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Weathering Conditions Evaluation of Banded Iron Formations of Bonito Mine (Northeastern Brazil) Based on Coupled Cluster-Correspondence Analysis

Avaliação de Condições de Intemperismo de Formações Ferríferas Bandadas da Mina do Bonito (Nordeste do Brasil) com Base na Análise de Correspondências-Agrupamentos Acoplada

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Abstract

This research was focused on weathering conditions regarding Banded Iron Formations (BIF) ore exploitation at Bonito Mine. The database is stemmed from an exhaustive drilling program at the mining site. Therefore, hundreds of iron ore samples were assayed for Fe2O3, SiO2, Al2O3, P and Mn grades, and qualitative geotechnical data such as weathering grades, physical ore type, voids, and coring depth levels were collected from drilling core samples. A previous petrographic study has shown that there are four BIF types: amphibolitic itabirites, martitic itabirites, hematitic itabirites, and magnetitic itabirites. In order to enhance this study, a multivariate model using geochemical and geotechnical data under a systemic approach was employed. This approach was conceived to account for the whole available information, both quantitative and qualitative, through the Correspondence Analysis and Cluster Analysis grounded appropriate methodology. This innovative strategy disclosed the presence of two groups of samples, denoted in the sequel Cluster 1 and Cluster 2. Cluster 1 is characterized by the Fe-poorer/High-Al BIF ores describing an association of magnetitic itabirites, martitic itabirites to amphibolitic itabirites which are conditioned to depths deeper than 70 meters and they usually stand as slightly weathered rocks or fresh rocks. Cluster 2 encompasses Fe-richer/Low-Al BIF ores composed of martitic, magnetitic and hematitic itabirites which are described as moderate to highly weathered porous friable ore materials. The proposed multivariate modeling strategy can deal with a wide range of miscellaneous geological issues.
Keywords: Itabirites; multivariate modeling; methodological strategy; weathering grades; Serra dos Quintos Formation

Resumo

O presente trabalho objetivou a avaliação das condições de intemperismo dos protominérios das formações ferríferas bandadas da Mina do Bonito. A base de dados analisada é derivada de um extenso programa de prospecção executado na área da mina. Em razão disso, centenas de amostras foram analisadas para teores de Fe2O3, SiO2, Al2O3, P e Mn e, também, dados qualitativos relativos aos tipos geomecânicos, graus de intemperismo, vazios e profundidade de coleta das amostras. Um estudo petrográfico prévio mostrou que há basicamente quatro tipos de rochas mineralizadas: itabiritos anfibolíticos, itabiritos martíticos, itabiritos hematíticos e itabiritos magnetíticos. Com o intuito de aperfeiçoar esta investigação, uma proposta de análise multivariada utilizando dados geoquímicos e geotécnicos sob uma abordagem sistêmica foi concebida e empregada para agrupar toda informação disponível, tanto quantitativa como qualitativa através da Análise de Correspondências. Com a Análise de Agrupamentos foi possível realizar o pós-processamento dos dados fatoriais permitindo uma avaliação conjunta de dados geoquímicos e geotécnicos no mesmo espaço. Essa estratégia inovadora mostrou a presença de dois grandes grupos ou clusters. O Cluster 1 é caracterizado por rochas mineralizadas com baixos teores de Fe2O3 e altos teores de Al2O3 descrevendo a associação de itabiritos magnetíticos com alto Al2O3 e itabiritos martítico-anfibolíticos condicionados a profundidades superiores a 70 m e geralmente aparecem como rochas levemente intemperizadas ou sãs. O Cluster 2 agrupa rochas com teores mais elevados de Fe2O3, teores mais baixos de Al2O3 e SiO2 e são descritas como moderadamente a altamente intemperizadas, além de ser mais friáveis e mais porosas. A integração de dados petrográficos aos resultados da análise multivariada acoplada revela uma incidência mais intensa de intemperismo físico. A estratégia metodológica proposta neste trabalho tem um relevante potencial para aplicação em diversas situações em que há necessidade de analisar extensas bases de dados geológicos, considerando a concatenação de variáveis de diferentes naturezas.

Palavras-chave: Itabiritos; modelamento multivariado; estratégia metodológica; graus de intemperismo; Formação Serra dos Quintos

1 Introduction

Geological evaluation of ore deposits always has been an important task during the development of the mining project. As a fundamental step prior to mining planning, weathering conditions appraisal must be taken into account in order to expand the knowledge about the most friable zones of the iron ore and, conversely, the hardest ones. Hence, one of the great challenges nowadays relies on understanding how to treat and interpret exhaustive and large geological databases. This issue becomes even more incisive when dealing with the decision making related to increasing geological information framework or ore mining operations.

One of the many approaches to deal with large geological databases is represented by multivariate analysis methods which were designed to evaluate the variance between variables and samples, jointly or not. Factorial methods have been used for decades in order to reduce multi-dimensionality and present the most important factors that explain geological relations and processes (Pereira *et al.,* 2015).

Among many tasks, mining geology work comprises core identification and description which may disclose relevant qualitative data that can be collected by observing some physical or geomechanical aspects of ore material, such as the weathering grade, ore type and voids. This qualitative information, often neglected, is crucial for ore geological research, especially regarding iron ore from banded iron formations which are naturally heterogeneous rocks and their mineralogical composition can input geological uncertainties during the ore assessment process.

Rodrigues & Brandão (2017) reported that distinguishing hard ore and friable ore types will impact the production costs, in terms of energy outlay and loss of efficiency in comminution and concentration processes. Compact iron ore types standing out of the specifications are able to prejudice mineral liberation and metal recovery. Thus, the raise of production costs sometimes can create a negative input to cash flow of the mining project. Establishing a previous zoning of occurrence of compact and friable ore materials enriches the mineral processing planning steps.

Although the geological expression *Banded Iron Formations* (BIFs) is already worldwide known describing rocks with alternating bands of iron ore minerals and silicate minerals, in this work, we also refer to itabirites as metamorphosed BIFs which have been studied since the 19th century (Eschwege, 1824 *in* Renger, 2005; Leith & Harder, 1911; Harder, 1914; Dorr II & Barbosa, 1963; Maxwell, 1972; Castro, 1994; Veríssimo, 1999; Rossi *et al.,* 2019).

The Bonito Banded Iron Formations (BIF) mine is located at Rio Grande do Norte State, Northeastern Brazil where the mining operations were first orientated to richer iron ore depicted by magnetitites and iron skarns (> 80% Fe_2O_3) (Barbosa, 2013). The BIFs were classified as the poorer iron ore yet its geological significance remains as the one of the outstanding records in a Neoproterozoic metasedimentary sequence within the Seridó Mobile Belt (Jardim de Sá *et al.,* 1995; Sial *et al.,* 2015; Dantas *et al.,* 2017) (Figures 1 and 2).

Throughout the geological time, landscapes and soil covers are developed and some weathered mineral products in soils can be recognized as indicators of neoformation of chemical processes of which they occurred. Temperature gradients, wind and the action of the rainfall and flowing water would be considered the most important weathering agents (Carvalho, 1995; Fookes, 1997).

In this research, the main goal is to recognize plausible relations between geochemical data and geological-geotechnical data in order to identify weathering conditions of banded iron-formations related to a mining site. On the other hand, a strategical methodology is proposed aiming to be applied to other mining geological settings.

2 Material and Methods

2.1 Geological Database

The Bonito mine was extensively explored by MHAG Serviços e Mineração S/A company who is the owner of the legal mineral right. The database which was submitted to the multivariate modeling derives from an exhaustive drilling program developed by that company which includes 1,335 samples

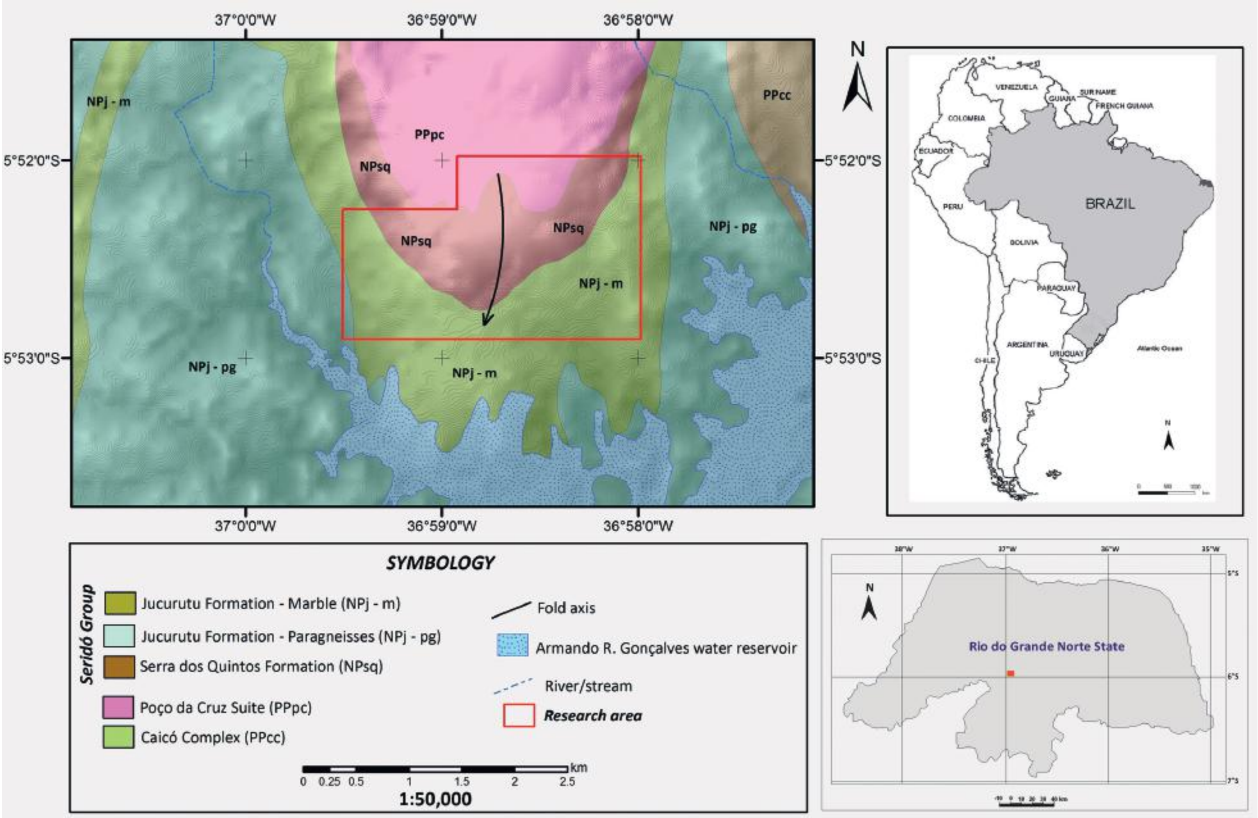

Figure 1 Geological map of the research site (Simplified after Angelim *et al*., 2006).

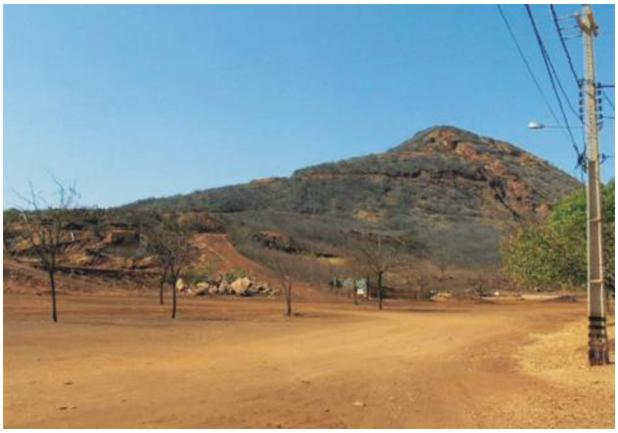

Figure 2 Front view of Bonito BIF mine, Northeastern Brazil. The higher grounds were exploited due to the presence of richer iron ores.

collected from 86 boreholes located at the mining site (Figure 3). In this work, marble, schists, phyllite, amphibolite and gneiss were not analyzed. All available geochemical and geotechnical data are exclusively related to itabirites.

Geochemical database includes Fe_2O_3, SiO_2, Al_2O_3, P and Mn grades which were obtained by XRF spectrometry analysis at SGS-GEOSOL Labs. Ltd. Geotechnical qualitative data such as weathering grades, ore mechanical type, voids and borehole depth intervals were collected from drilling core logs.

Furthermore, BIF samples were specifically collected to support a petrographical study regarding mineralogy, fabrics, intergrain and mineralogical relations based on optical microscopy work on 26 polished sections and 12 thin sections (Fonteles *et al.,* 2018).

