Geofísica Internacional (2024) **63-3**: 1033 - 1043

Groundwater identification using geophysical tools and its implications for the stability of slopes in an open pit mine

Beatriz Guzzo Duz[1], César Augusto Moreira[1], Marcos Eduardo Hartwig[2], Felipe Queiroz Miano[1] and Ana Flávia Araújo[1]

Abstract

The open pit mining development begins with the opening of pits with the rock mass excavation and formation of slopes and berms for ore exploration. Knowledge about the geological conditions represents an important step in this process, since rock masses generally have heterogeneous characteristics and the presence of discontinuities can become an aggravating factor in the safety of operations. The characterization and classification of these discontinuities, as well as the identification of the groundwater in the rock mass, has a great importance to ensure the safety of operations during the mine's production process, in addition to ensure the effectiveness of its decommissioning process. The use of DC resistivity geophysical method has been increasing to characterization and identification lithological types and presence of water, since it is a non-invasive research tool with fast ability to obtain data. DC resistivity together with visual investigation methods, such as obtaining the discontinuities orientation and their alteration characteristics, provides important information for the characterization of the rock mass. Given this importance, the present work aimed to use DC resistivity to identify the presence of water and its correlation with lithology and rock mass structure in order to identify how these variables influence the occurrence of ruptures. To this end, two-dimensional resistivity sections were designed and related to visual inspection data and kinematic analyzes obtained from structural data of the rock mass. The integration of these results indicated that the ruptures present in the investigated mine slopes are related to zones whose predominant lithology is volcanic breccia with the presence of water in the subsurface. These ruptures compromise the stability of the slopes and consequently make the decommissioning mine process difficult.

Key words: geophysics, DC resistivity, aquifer, structural analyses, ruptures.

Resumen

El desarrollo de la minería a cielo abierto comienza con la apertura de tajos con la excavación del macizo rocoso y la formación de taludes y bermas para la exploración de mineral. El conocimiento de las condiciones geológicas representa un paso importante en este proceso, ya que los macizos rocosos generalmente tienen características heterogéneas y la presencia de discontinuidades puede convertirse en un agravante en la seguridad de las operaciones. La caracterización y clasificación de estas discontinuidades, así como la identificación del agua subterránea en el macizo rocoso, tiene gran importancia para garantizar la seguridad de las operaciones durante el proceso productivo de la mina, además de garantizar la efectividad de su proceso de desmantelamiento. El uso del método geofísico de resistividad eléctrica ha ido en aumento para la caracterización e identificación de tipos litológicos y presencia de agua, ya que es una herramienta de investigación no invasiva y con rápida capacidad de obtención de datos. La resistividad eléctrica junto con métodos de investigación visual, como la obtención de la orientación de las discontinuidades y sus características de alteración, proporciona información importante para la caracterización del macizo rocoso. Dada esta importancia, el presente trabajo tuvo como objetivo utilizar la resistividad eléctrica para identificar la presencia de agua y su correlación con la litología y la estructura del macizo rocoso con el fin de identificar cómo estas variables influyen en la ocurrencia de rupturas. Para ello, se diseñaron secciones de resistividad bidimensionales y se relacionaron con datos de inspección visual y análisis cinemáticos obtenidos a partir de datos estructurales del macizo rocoso. La integración de estos resultados indicó que las rupturas presentes en los taludes mineros investigados están relacionadas con zonas cuya litología predominante es de brecha volcánica con presencia de agua en el subsuelo. Estas rupturas comprometen la estabilidad de los taludes y en consecuencia dificultan el proceso de desmantelamiento de la mina.

Palabras clave: geofísica, resistividad eléctrica, acuífero, análisis estructural, rupturas.

Received: November 3, 2023; Accepted: May 16, 2024; Published on-line: July 1, 2024.

Editorial responsibility: Dra. Norma Patricia López-Acosta

* Corresponding author: Beatriz Guzzo, b.duz@unesp.br.

[1] São Paulo State University (Universidade Estadual Paulista), Department of Geology, Av. 24A, 1515, CEP: 13506-900, Rio Claro (SP), Brazil.

[2] Department of Geology. Federal University of Espírito Santo. Alto Universitário, Guararema District, no number, Alegre, ES, Brazil.

Beatriz Guzzo Duz, César Augusto Moreira, Marcos Eduardo Hartwig, Felipe Queiroz Miano, Ana Flávia Araújo

https://doi.org/10.22201/igeof.2954436xe.2024.63.3.1755

1. Introduction

The development of an open pit mine involves the excavation of slopes with a certain height and inclination in order to obtain the lowest possible strip ratio, without harming the safety of mining operations (Alegre et al, 2019). During the rock mass excavation occurs a redistribution in the state of stress, as well as the exposure of the rock head to weathering agents, which causes the deterioration of rock mass strength (Liu *et al.* 2022; Marques *et al.* 2010; Read and Stacey 2009).

Rock slopes generally exhibit discontinuity planes such as joins and faults (ISRM 1978). Low strength geological structures with unfavorable spatial orientation are critical for slope stability (Kolapo *et al.* 2022). In addition to the presence and condition of the discontinuities on the rock mass, information regarding the presence of water in the subsurface has major importance to evaluate its influence on the occurrence of ruptures (Menezes *et al.* 2019). The presence of subsurface water is one of the main triggers for the occurrence of slope failures and its accumulation is conditioned by the presence and non-connectivity between fractures and an impermeable layer, with consequent formation of aquifers (Banks *et al.* 2009).

Fractured aquifers are considered complex, due to the condition of water storage and transmission throughout the fractured planes. In many cases, the existence of groundwater in fractured zones is not always evident from the surface (Singhal and Gupta, 2010; Fetter, 2018).

Geophysical methods represent an important tool in the study of fractured rock aquifers, in view of their potential to measure physical parameters that change in the presence of water, wide spatial and in-depth coverage, non-invasive and fast data acquisition (Telford *et al.* 2004; Moreira and Helene, 2022).

Geophysical methods, such as DC (Direct Current) resistivity, have been widely used to map fractured aquifers on rock mass (Porsani *et al.*, 2005; Gomes de Oliveira *et al.* 2014; Hamdan *et al.* 2014; Moreira *et al.* 2016; Pádua and Campos 2020; Whiteley *et al.* 2021; Yan *et al.* 2022). Frequent events of intense precipitation, as recorded in tropical climate countries, can aggravate the risk of rupture from the elevation of pore pressure in the rock mass (Corrêa *et al.* 2021; Sun *et al.* 2021; Wyllie and Mah 2004). The sum of these factors can make the rock mass even more prone to long-term instabilities (Hartwig and Moreira 2021; Perrone *et al.* 2008).

In this way, this study aims to investigate the SE pit slopes of the Osamu Utsumi Mine from the acquisition of DC resistivity data combined with geomechanical survey in order to evaluating the use of this geophysical tool as a preliminary analysis of potentially unstable zones.

2. Study Area

The Osamu Utsumi Mine, owned by Nuclear Industries of Brazil (INB) was built in 1959 and is located in the municipality of Caldas, Minas Gerais Stare, Brazil (Figure 1). Operational activities started in 1981, with the discovery of caldasite deposits and consequently zones with uranium ores, formed by the hydrothermal process.

An estimated reserve of 17,200 tons of uranium was exploited with operations between 1981 and 1995. During that time, around 45 million m³ of waste rock were removed, which 33 million m³ came from stripping and 12 million m³ of rock (Souza *et al.* 2013). The mining complex has been under decommissioning since the end of its activities in 1995, but for the effective closure, it is necessary to ensure the safety and stability of the site. In particular, the stability of the SE mine slopes which have experiences several failures over the years (Gastmaier Marques *et al.* 2022; Moreira *et al.* 2021). One possible explanation for that includes hydrologic events as the region records annual rainfall (1,700 mm/year) (Holmes *et al.* 1992).

3. Materials and Methods

3.1 DC resisitivity

The geophysical method used in this study was the DC resistivity in order to characterize the materials presents in the subsurface of slopes and identify water in fractures, as well as present in the works made by Casagrande *et al.* 2020; Nascimento *et al.* 2022 and Oliveira *et al.* 2010. The electrical resistivity method is based on the physical parameter of electrical resistivity (ρ) which consists of the difficulty to the passage of electric current (Telford *et al.*, 2004). The resistivity values measured in (Ω.m) are intrinsic to each geological material and arbitrarily in this study area, high resistivity values are associated with unaltered rocks (>1000 Ω.m) and are represented by warmer colors (red). Altered or intensely fractured rocks present intermediate values of resistivity (from 100 to 1000 Ω.m) and yellow-orange color. The presence of water is represented by values lower than 100 Ω.m and are associated with cold colors (blue) (Palacky 1987).

The DC resistivity survey, as well as structural geotechnical analysis, were carried out in 3 different sections, inserted in the SE front, with a total length of 100m per line, electrodes spaced every 5m and with Schlumberger array (Figure 2). These three different sectors were chosen in order to cover a large part of the SE front, in addition to presenting different geotechnical behavior among themselves. Data acquisition was performed in January 2022 and the equipment used was the ABEM Terrameter LS.

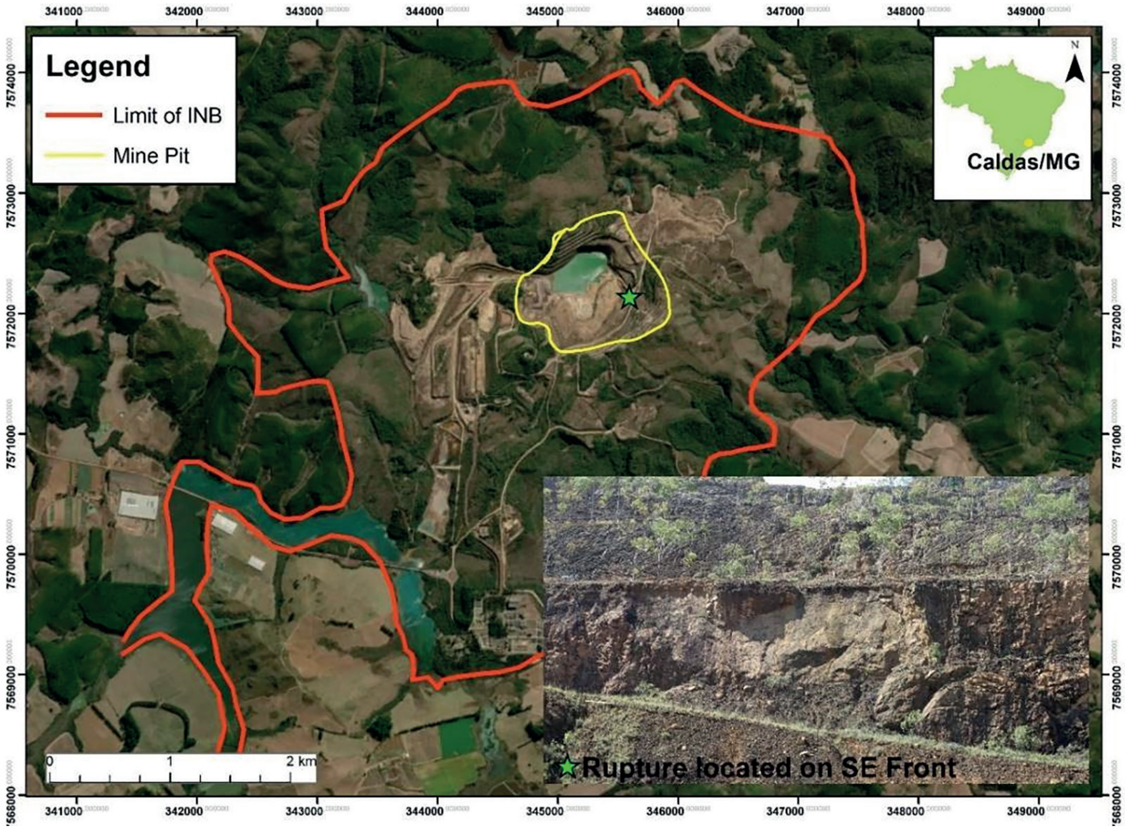

Figure 1. Study area location. The inset shows its position in Brazil.

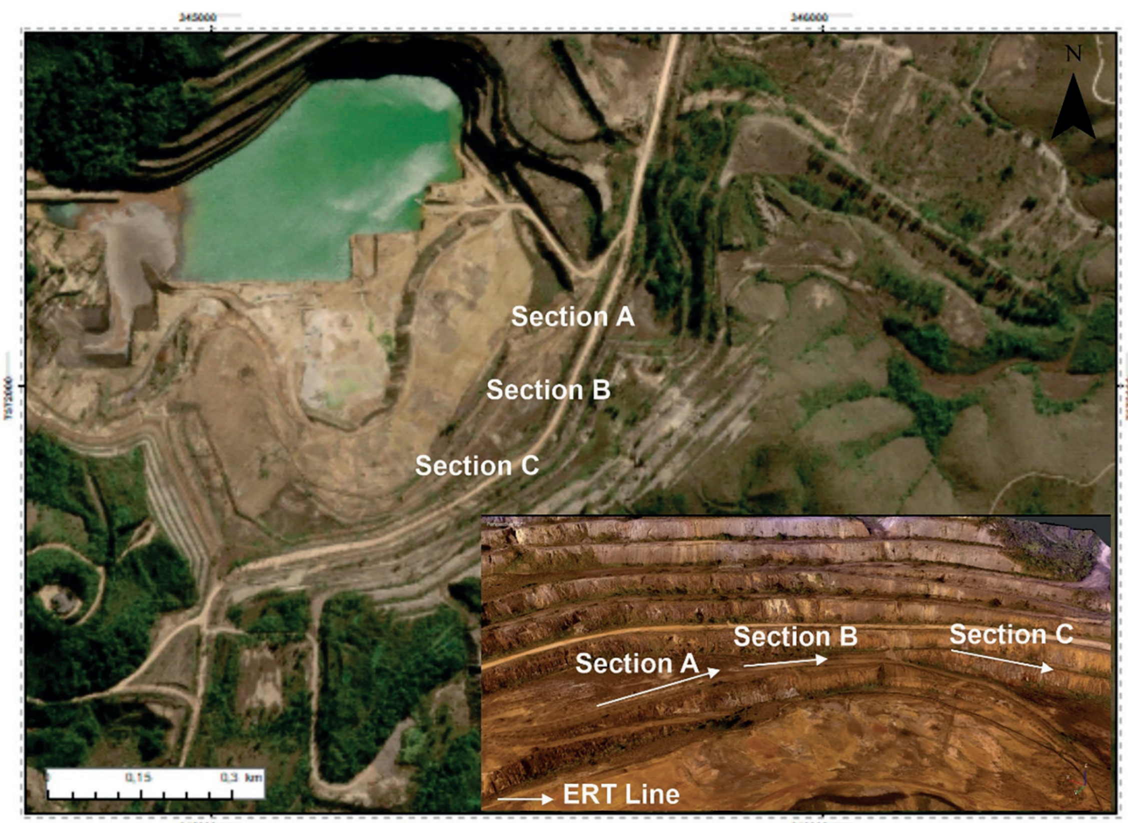

Figure 2. Sections analyzed from SE front.

This equipment has a power of 250W, a maximum current of 2.5 A, a resolution of 1μV and allows automatic data acquisition (ABEM 2012). The configuration parameters for carrying out this study were: current of 500 mA, transmission time of 1 second and reading time after the current cut-off of 0.3 seconds.

Geophysical data were processed in RES2DINV software and presented as a resistivity inversion model with distance × depth sections (Martins *et al.* 2016). This software is used to process large data sets in two dimensions acquired through electrical imaging. The inversion process consists of a series of rectangular blocks, whose layout are related to the distribution of data points in a pseudo-section, that is, the section generated by the theoretical field data. The distribution and size of the blocks are automatically generated by the program according to the distribution of data points. The depth of the bottom row of blocks is set to be approximately equivalent to the investigation depth of points with the greatest spacing between electrodes (Edwards 1977).

3.2 Geomechanical survey

The geomechanical survey comprised lithological description and classification (Jerram and Petford 2012) and joint mapping and characterization. For the rock joint survey the scanline method was used (Priest and Hudson 1981), covering the total length of the geophysical lines previously described (Figure 3). Joints attitudes were recorded with a compass and the dip direction/dip notation has been adopted (Porto *et al.* 2012). Joint properties such as weathering, roughness, strength and water infiltration were evaluated based on Barton 1988 and ISRM (1978). The average angle of friction of joint planes was estimated based on Barton (1988).

Structural data was processed, analyzed and interpreted with Dips software (Rocsience). Kinematic analyzes was performed as described by Kliche (1999) and Wyllie and Mah (2004). Toppling failure mode has not been tested because it is unlikely in the lithotypes mapped in the mine.

4. Results and Discussion

4.1 Section A

The visual analysis of the slope face of section A indicated the presence of the foiaite rock in the first 50 meters analyzed and, in the rest, the presence of the volcanic breccia was observed. Although both lithologies show alteration characteristics, notably observed due to the presence of an oxidation film (Figure 4), the mechanical resistance found for the breccia lithology is less than 50 MPa, corresponding to the resistance of the foiaite.

Figure 3. Scanline method: slope demarcation every 10 meters and investigation of slope conditions and structural measures.

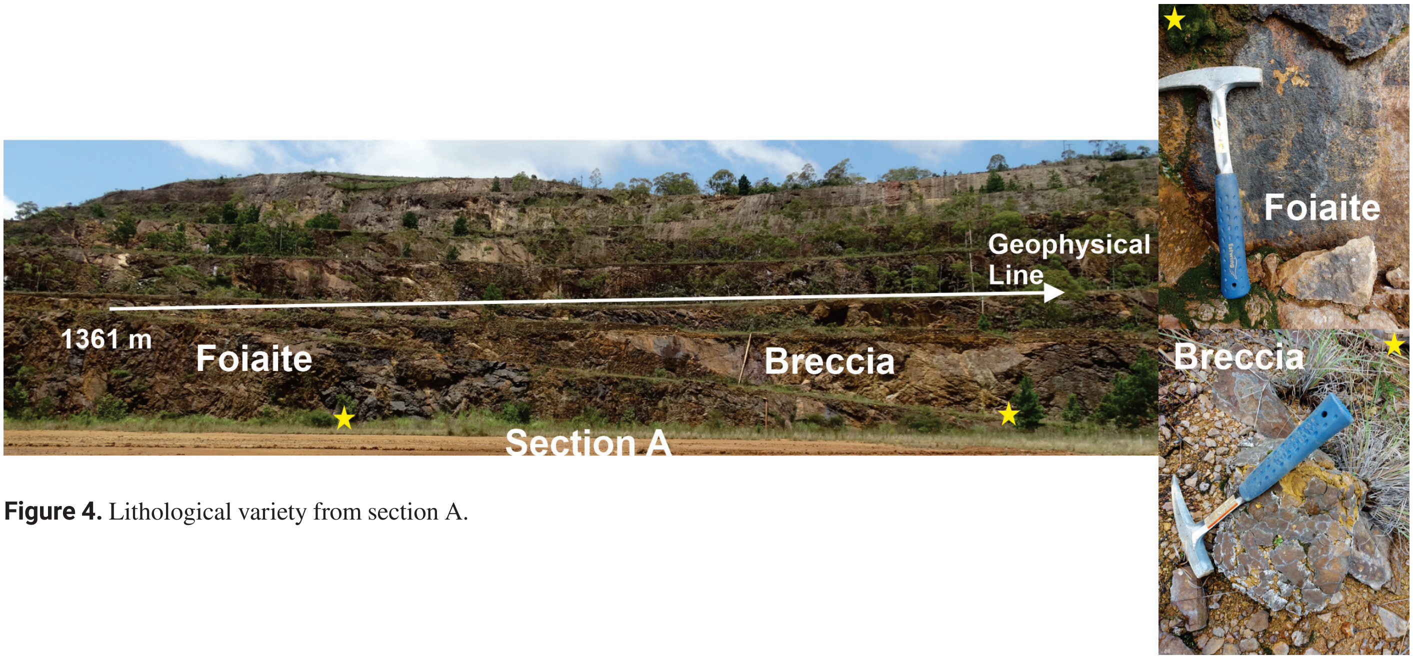

Figure 4. Lithological variety from section A.

The extrusive and hypabyssal varieties of nepheline syenite forms phonolites, tinguaites and foiaites, a textural variety of nepheline syenite with hydrothermal alterations (Fraenkel *et al.* 1985). Volcanic breccias were formed by hydrothermal processes, which caused changes in temperature and pressure. These changes, combined with gaseous emissions and thermal solutions, created breccias with high permeability and porosity, which allowed the rise of mineralized hydrothermal solutions and, consequently, mineralization. The products from the hydrothermal process are fluorite, zirconium, molybdenum and uranium (Ulbrich *et al.* 2000).

A total of 25 rock joints have been recorded for Section A. These are grouped in four joint sets. The average friction angle is close to 44°. Figure 5 shows the kinematic stability analyzes for wedge and planar failure models. Planar failure mode is very likely for Section A and wedge failure mode has a marginal risk. During the field survey only planar failures were observed (Figure 5). Failure surfaces are highly irregular and wavy.

The geophysical results in Section A corroborated with lithological variety highlighted by the difference in resistivity values: foiaite with resistivity values up to 4116 Ω.m and volcanic breccia with resistivity values between 697 and 4116 Ω.m (Figure 6). This decrease in electrical resistivity may be related to the lower mechanical resistance breccia lithology (25 to 50 MPa) linked to its mineralogical composition and porosity that retains the water mainly in the rainy season. When saturated, the resistance of this rock decreases and can cause ruptures. It's possible to observe the water presence near 80 meters, with resistivity values near to 118 Ω.m. The planar rupture in this sector is coincident with breccia lithology and groundwater.

4.2 Section B

The rupture that covers a large part of section B is related with the volcanic breccia lithology (between 20 and 60 meters) (Figure 7a). During the visual inspection of the slope face water surgency was identified at three different locations, in volcanic breccia and in the foiaite, nearest to the end of the investigation geophysical line (Figure 7b). In this sense, it is possible to interpret that the central sector of the SE front of the mine receives a lot of water, which infiltrates and is stored in the porous of breccias and infiltrates and percolates through the fractures of the foiaite. It was also possible to notice the presence of relic structures of mineralizations in the breccias (Figure 7c).

A total of 24 rock joints have been recorded for Section B. The average angle of friction is 48°. Figure 8 shows the kinematic stability analysis for wedge and planar failure models. It can be deduced that Section B has a marginal risk for both failure modes. The field survey revealed a large wedge failure at the center of Section B associated with volcanic breccia (Figure 8).

The geophysical results of electrical resistivity (Figure 9) indicated the presence of groundwater throughout section B evidenced by resistivity values lower than 118 Ω.m and at some points close to 20 Ω.m, which indicate the presence of solutes in water from rock alteration.

4.3 Section C

Section C is made of fresh to slightly weathered tinguaite with strength well above 50 MPa. Drill mark for rock blasting are

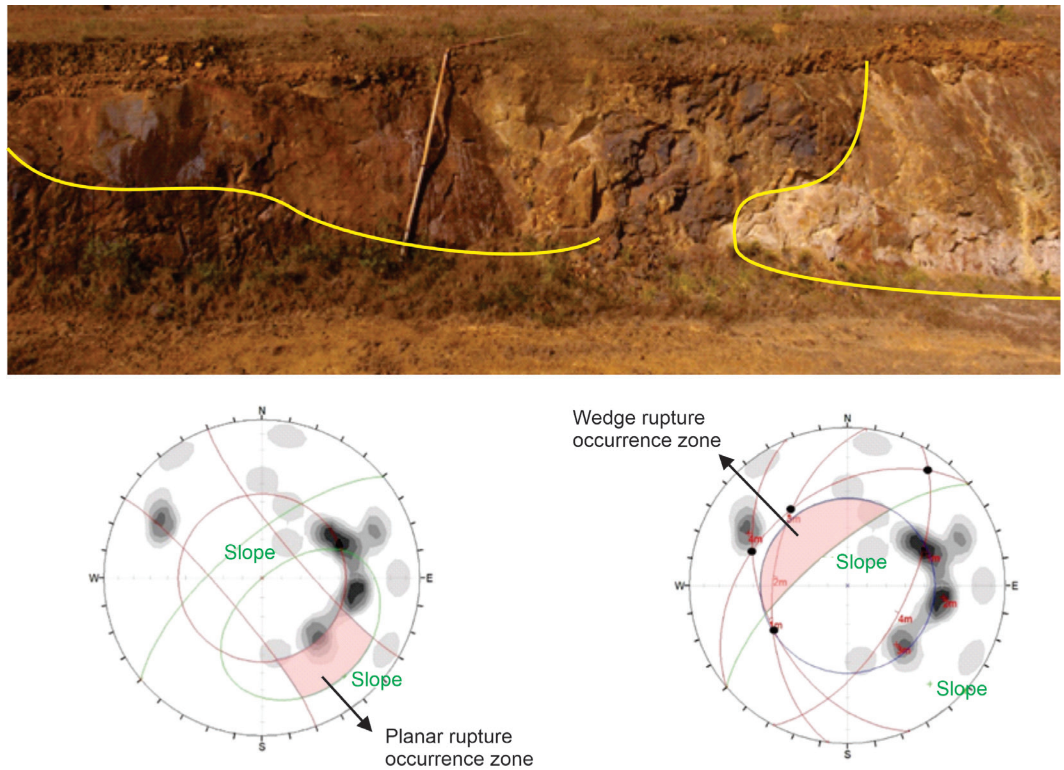

Figure 5. