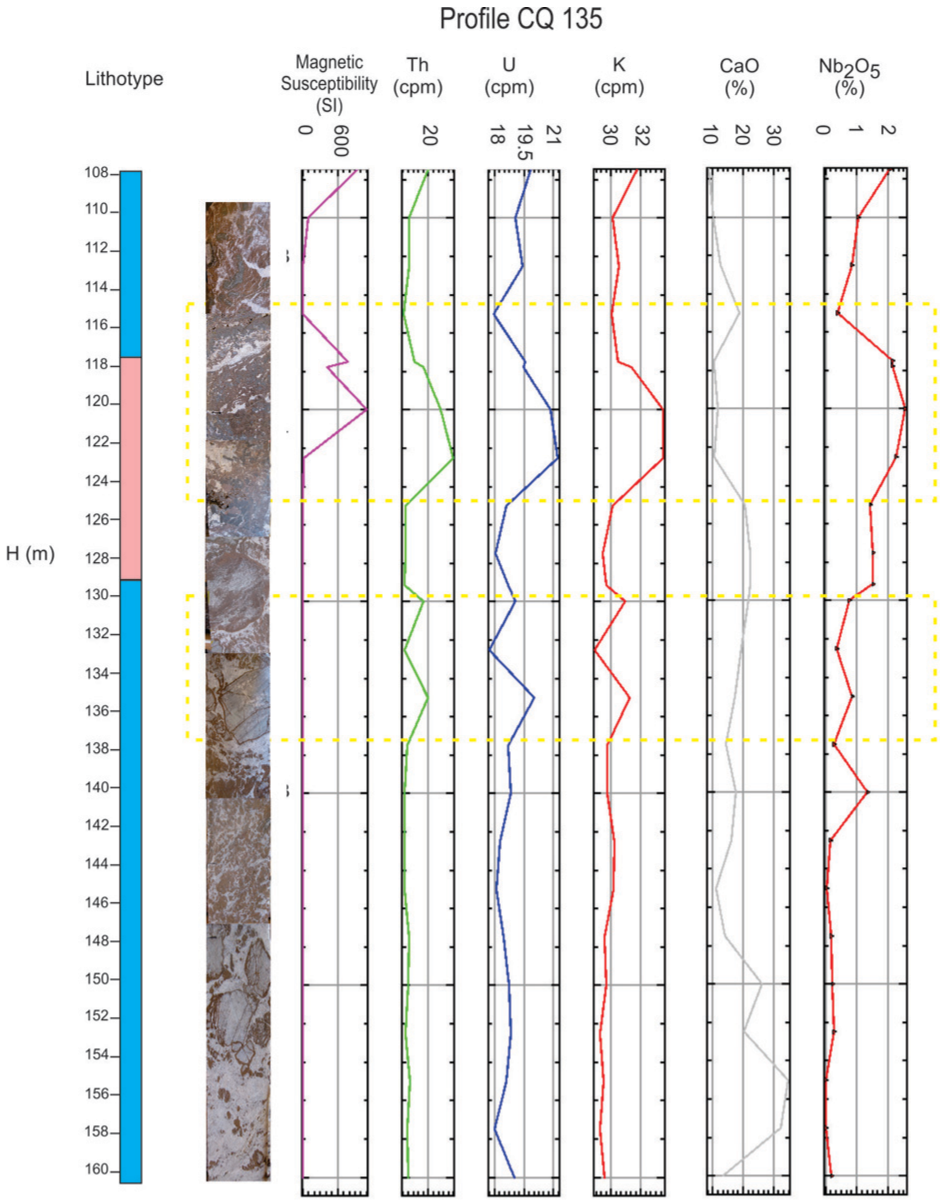

Figure 5 – Geophysical log of the CQ135 drill hole, showing the correlation between nelsonite and positive anomalies in magnetic susceptibility and in the K, U and Th gamma-ray spectrometry channels.

The data have been standardized in each unit. This was necessary because the use of different measurement units for different analyzed elements could influence the results (Davis, 2002). In the regression analysis, Nb_2O_5 (%) was used as the dependent variable while K (cpm), U (cpm), Th (cpm), U/Th, U/K, Th/K and magnetic susceptibility (SI) were the independent variables.

The initial regression modeling based on the geophysical measurements yielded high residuals errors. These residuals errors were removed from all data and the second regression modeling yielded the following equation Eq. (1):

$$\begin{aligned}\text{POI Factor} &= 0.224 + 2.62\,[\text{Th}] + 0.166\,[\text{CT}] \\ &\quad - 0.421\,[\text{K}] - 1.06\,[\text{U}] \\ &\quad - 0.000676\,[\text{magnetic susceptibility}] - 0.863\,[\text{U/Th}] \\ &\quad + 1.17\,[\text{U/K}] - 2.41\,[\text{Th/K}]\end{aligned} \tag{1}$$

This equation computes a Potential Ore Indicator (POI) Factor. This factor explains 57.1% of all data (using Minitab® 15.1). The set of gamma-ray spectrometry and magnetic susceptibility

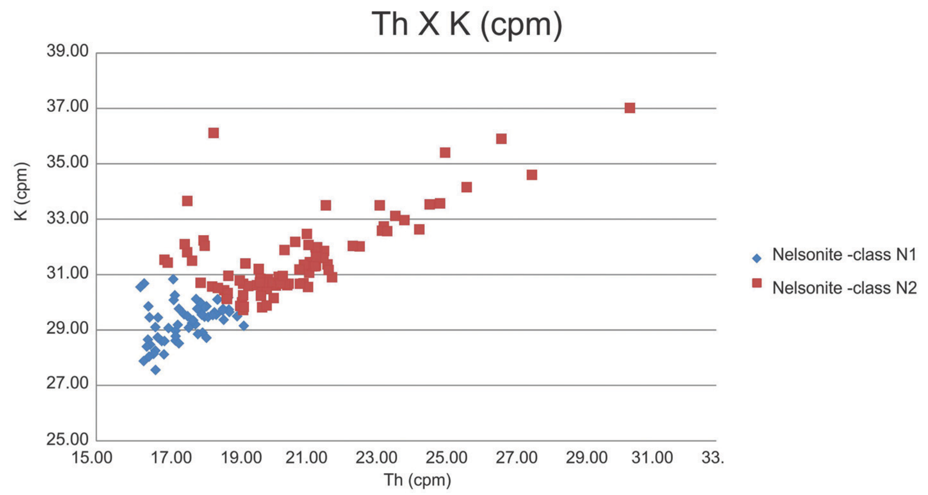

Figure 6 – Non-supervised classification of nelsonites based only on the radiometric measurements. Nelsonites can be divided in two sub-classes: N1 and N2, where N2 has higher K (cpm) and Th (cpm) values.

Table 2 – Correlation coefficients between geophysical and geochemical variables in nelsonites.

NEL 2	Nb_2O_5	SiO_2	CaO	P_2O_5	CT	K	U	Th	Fe_2O_3	MgO
Nb_2O_5	1	–0.173	–0.139	0.101	0.418**	0.254*	0.051	0.507**	0.097	–0.024
SiO_2		1	–0.252*	–0.381**	–0.187	–0.113	–0.156	–0.165	–0.543**	0.081
CaO			1	0.580**	0.249*	0.253*	0.243*	0.205	0.503**	–0.388**
P_2O_5				1	0.319**	0.425**	0.482**	0.163	–0.101	–0.284
CT					1	0.888**	0.747**	0.925**	–0.091	–0.148
K						1	0.921**	0.677**	–0.11	–0.167
U							1	0.456**	–0.051	–0.205
Th								1	–0.094	–0.057
Fe_2O_3									1	0.191
MgO										1
NEL 1	Nb_2O_5	SiO_2	CaO	P_2O_5	CT	K	U	Th	Fe_2O_3	MgO
Nb_2O_5	1	–0.529**	0.082	0.065	0.196	–0.053	–0.221	0.413**	0.376**	–0.015
SiO_2		1	–0.469**	–0.497**	–0.177	–0.112	–0.018	–0.156	–0.629**	0.194
CaO			1	0.674**	0.092	0.213	0.13	0.004	–0.138	–0.558**
P_2O_5				1	0.139	0.262*	0.187	–0.051	0.091	–0.466**
CT					1	0.787**	0.703**	0.811**	0.074	0.074
K						1	0.843**	0.396**	–0.045	–0.347**
U							1	0.257*	–0.067	–0.379**
Th								1	0.079	–0.016
Fe_2O_3									1	0.108
MgO										1

NEL = nelsonite

* = Correlation is significant at the 0.05 level (2-tailed)

** = Correlation is significant at the 0.01 level (2-tailed)

Table 3 – Statistics (average ± standard deviation) of carbonatite classes C1, C2a and C2b.

Carbonatite classes	CT (cpm)	K (cpm)	U (cpm)	Th (cpm)	Magnetic Susceptibility (SI)
C1	248.99±17.01	31.44±2.97	20.19±2.63	16.14±1.98	629.88
C2a	220.04±3.76	28.53±0.47	17.68±0.38	16.24±0.40	27.76
C2b	228.97±3.99	29.41±0.46	18.43±0.40	17.13±0.51	85.44

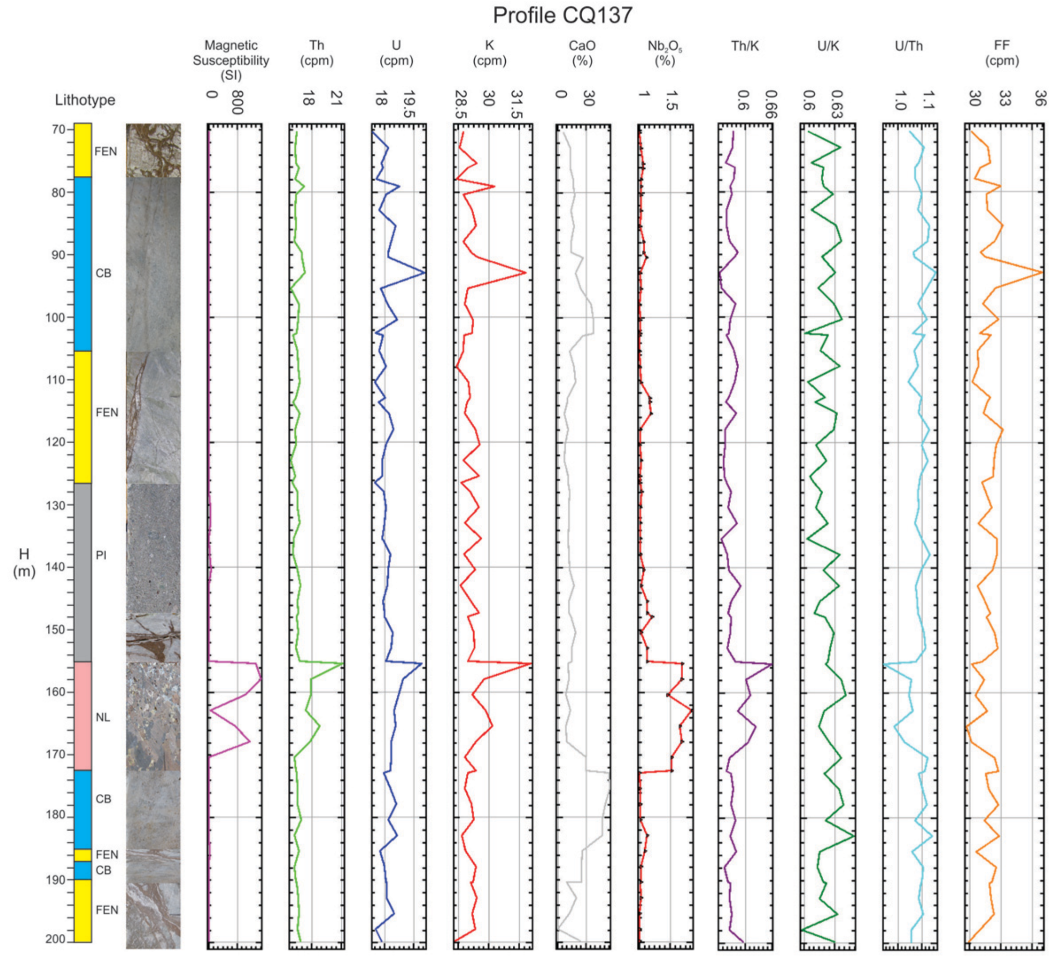

Figure 7 – Log of the CQ137 drill cores, showing the evident correlation between the Nb geochemical anomaly, as well as the positive geophysical signatures for radiometric K, U, Th and magnetic susceptibility values. Nb geochemical anomaly has a negative correlation with CaO.

measurements from this equation estimates the Nb_2O_5 of the measured geophysical samples. The three-dimensional distribution of these estimates was interpolated by the Inverse Distance Algorithm (using Voxler Software, Golden Software, 2012).

The Inverse Distance method is a weighted average interpolator that yields either an exact or a smoothing interpolation. Data are assigned a weight during interpolation using a weighting Power that controls how the weighting factors diminish as distance from a lattice node increases. The greater this power, the less influential the points far from the lattice node are, during interpolation. As the power increases, the lattice node value approaches the value of the nearest point. For a smaller power, the weights are more evenly distributed among the neighboring data points. The gridder module of the isosurface software (Davis, 2002) interpolates scattered point data onto a uniform lattice. Subsequently, a POI Factor isosurface was computed, and designated as a Potential Ore Indicator Zone. For the purposes of this study, a power of 2 was used for the interpolating function.

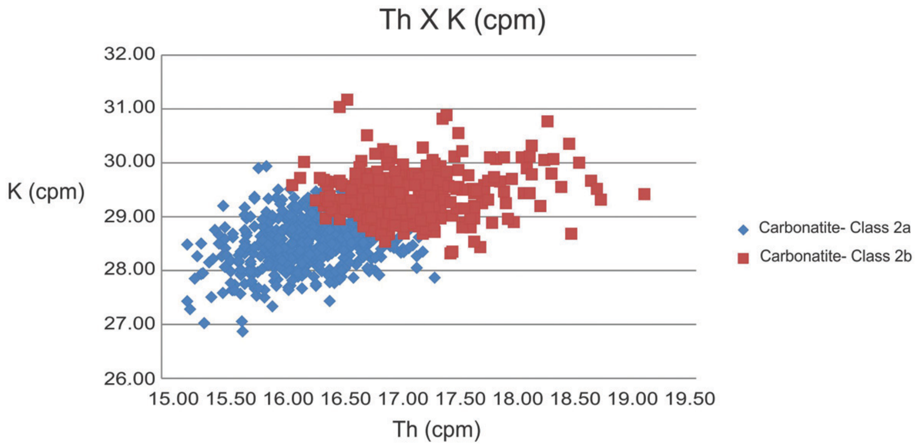

Figure 8 – Subdivision of class 2 carbonatite into two separate classes. The C2b class corresponds to high Th (more than 17 cpm) or high K (more than 29 cpm) while C2a is a low-Th and low-K class.

Table 4 – Correlation coefficients between geophysical and geochemical variables in carbonatites.

CB 2b	Nb_2O_5	P_2O_5	CT	K	U	Th	Fe_2O_3	TiO_2
Nb_2O_5	1	0.626**	0.245**	0.004	0.009	0.349**	0.577**	0.684**
P_2O_5		1	0.282**	0.069	0.133*	0.281**	0.495**	0.484**
CT			1	0.536**	0.583**	0.718**	0.225**	0.055
K				1	0.430**	0.108	0.025	–0.101
eU					1	0.131*	0.088	–0.064
eTh						1	0.262**	0.179**
Fe_2O_3							1	0.782**
TiO_2								1
CB 2a	Nb_2O_5	P_2O_5	CT	K	U	Th	Fe_2O_3	TiO_2
Nb_2O_5	1	0.464**	–0.096*	–1.61**	–0.085	0.083	0.537**	0.591**
P_2O_5		1	–0.082	–0.184**	–0.013	0.011	0.307**	0.268**
CT			1	0.576**	0.680**	0.723**	–0.194**	–0.157**
K				1	0.310**	0.253**	–0.127**	–0.104*
U					1	0.392**	–0.127**	–0.111*
Th						1	–0.082	–0.025
Fe_2O_3							1	0.775**
TiO_2								1

CB = carbonatite

* = Correlation is significant at the 0.05 level (2-tailed)

** = Correlation is significant at the 0.01 level (2-tailed)

Figures 9 and 10 show different views of the Potential Ore Indicator Zone. This zone is an E-W elongated body approximately 850 m maximum deep, ∼100 m wide and ∼300 m long. It coincides with a zone of dike swarms of pyrochlore-rich nelsonite which ascended mostly through old E-W fractures (Palmieri et al., 2011).

The inner zone of the modeled body consists of apatite carbonatites which are cut by nelsonite dikes and late-stage tetraferriphlogopite- and magnetite-bearing carbonatite. The outer zone consists of almost pure, medium to coarse grained carbonatite that crosscuts the fenitized Precambrian country rocks (Palmieri et al., 2011 and this work).