2.2 Multivariate Modeling Tools

The primary aim of factorial analysis methods is to reduce the multidimensionality of large datasets (Grenacre & Blasius, 2006; Pereira *et al.,* 2015). For this case, let us consider a large data matrix composed of *n* observations (rows) tabulated according

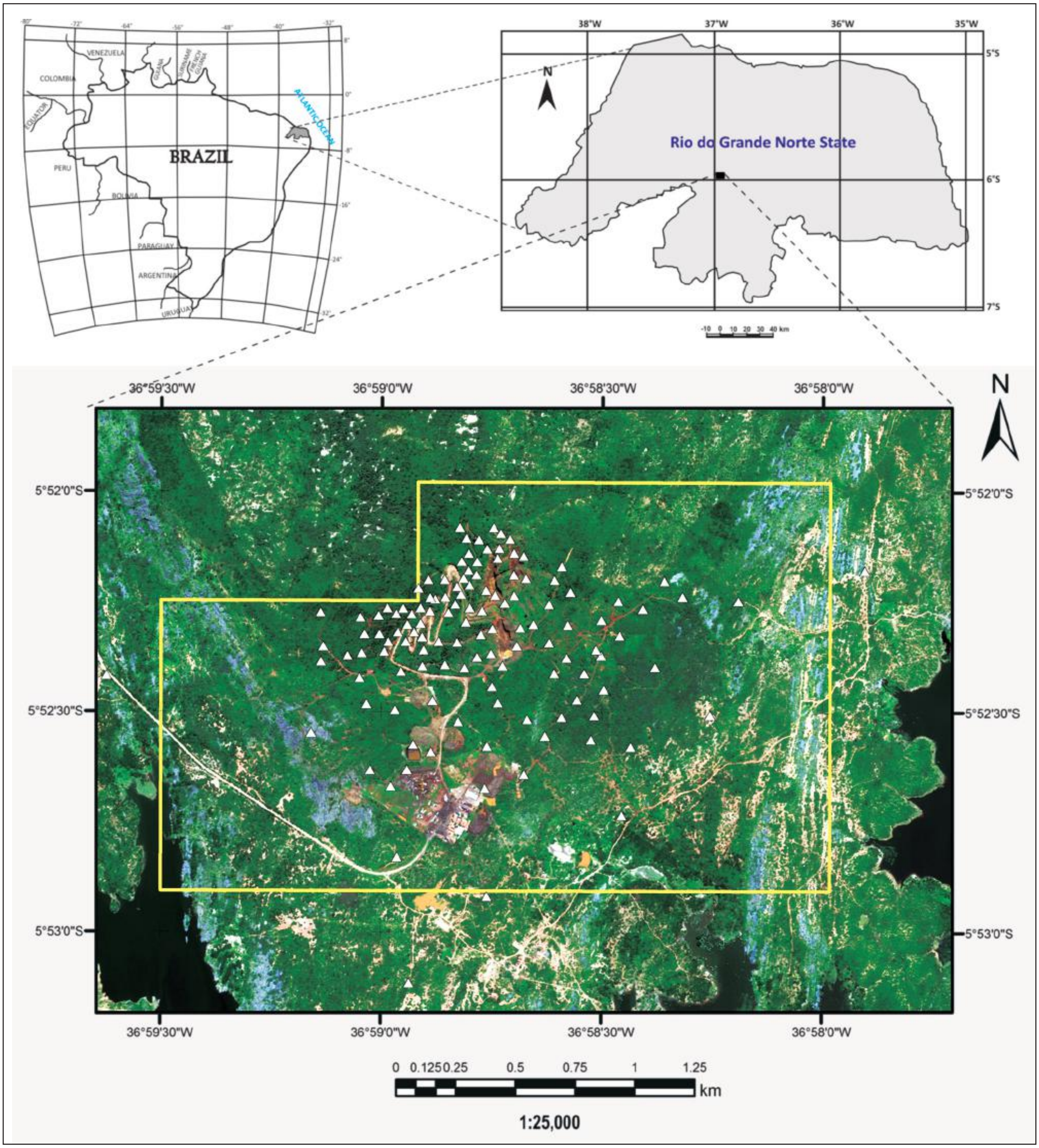

Figure 3 Location map of the research site (yellow polygon) and boreholes (white triangles).

to *p* variables (columns) which exhibits geological, geochemical or geotechnical data, altogether. Quantitative data (hard data) may be represented by geochemical content (%wt), mineral percentages, density values and uniaxial compressive strength test values. Qualitative data (soft data), on the other hand, is depicted by categorical, ordinal or binary codes which convey geological information.

The input table, under the form of an n x p matrix, can be geometrically represented by displaying the elements contained in its rows and/or columns as coordinates of points in an abstract space. As illustrated in Figure 4, depending on how the matrix is inspected (along columns or along rows), it may be converted into a cloud of n rows in the R^p space (Case 1), or into a cloud of p columns in the R^n space (Case 2). The fundamental thesis of CA is that the two geometric representations in R^p and R^n are equivalent, as demonstrated mathematically by Pereira *et al*. (2015). This entails looking for similarities and differences from column to column, from row to row, and between columns and rows, trough proximity, opposition or orthogonality analysis of the graphical outputs in terms of the topology of projections onto such graphs of the relevant input codes (representing items given in rows and columns).

This allows for the joint interpretation of rows and columns in the same plot, which means that the separate graphs displayed in Figure 4 can be combined into a single plot, even though they are produced by two different ways of viewing the basic matrix (for Case 1, rows are projected onto the columns space and the reverse for Case 2).

The most significant outputs from CA are standard Cartesian graphs showing the simultaneous projection of the points representing rows and columns onto the axes that convey the maximum fraction of the total inertia of the input matrix (being this total inertia the same for both clouds, and denoting the analogue of variance in classic statistics, *i.e.* – in geometric language – the product of the point mass by the squared distance to the entire cloud centroid). Moreover, given the symmetric encoding of the contingency tables, the axes produced by CA define a single coordinate system.

The approach given in this work was improved by the unique advantage of CA that is the joint display of active and supplementary variables onto the same factorial space. This procedure also allows simultaneous analyses of quantitative and qualitative variables. The main structure of the factorial space is conveyed by the geochemical data which describes the driving ‘picture’ of the geological information regarding the BIF from the Bonito Mine. Additionally, geotechnical data was introduced as an auxiliary input to a most comprehensive analysis.

Though geotechnical qualitative attributes were treated as supplementary variables, they are not less important source of geological information to assess the weathering conditions of BIF rocks. The main concern is to establish the factorial output providing a recognizable data structure within the complete disjunctive matrix post-processing by projecting it in terms of CA.

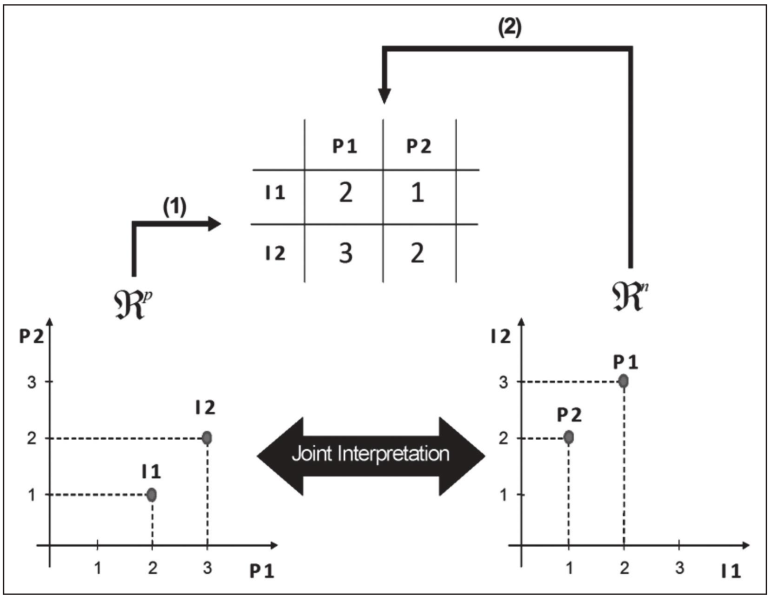

Figure 4 Example of the geometric representation of the elements of a simple fictitious matrix for visualization purposes.

Avoiding a “blind” exhaustive factorial representation, petrographic samples classification was used as a reference to a supervised assessment on multivariate analysis by matching their geochemical composition to petrographic/mineralogical contents.

Among the grouping techniques, clustering methods are the most popular multivariate analytic tools. Ascending Hierarchical Classification (AHC) algorithms are often used in geological investigation (Hongjin, *et al.* 1995; Maerz and Zhou, 1999). Several grouping algorithms or linkage rules are available for AHC clustering: single linkage (nearest neighbor), complete linkage (furthest neighbor), Ward’s method (minimum variance method), weighted pair-group average, unweighted pair-group average (median linkage) and weighted pair-group centroid (Podani, 2000).

Many options of dissimilarities or distance measures are available to perform the amalgamation process such as Euclidean, squared Euclidean, City-Block (Manhattan), Chebyshev metric and Minkovski Power metric. Some of those are commonly used taking into account the previous knowledge of the nature of the database and its geological features.

Once CA outcomes provide a clear and comprehensive topological space where samples and variables can be interpreted, the AHC methods can help the perceptiveness of the relation between the groups formed in that space. As shown by Sousa (1988), Guterres (1993) and Hongjin *et al.* (1995), cluster analysis methods have been currently used to acknowledge and solve geological resources issues.

The statistical work was carried on ANDAD 7.20 (CVRM, 2002) software and Statsoft Statistica® 10 Enterprise software package. Spatial data management was fully supported by Microsoft Access® 2010 and ESRI ArcMap® 10.1 systems.

3 Geochemical and Geotechnical Data Encoding for Multivariate Analysis

The active variables will draw the main factorial input, which is the geochemical data. As CA modeling algorithm calls for a discrete data encoding, the quantitative geochemical raw data was ranked into classes as shown in Table 1

Variable	Class	Cum. Freq.	Grade limits%
Fe_2O_3	Fe1	0.334	4.18 – 40.60
	Fe2	0.668	40.60 – 45.62
	Fe3	1.000	45.62 – 70.10
SiO_2	Si1	0.501	28.11 – 55.68
	Si2	1.000	55.68 – 90.23
Al_2O_3	Al1	0.517	0.010 – 0.505
	Al2	1.000	0.505 – 18.23
P	P1	0.479	0.007 – 0.039
	P2	1.000	0.039 – 0.252
Mn	Mn1	0.368	0.010 – 0.160
	Mn2	0.679	0.160 – 0.300
	Mn3	1.000	0.300 – 2.030

Table 1 Class limits defined for encoding of geochemical variables.

The geotechnical data was collected during a systematic description of the boreholes’ lithological sampled material. From each borehole’s 3 meter-interval core data - such as ore/rock type, structures, fracturing, core recovery, mechanical type and weathering grade were organized on a database system for further comparisons and analyses.

Most of these data sources can be depicted as categorical data and the properties disclosed by them can be encoded describing important geotechnical aspects. Three qualitative variables were added to the multivariate analysis: weathering condition, mechanical type and voids.

The weathering condition data was tabulated according to Dearman (1974), Fookes (1997) and Basu *et al.* (2009) as described in Table 2.

Weathering Grade	Description	Code
Unweathered (UW)	Rock shows no evidence of weathering or staining.	1
Slightly (SW)	Rock shows weak or slightly discoloring with little or no change of strength from fresh rock.	2
Moderately (MW)	Rock strength is usually reduced by weathering. The rock may be highly discolored basically by Fe staining.	3
Highly (HW)	Rock has almost similar properties as soils and has weak strength in the presence of water.	4

Table 2 Description and encoding of weathered ore/rock mass (Adapted after Dearman, 1974; Fookes, 1997; Basu *et al.,* 2009).

The category 'mechanical type' was adopted in this work as an attribute describing the physical aspect of the BIFs as it was observed at mining site and in the drilling cores. The complete description is given in the Table 3.

Type	Description	Code
Friable (FRB)	Weathered BIF crushed down under one field hammer blow. Eventually flattened BIF with irregular shapes and powdered BIF that usually passes through 100 mesh sieve can be found.	1
Compact (COMP)	Hard BIF rock that breaks under several field hammer blows. It's clearly correlated to unweathered rocks.	2

Table 3 Description and encoding of mechanical characteristics of the BIFs.

Void classification was done by visual observation during the inspection and describing procedures of the lithologies in drill cores. It was not a purpose providing exact figures or replace strict porosity tests' results but only to point out this visual feature with a descriptive mark. Therefore, the classification scheme adopted in this research relies on visual aspect concerning the presence of voids or cavities in the sample. Table 4 exposes the description and ranking of core samples.

Type	Description	Code
Porous (HP)	Presence of visible voids or cavities in ore rock samples due to prior weathered minerals.	1
Non-porous (NP)	Massive aspect of the ore rock's fabric without expressive pores or voids.	2

Table 4 Voids characterization and encoding for BIF ores.

Depth intervals values (m) were obtained directly from the operational drilling core data and ranked in three categories. Thus, depth interval values will be treated as another qualitative variable (Table 5).

Depth (m)	Code
Dep1: 0 - 70	1
Dep2: 70 - 145	2
Dep3: > 145	3

Table 5 Depth intervals encoding for BIF ores.

4 Basic Geological Setting of the Bonito Mine

4.1 Lithostratigraphy of Seridó Group

The Bonito BIF mine is related to the Seridó Mobile Belt which covers an expressive area at Rio Piranhas-Seridó Domain in Northeastern Brazil. Its geodynamics is well-marked by strong deformation processes (especially the transpressional strain), granitic magmatic accretion and the development of NNE-SSW transcurrent structures during the Brasiliano/Pan-African orogenesis in Borborema Province (Jardim de Sá *et al.,* 1995; Nascimento *et al.,* 2004; Angelim *et al.,* 2006; Sial *et al.,* 2015).

