Geophysical well logging applied to an iron cave investigation, Carajás-PA

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Abstract

Caves are an ordinary landform in karst reliefs, commonly attributed to dissolution processes in carbonatic rocks. Still, there are sites (Carajás – Pará State and Quadrilátero Ferrifero – Minas Gerais State, for example) with caves developed by dissolution of ferruginous rocks. Usually these caves have small horizontal projection, with asymmetric or straight projection and narrow entrances. Legally in Brazil, caves are under government responsibility and protected by law. In order to obtain environmental license in sites with or without such landforms, the applicant must perform technical-scientific investigation in the area. Carajás district is well known for its high-grade iron deposits and mining complexes. In Carajás most important iron-bearing lithotypes are the *ferruginous lateritic crust (“canga”)* and the *banded iron formation*. Often this iron enriched bodies are located in caves sites. This scenario justifies the application of geophysical methods for caves investigation, applied to the structure and its boundaries. Several geophysical methods were combined, as suggested in literature. This paper is focused on presenting well logging and drilling results. The current methodology was first tested to N4E-0026 cave, N4EN mine located in Carajás, Pará State, Brazil.

Introduction

In the late 60´s, high-grade iron deposits were discovered in Serra dos Carajás (Tolbert et al 1971). Further exploration revealed the existence of other minerals (Au and Cu, for example), and for this reason the district was called Carajás Mineral Province which hosts several mining operations, owned by VALE.

The iron ore produced in N4EN Mine comes from rocks enriched with hematite known as *hematitite* (*Figure 1A*), who originally were archean age *banded iron formations - Carajás Formation, also known as jaspillites* (DOCEGEO, 1988) (*Figure 1B*). Described as intercalations (millimetre to centimetre thick) of iron oxide bands with jasper. Archean intrusive mafic bodies can also be found in association with hematitites and jaspillites.

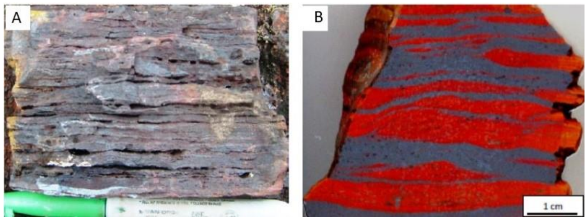

Figure1 – A: hematitie sample, from Carajás district; B: jaspillite sample with preserved bands, from Carajás district. Adapted from Pereira, 2009.

Natural caves in Carajás region, including N4E-0026 cave studied in this paper, are hosted in ferruginous lateritic crust (so called “canga”) associated with enriched banded iron formation, usually at low depths (around 20m) (Gonçalves et al. 2016 ab). This canga (*Figures 2A and 2B*) is formed by the interaction between *jaspillite* and weathering processes, plus local climate conditions. It is composed by weathered blocks of jaspillite, hematitite and other debris, with hydrated iron oxide cement. This cementation turns the canga into a rock with high mechanic resistance. It is part of the caves, as a mechanism for supporting its roof. Canga is also found in the Carajás typical dissected plateaus relief.

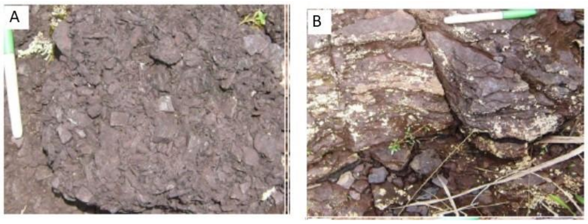

Figure 2- Canga varieties in Carajas. A: detrital canga; B: structured canga. Adapted from Pereira, 2009.

These features represent sites who may become unstable during mining operations. The aim of this pioneering investigation is to demonstrate that geophysical logging in drilling holes can be useful in complementing the litho-structural mapping of iron caves surroundings, even better, when combined with other geophysical electrical and electromagnetic methods applied over the caves as in recent studies by Gama et. al. (2018) and Prosdocimi et. al. (2018). In this paper, the objective is to interpret geophysical strip logs within the surroundings of an iron cave

Method

The interpretation in this paper used geophysical well logging data, presented as strip logs combined with drill core rock descriptions. The drilling campaign consisted of a total of 8 drill holes and well logging, disposed in a linear array. Three of them were located near the N4E-0026 cave and an electroresistivity section (*Figure 3*), therefore these three boreholes were chosen for interpretation.