Table 5 – Statistics (mean ± standard deviation) of geophysical variables for other rock types.

Rock types	CT	K	U	Th	N
Fenite	220.98±13.27	28.79±0.75	17.81±0.61	16.40±0.65	297
Phlogopitite	217.05±6.99	28.70±0.88	17.60±0.93	15.95±0.37	9
Picrite	222.94±13.82	28.84±1.57	18.06±1.63	16.43±0.72	39
Pyroxenite	226.79±2.50	29.21±0.30	18.28±0.34	16.94±0.32	8

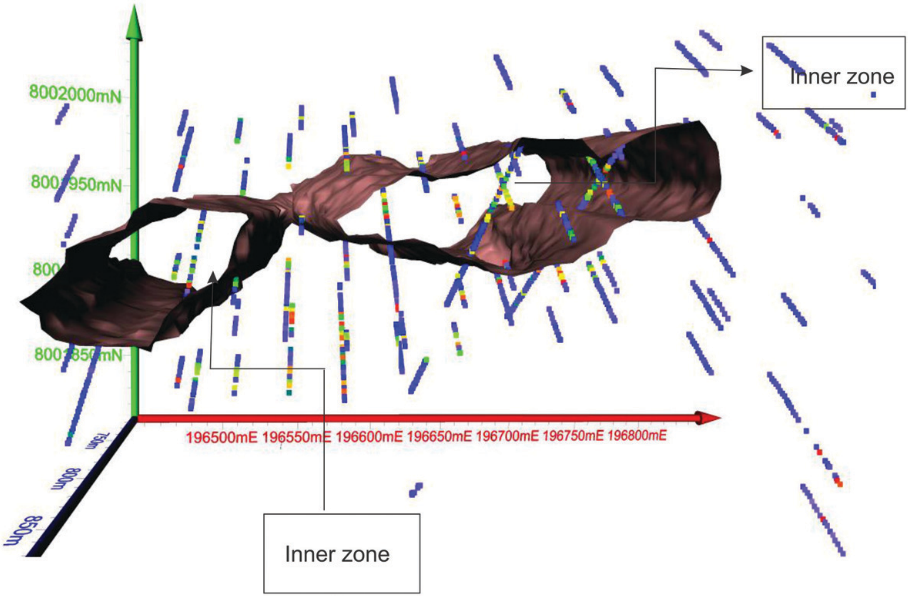

Figure 9 – Potential Ore Indicator Zone corresponding to the surface, whose Nb_2O_5 cut off is 0.5% (view from the top).

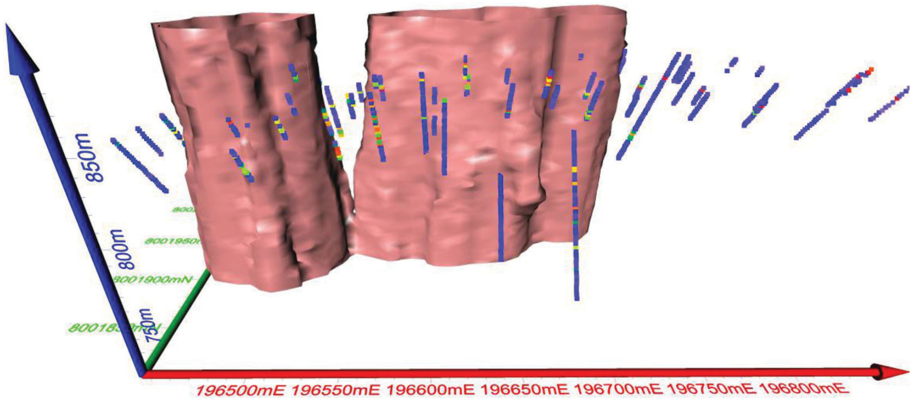

Figure 10 – Potential Ore Indicator Zone corresponding to the surface, whose Nb_2O_5 cut off is 0.5% (view from the front).

The central part of the model is relatively narrow because the number of drill holes in this area is small and, therefore, this may not be a real geometric feature of the body depicted in Figures 9 and 10.

Figure 11 shows the modeling of the geochemical Nb_2O_5 data, considering a cut off grade of 0.5%. Compared to the computed geophysical Potential Ore Indicator Zone, the geochemical model is larger and more elongated toward SW and E, reaching approximately 400 m long and 150 m wide, SW. These remarkable differences possibly occur because the geophysical samples are punctual measurements, while the geochemical sampling is characterized by a larger individual sample volume.

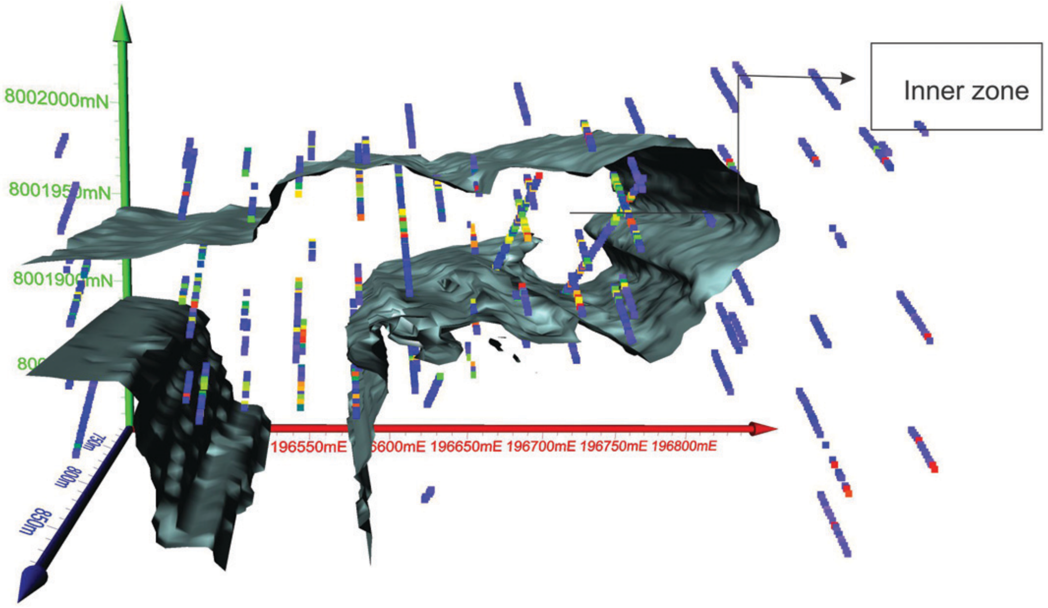

Figure 11 – Isosurface 0.5% Nb_2O_5 cut off (view from the top).

CONCLUSIONS

The statistical multivariate analysis of magnetometry and gamma-ray spectrometry data was used to define different geophysical signatures associated with different classes in the same rock type.

The Morro do Padre Niobium Deposit is composed of 2 nelsonite and 3 carbonatite classes. The first nelsonite class corresponds to lower K, U and Th content. The carbonatites may be divided into 2 sub-types: magnetic carbonatites and non-magnetic carbonatites. The nonmagnetic carbonatites are divided into 2 classes with the first corresponding to lower K, U and Th. In both carbonatites and nelsonites, higher K may be associated with higher phlogopite contents, whereas U and Th may be associated with pyrochlore, apatite and monazite.

The multiple linear regression technique was used to build the geophysical 3D model and define the Potential Ore Indicator (POI) Zone. This zone is E-W elongated and approximately 850 m maximum deep, ~100 m wide and ~300 m long. This body is also characterized by higher abundance of pyrochlore-rich nelsonite dikes.

The regression model explains about 60% of all data and shows good agreement with main geological and geochemical features. The results can be considered good when considering complexities such as the sampling space geophysics, the ore complex distribution within the deposit and interdigitation of different rock types. Certainly, a denser geophysical spacing would map more precisely the ore distribution in the deposit. Results suggest that the approach used in this study is an alternative methodology that can contribute to evaluate the ore deposit spatial distribution.

The technique has proven to be a useful and cost-effective tool for mineral exploration, which can be used in other similar deposits. The lithological and structural complexity of the primary mineralization in the Morro do Padre Deposit suggests that a more detailed geophysical sampling could also set, different parameters for the geochemical sampling and analysis. The significant correlation results observed among geophysical and geochemical data support this. The much faster and cheaper geophysical methodology could be used to guide geochemical studies of similar deposits.

The results obtained in this study suggest that anomalies identified by airborne gamma-ray and magnetic surveys in carbonatite exploration programs, could be followed up in the field by corresponding ground techniques to indirectly investigate the possibility of niobium mineralization.

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