In this work, the adopted stratigraphic scheme was presented by Angelim *et al.* (2006) suggesting the Seridó Group to be formed by the following units (from the base to top): (a) Serra dos Quintos Formation (NPsq) which is composed of quartzites, itabirites (BIF), schists, gneisses and locally metamafics and metaultramafics rocks; (b) Jucurutu Formation (NPj) is constituted by paragneisses interbedded by metaconglomerates, marbles, calc-silicatic rocks, mica-schists, iron formations and metavolcanics; (c) Equador Formation is formed mainly by muscovite-quatizites with interbedded metaconglomerates; (d) Seridó Formation is basically composed of feldspathic mica-schists. Locally, marbles, calc-silicatic rocks, quartzites and metavolcanics can appear within the main lithology (Figure 1).

4.2 Petrographic Study of the BIF

This research was focused on weathering conditions evaluation of low-grade iron ores (BIFs) of Serra dos Quintos Formation which are essentially formed by a metasedimentary sequence containing rocks with alternating bands of iron oxides (hematite, magnetite and martite) and silicatic minerals such as amphiboles and quartz, mainly as listed in Table 6 (Fonteles *et al.*, 2018).

Petrographic work carried by Fonteles *et al.* (2018) has revealed that the Bonito Mine BIFs are comprised of hematitic itabirites, martitic itabirites, magnetitic itabirites, and amphipolitic itabirites

BIF Type	Quartz	Amphiboles	Magnetite	Martite	Hematite	Pyrite	Chalcopyrite
AmI	14 - 34	40 - 75	0 - 10	0 - 25	0	1 - 10	0 - 1
HI	50 - 60	15 - 25	0 - 1	0 - 5	19 - 20	0 - 1	0
MI	30 - 60	20 - 25	1 - 15	15 - 35	0	0 - 1	0
MgI	30 - 70	10 - 40	30 - 50	0 - 1	0	1 - 5	0 - 1

Table 6 Petrographic composition of the BIF types (%) obtained by microscopy analysis (AmI – amphibolitic itabirite, HI – hematitic itabirite, MI – martitic itabirite and MgI – magnetitic itabirite).

(Figure 5). These BIF rocks occur in different depth levels displayed as lens forms as illustrated by a NW-SE geological section (Figures 6 and 7). This section was constructed on the basis of lithological interpretation of nine drill holes logs positioned on that direction.

Figure 5 Banded iron formations (itabirites) drillcores exhibiting some accounted geological features. A. Unweathered non-porous martitic itabirite (fresh rock); B. Slightly weathered amphibolitic itabirite; C. Moderately weathered hematitic itabirite; D. porous weathered hematitic itabirite; E. highly weathered magnetitic itabirite; F. friable highly weathered magnetitic itabirite.

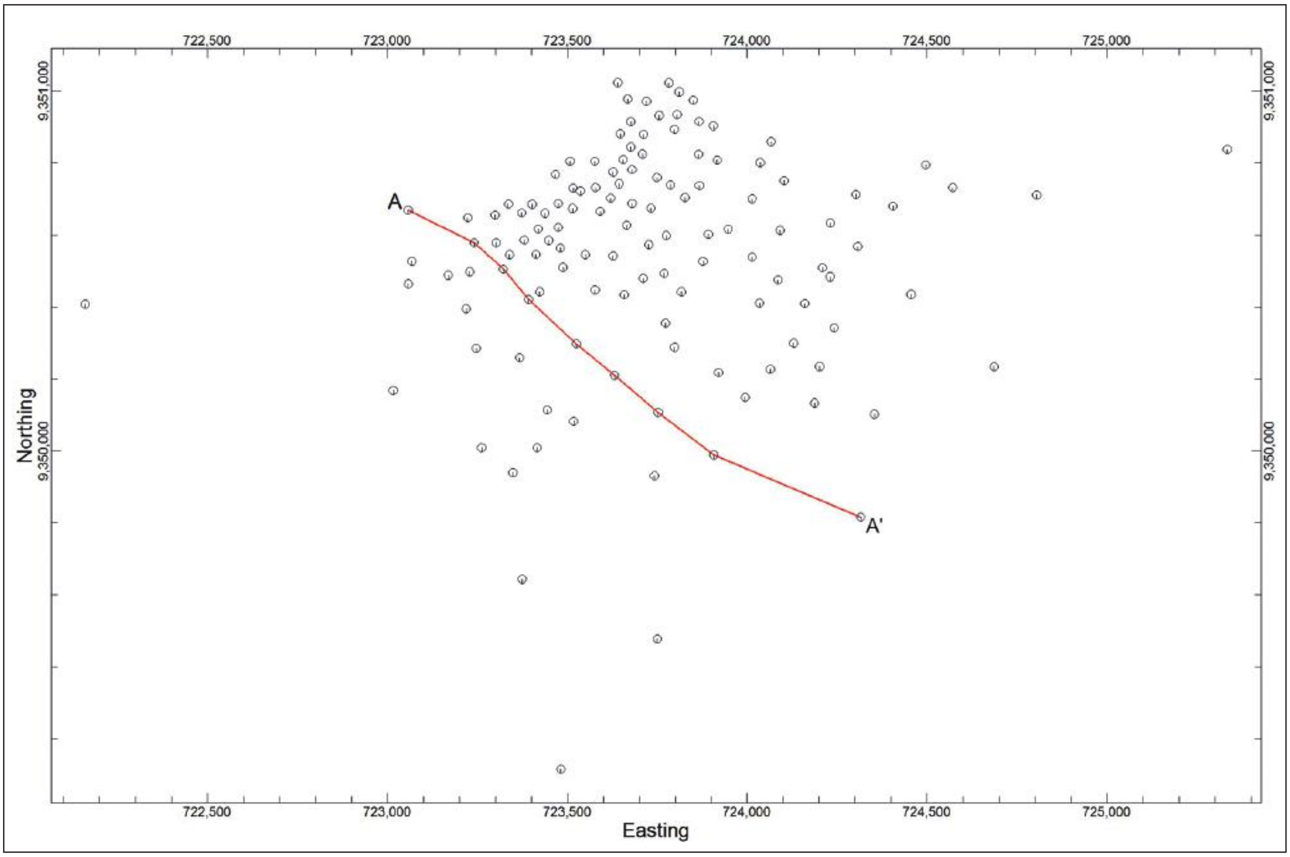

Figure 6 Locational map of the geological section A-A’.

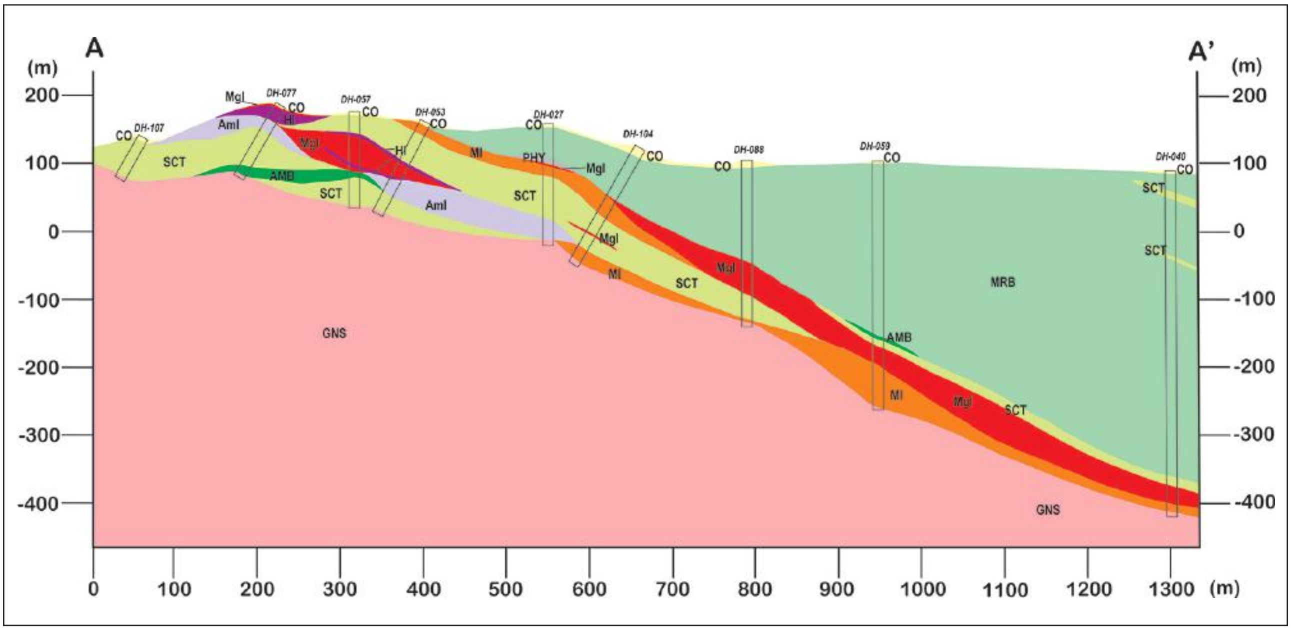

Figure 7 Geological cross section of the Bonito Mine. Lithologies acronyms: AmI – amphibolitic itabirite; HI – hematitic itabirite; MgI – magnetitic itabirite; MI – martitic itabirite; MRB – marble; SCT – schist; AMB – amphibolite; PHY – phyllite; CO – colluvium; GNS – gneiss.

5 Weathering Conditions Evaluation: A qualitative approach using a Coupled Cluster- Correspondence Analysis Strategy

The joint projection of active and supplementary variables onto A1-A2 factorial plane (Figure 8) allows identifying a clear separation of Fe-poorer/unweathered/compact/non-porous BIF ores (left side of factorial plane) and the Fe-richer/moderately to highly weathered/friable/porous BIF ores (right side). Looking closer to Axis 1, one can note that the depth of the samples tend to decrease from the negative to the positive side of that axis. As shown on Table 7 the first two axes explain more than 66% of the total inertia - accumulated explained variance.

Axis	Eigenvalue	% Exp.	% Accum.
1	0.1838	49.9680	49.97
2	0.0608	16.5261	66.49
3	0.0452	12.2891	78.78
4	0.0362	9.8048	88.59
5	0.0237	6.4188	95.01
6	0.0170	4.6039	99.61
7	0.0015	0.3917	100.00

Table 7 Eigenvalues. The bold value expresses the amount of accumulated retained inertia that explains the most part of the variance within the multivariate database.

Taking advantage of a singular feature available on CA, Figure 9 displays the joint projection of all variables and petrographic samples onto the A1-A2 factorial plane. The negative side of Axis 1 plot is linked to the Fe-poorer BIFs, mainly exposing martitic and amphibolitic itabirites. The Fe-richer BIFs are composed of magnetitic and hematitic itabirites.

The factorial coordinates obtained from the two axes of CA (Table 7) were employed to build up an input matrix in order to model a single dendrogram assembling active and supplementary variables and the representative samples onto the same space (Figure 9).

After several experiments aiming to reach a structure that would describe and reveal a sound multivariate arrangement, the ultimate result has produced a model based on the Complete Linkage and Minkovski Power metric (Nishisato, 2002). The metric's values were normalized giving a proportional distance measure among the clusters. As presented in Figure 10, two major groups were identified exhibiting substantial differences which are defined by an opposition of geotechnical variables.

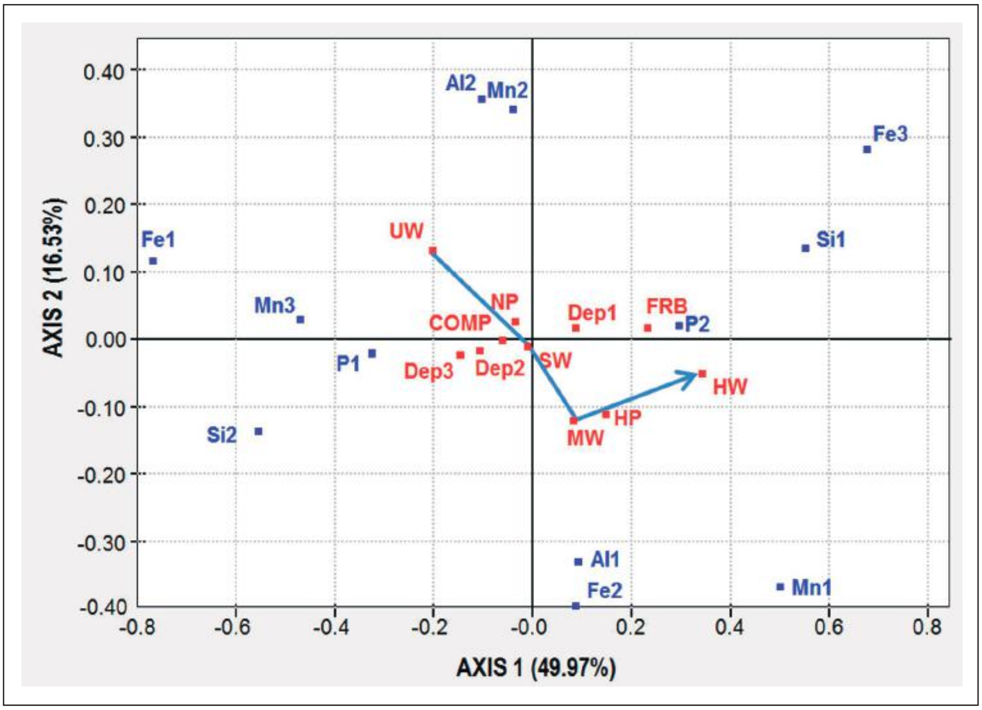

Figure 8 Plot of active (blue) and supplementary (red) variables onto factorial plane A1-A2. The blue arrow shows the weathering path through the graphic display.

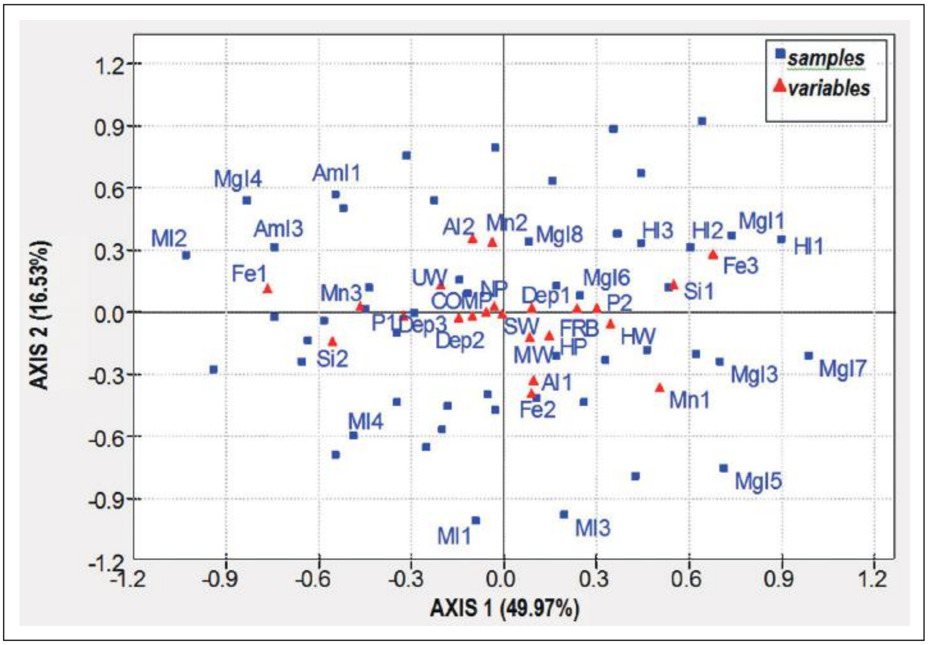

Figure 9 Projection of all variables and samples onto A1-A2 factorial plane. Some petrographical samples occupy the same position in the plane: AmI1=AmI2; MgI1=MgI2.

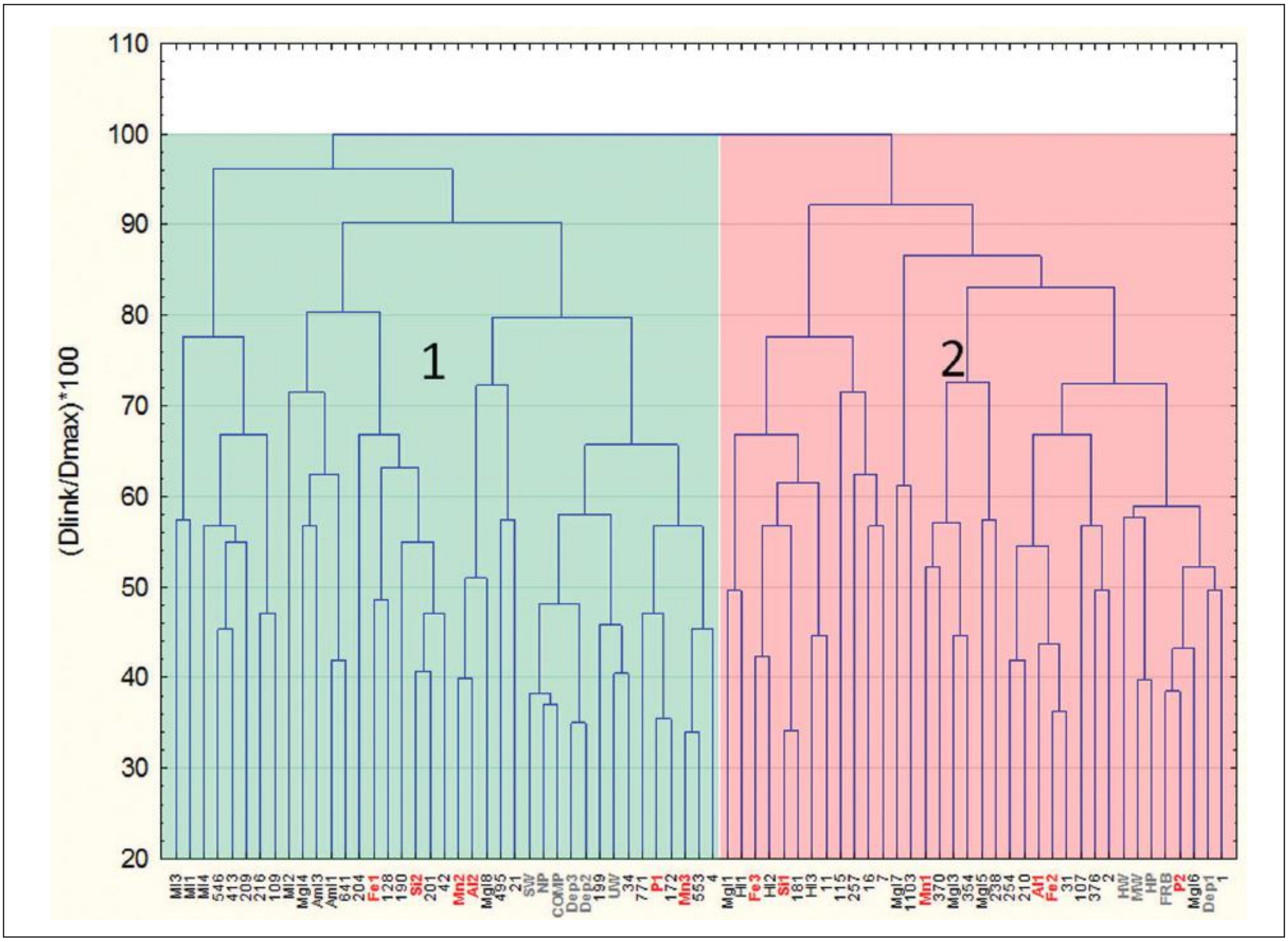

Figure 10 Dendrogram of active and supplementary variables (colored text) jointly represented with supervising BIF samples. The numbers represent samples codes according to the primary geological database.

6 Discussion

Correspondence Analysis (CA) provided a factorial scenario with the geochemical (active) and geotechnical (supplementary) variables and samples displayed onto the same space. Examining the eigenvalues (Table 7) one can notice that almost 70% of total inertia was retained by the first two axes (factors).

Petrographic study by Fonteles *et al.* (2018) did not recognize mineralogical alteration products like goethite or any aluminous mineral occurring extensively and massively throughout the drilling core samples. Silica-richer BIF ores tend to resist more than the oxide-richer ones at the research site. Aluminum oxide grades lowering along the Axis 2 (Figure 8) shows a decrease of Al-Fe-Mg hydrated-silicates (amphiboles) modal content in BIF rocks (See Table 6 for reference).

The two major clusters unfold the inter-related active and supplementary variables and petrographic samples. Cluster 1 is characterized by the Fe-poorer/High-Al BIF ores describing a peculiar association of magnetitic itabirites martitic, itabirites to amphibolitic itabirites. These BIF materials are tended to be positioned deeper than 70 meters and they are usually slightly weathered or unweathered. Cluster 2 groups Fe-richer/Low-Al BIF ores composed of martitic, magnetitic and hematitic itabirites which are described as moderately to highly weathered porous friable ore materials. Despite the lithological banding feature, the BIF's in Cluster 1 behaves like compact and non-porous itabirites.

As already shown, Cluster 1 encompasses all amphibolitic itabirites with higher percentages of Al-amphiboles (Fe-gedrite and hornblende) and, some samples of magnetitic and martitic itabirites with Fe-poorer content (see Table 6 for reference). These BIF types are related to deeper levels (> 70m) in the mining site (Figure 11).

The achieved results indicate the most incisive weathering processes are due to physical disintegration of the primary BIF rocks. The itabirites of Bonito Mine seem to be an exception to some well-studied BIF deposits in the world (Aires-Barros, 1963; Dorr II & Barbosa, 1963; Bronner & Chauvel, 1979; Castro, 1994; Veríssimo, 1999; Morris & Kneeshaw, 1999); where assorted conditioning weathering processes broadly induced the formation of extensive deposits with well-formed soil profiles that often reach more than ten meters deep. Taking this into consideration, it remained unclear how intense

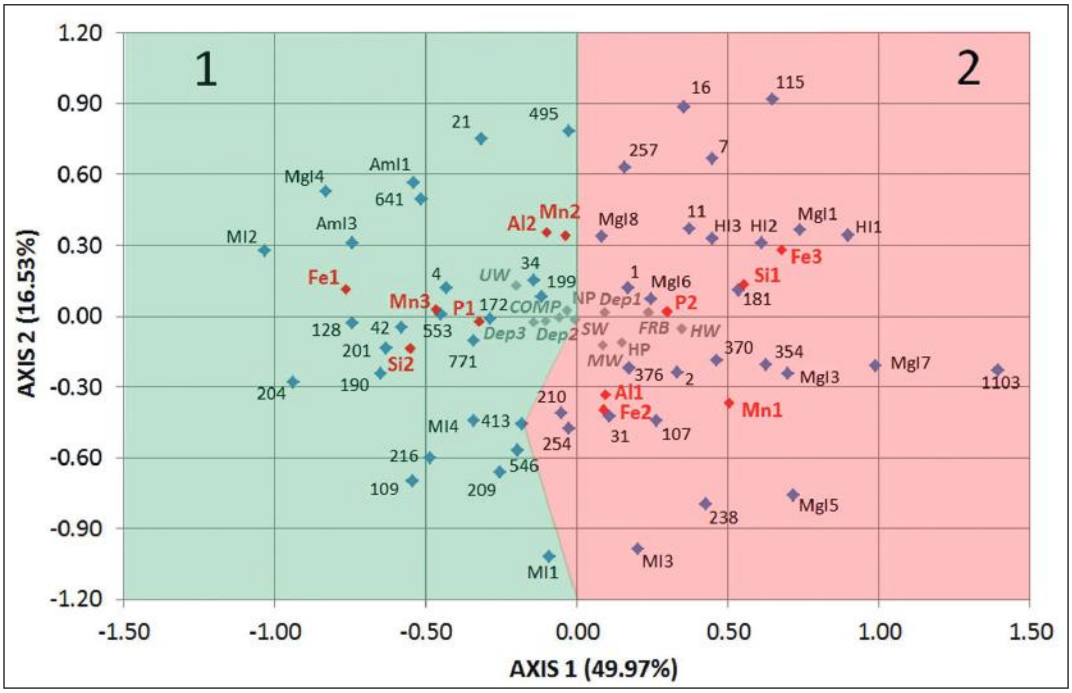

Figure 11 Factorial dual-display of variables samples regarding their positions on the dendrogram model. The numbers represent samples' codes according to the primary geological database.

chemical weathering has contributed to the balance between land forming and soil covering. Field work, however, has shown an absence of extensive and well-developed soil profiles topping at the studied BIFs.

7 Conclusions

This research stems from the combination of geochemical quantitative data and qualitative geotechnical data. Multivariate modeling disclosed important information regarding the differentiation of BIF rocks due to their geological characteristics.

In order to manage such a large database, multivariate modeling tools were applied as the obvious solution to summarize the whole bunch of diversified data. CA procedures integrated quantitative hard data (geochemical) and qualitative soft data (geotechnical).

The methodological strategy linking CA to clustering techniques was accomplished. Although the main structure was graphically and clearly understood some issues remained hazy, such as a border-like division for an intended classification of samples-variables interaction. In this particular case, petrographic samples were used as a proxy to a supervised classification.

Similarly to a try-and-error procedure, several clustering techniques were applied and the results have shown that Complete Linkage algorithm has delivered the most adequate model. Minkowski's Power metric was able to improve the interpretation of CA results taking into account that factorial scores are outcomes from an orthogonal transformation (Figure 10).

From the ore geology point of view, mining efforts can be orientated to BIF types within the Cluster 2 which gathers the Fe-richer itabirites classified as moderately to highly weathered friable porous materials. Conversely, BIF rocks assembled by Cluster 1 are less weathered and more compact non-porous materials, mostly positioned at deeper levels which may implicate higher exploitation costs. Additional considerations must follow a broader analysis that would be provided by geostatistical and/or geological modeling of the mining site.

According to the proposed methodological strategy, an overload of information on dendrogram compressed structure was avoided. The limits built on Figure 11 rely on a broad principle to interpret the factorial plane where closer samples and variables are positively associated, and otherwise, they are not or they are negatively associated. The supervised classification provided by the joint interpretation is the base of the model. Therefore, we think this approach is suitable to any situation and despite of the geological setting, it can deal with a wide range of miscellaneous geological issues.

Finally, one can consider that some mining and mineral processing issues of Bonito mine were not completely addressed. Since some groups of Fe-richer itabirites were gathered in a major multivariate structure, namely Cluster 2, a detailed emphasis can be drawn on these types. Cluster 2 is electable to be treated is a subset in terms of more specific mining operational constraints such as depth intervals, BIF typology, geochemical grades and geomechanical characterization. Further analysis could call for additional geological and mining variables to be introduced into a new round of multivariate modeling aiming to improve the decision making.

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