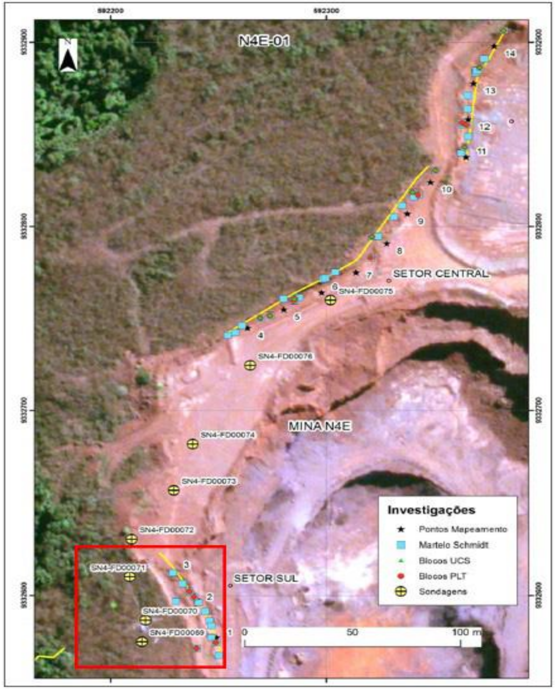

Figure 3 – Study area. Yellow points represent wells location. The three selected ones are inside the red square.

The logging survey contemplated three profiles: caliper, natural gamma-ray and density log. The natural gamma ray profilling is applied to measure natural radioactivity in the borehole environment. In this type of survey there is no need to artificially stimulate the target.

The density logging requires the target to be stimulated by a radioactive source of Ce^{137}. When the target is exposed to *gamma radiation*, density can be calculated based on the quantity of radiation that returns to the detectors in the logging tool. The density logging tool is equipped with a pair of detectors (far detector and near detector) separated from the source by different distances. Both detectors register the response radiation and density is calculated through a correction factor.

The caliper log is used to monitor the diameter of the borehole. The tool is composed by a pivot, which is in contact with the wall inside the borehole. Any changes in the pivot´s length means alterations in the hole diameter. Data were processed and displayed using the software Oasis Montaj v 9.4.4, by Geosoft.

Results

The interpretation of the well log data was based on curve analysis and drill hole description data. In addition, two other studies were important to complement interpretation: a geological-geotechnical mapping (CARSTE, 2017) in the N4E-0026 cave and surroundings and the conclusions of a study on electroresistivity data of rocks near N4E-0026 (Barbosa, 2018)

Natural Gamma-ray

Considering this log in all three wells, three intervals were recognized (*Figure 4*) based on natural radioactivity. Then, it is plausible to suggest the existence of at least three different lithotypes. Initial interval at 069 and 070 holes varies between *5 cps* to *45 cps* and *3 cps* to *45 cps*, respectively. The intermediate interval presented similar values in all holes: *069: 3 cps to 40 cps*; *070: 5 cps to 39 cps*; *071: 7 cps to 45 cps*. The last interval in holes 069 and 070 is the same, from *0 cps* to *20 cps*. Analysing the three holes at the same time, it is possible to observe that natural radioactivity tends to decrease from the initial interval to the final interval.

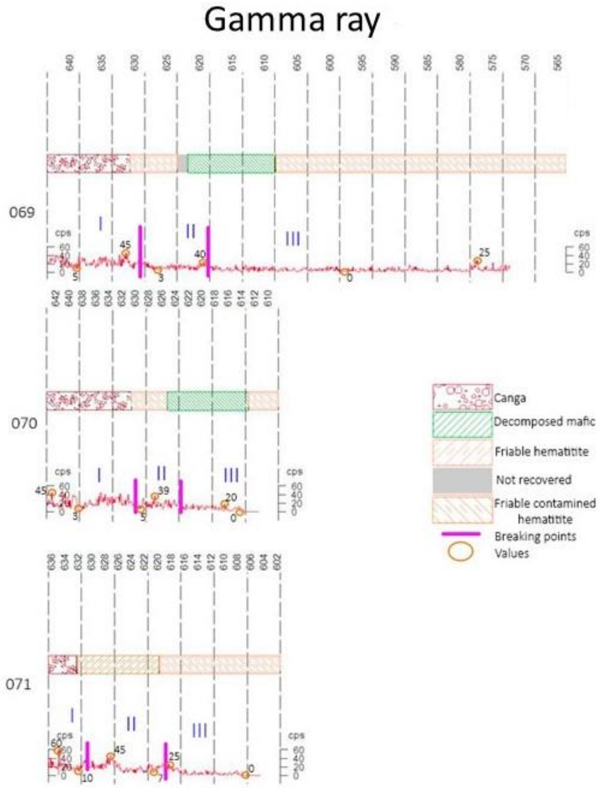

Figure 4 – Gamma ray log in the three selected holes. Three intervals were identified in each hole.

Density

In the 070 and 071 wells, 3 intervals were identified, while 071 well presents 4 intervals. Just as the gamma-ray log, three lithologies were observed. However, only the 071 well has friable contaminated hematitite. The final interval in 070 and 071 wells presents close intervals and share the same minimum value: $2{,}1\ g/cm^3$ to $3{,}7\ g/cm^3$ to $2{,}1\ g/cm^3$ to $3{,}4\ g/cm^3$, respectively. Generally, all the intervals interpreted in each well presented very close values. This trend can be observed in Table 1 with values of average density typical of hematitites. Density log results variations are small enough to show how difficult is to separate lithologies using only this property. So, it is needed to combine gamma ray and density logs to come to further conclusions about lithologies.

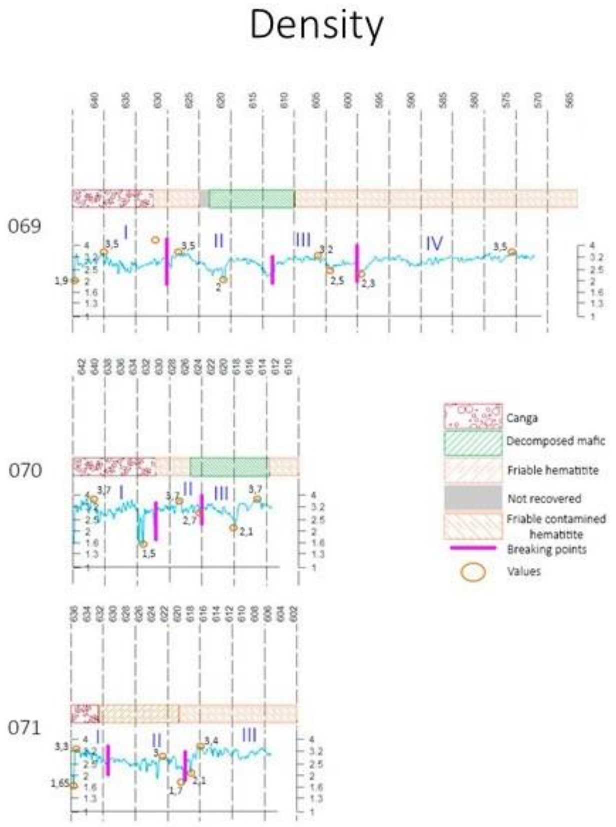

Figure 5 – Density log in the three selected holes. 069 has four intervals, while 070 and 071 has three intervals.

Hematitite average density (g/cm^3)	
069 (**interval** II)	2,8
069 (**interval** IV)	2,9
070 (**interval** II)	3,2
070 (**interval** III)	3,4
071 (**interval** II)	2,35
071 (**interval** III)	2,9

Table 1 – Estimate average density for hematitites in each hole and break.

Caliper

In the 070 well, variation is tenuous (<0,5 mm). So, identifying intervals and contrasts, such as in the previous results, is hard. On the other hand, the wells 069 and 071 presented two intervals (*Figure 6*). The first interval has diameter equal to 80 mm and variation lower than 0,5 mm, for both wells. Final interval diameter is 79,5 mm. In all three wells, despite subtle variations, the diameter remains stable.

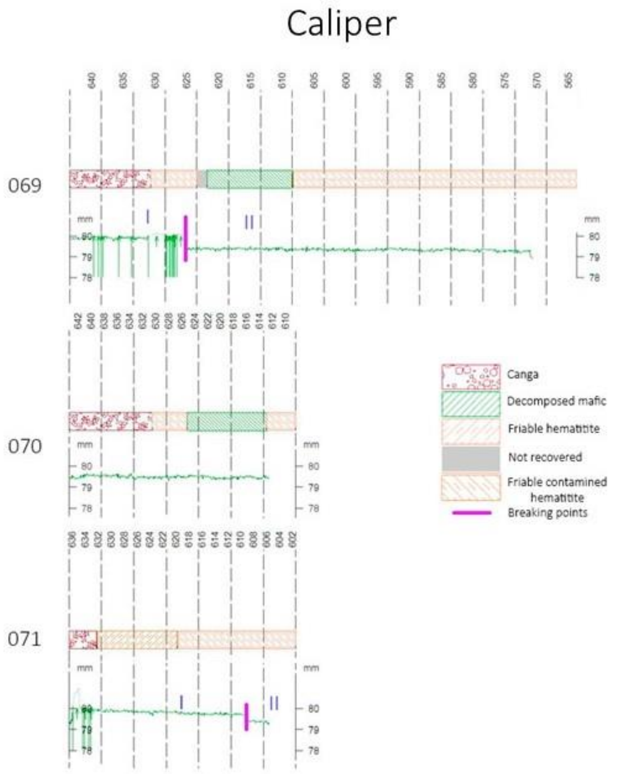

Figure 6 – Caliper log in the three selected wells. 069 and 071 has two intervals.

Discussion

In all 3 holes, the maximum values for the natural gamma-ray curve were in the initial interval (see figure 4). According to the drill core geological description, these intervals are represented by lateritic crust. The canga is described as hydrated, with clay minerals and hematitite debris. On the other hand, the lower values for the natural gamma-ray curve were associated with hematitite (see drill core graphic representation, figure 4). The trend in the natural gamma-ray curve to decrease is corroborated by the lithological changes observed. That is, the maximum values are attributed to canga due to the abundance of clay minerals, and the lower values correspond to decomposed mafic or hematitite, due to their mineral composition.

For the density profile, the maximum values are attributed to intervals whose rocks are ferruginous (see drill core graphical representation, figure 5). It is important to notice that the initial interval also has low values, for both holes 069 and 070. Drill core data show that this interval is represented by canga, described as: highly weathered and disaggregated (069); totally weathered and highly fractured (070). In both cases, canga has dissolution cavities (from millimetres to centimetres). The presence of these features implies in increasing canga´s porosity and decreasing its density. Also, the porosity increasing correlates with sudden decreases of density value. Therefore, the combination of these characteristics suggests that canga (in both holes 069 and 070) has low mechanic resistance and potentially may have structural instability.

Generally, the canga and hematitite present the highest density values. The hematiite´s density is more uniform, and decomposed mafic rocks commonly present the lowest density values. According to the drill core description, the decomposed mafic rocks may have some intercalations of hematitite, so it is expected to find local points with high density, within the decomposed mafic intervals. Besides, in holes 069 and 070, the decomposed mafic rock is described as: highly weathered and fragmented; and completely weathered, respectively. In spite of the absence of dissolution cavities, the decomposed mafic rock is disaggregated, indicating that it may potentially have structural instability, just as the canga.

Besides the combination of different profiling methods, the drill core graphic representation may also accuse the presence of dissolution cavities. This hypothesis is based on hole 069 drill core graphic representation. In the grey interval (*not recovered* – see figure 4), there is a sudden break in the density value. Perhaps this interval consists of a cavity in the rock.

Geophysical well logging succeeded in indicating lithologies who may become structurally unstable and reveal details on the physical properties between the land surface and the cave roof, filling gaps of information that may appear during geological mapping or other geophysical techniques of investigation, for example.

Conclusions

The pioneering geophysical well logging in the cave surrounds showed the possibility to identify intervals, (from mm to cm) associated with lithotypes changes, surrounding iron caves. This technique can indirectly, along with other geophysical methods and direct geostructural mapping, elucidate lithostructural aspects that may help in the interpretation of caves structural stability.

It was feasible to calculate average densities for the ferruginous lithotypes that can be associated with porosity and resistance features, also helping cave structural stability studies.

Small variation in diameter values, performed by the caliper tool were enough to confirm the quality of the drilling campaign.

Electric and electromagnetic methods are the most recommended techniques in geophysics applied to caves investigation, according to Chalikakis et al 2011 and Putiska et al 2014. Possibly well logging is not mentioned because case studies presented by previous authors were on karst landforms in carbonate rocks. However, this study demonstrates that well logging can be a useful tool in order to complement geophysical methods applied to iron cave investigation.

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References

BARBOSA, M. R. Geofísica Espelológica – Metodologia para aplicação de eletrorresistividade na investigação de instabilidade litorestrutural de teto em cavidades ferríferas. Cavidade N4E-0026, mina N4E, Carajás, Pa, Brasil. Universidade Federal do Rio de Janeiro, 2018. 92p. Relatório final de pesquisa de pós-doutorado.

CARSTE. Definição dos parâmertros geotécnicos/geomecânicos de perfis de intemperismo em Serra Norte, Carajás. Relatório Parcial Consolidado de Campo 1. 2017. 72p.

CHALIKAKIS, Konstantinos et al. Contribution of geophysical methods to karst-system exploration: an overview. **Hydrogeology Journal**, v. 19, n. 6, p. 1169, 2011.

DOCEGEO, 1988, Revisão litoestratigráfica da Província Mineral de Carajás – Litoestratigrafia e principais depósitos minerais. XXXV Congresso Brasileiro de Geologia, Belém, SBG, Proceedings, 11-54.

DUTRA, G. M. Síntese dos processos de gênese de cavidades em litologias de ferro. In: **Anais do 32º Congresso Brasileiro de Espeleologia. Barreiras-BA**. 2013. p. 415-426.

ELLIS, D.; SINGER, J. M. Well logging for earth scientists. Dordrecht: Springer, 2007.

GAMA, M.F.P.; BARBOSA, M.R.; BRANDI, I.V.; Braga, M.A.S. 2018. Caminhamento elétrico aplicado ao mapeamento de cavidades naturais em minério de ferro, Carajás (PA). *In:* 49º Congresso Brasileiro de Geologia, Rio de Janeiro.

GONÇALVES, D.F.; DE PAULA, R.G.; BARBOSA, M.R.; TELES, C.; MAURITY, C.W.; MACAMBIRA, J.B. 2016.Lateritic terrains and the evolution of pseudokarstic features - case study in the iron ore mine N4E, Carajás region – Pará, Brazil. 24th World Mining Congress Proceedings. Rio de Janeiro, p. 227-236

GONÇALVES, D.F., DE PAULA, R.G., BARBOSA, M.R., TELES, MAURITY, C.W., J.B., MACAMBIRA, J.B. 2016. Perfis lateríticos e o desenvolvimento de cavidades naturais subterrâneas na mina N4E - Carajás, sudeste do estado do Pará. Anais do 48° Congresso Brasileiro de Geologia.: Porto Alegre [s.n.]

GRIMES, K. G.; SPATE, Andy. Laterite karst. In: unpublished poster displayed at the 7th international conference on geomorphology (ANZIAG), Melbourne. 2009.

PEREIRA, R. M. P. Geologia da região Sul da Serra Norte e características do minério de ferro do Depósito N8, Província Mineral Carajás. 2009.

PROSDOCIMI, G.**;** BARBOSA, M.R.; BRANDI, I.V.; BRAGA, M.A.S. 2018. Estudo de cavidade natural em formação ferrífera por meio da integração de métodos geofísicos rasos, Complexo Carajás, Brasil. *In:* 49º Congresso Brasileiro de Geologia, Rio de Janeiro.

PUTIŠKA, R., KUSNIRAK, D., DOSTAL, I., LACNY, A., MOJZES, A., HOK, J., PASTEKA, R., KRAJNAK, M., BOSANSKY, M. Integrated geophysical and geological investigations of karst structures in Komberek, Slovakia. Journal of Cave & Karst Studies, v. 76, n. 3. p. 155–163. 2014

TELFORD, W. M. et al. **Applied geophysics**. Cambridge university press. 770 pp. 1990.

TOLBERT, G. E. et al. The recently discovered Serra dos Carajás iron deposits, northern Brazil. **Economic Geology**, v. 66, n. 7, p. 985-994, 1971.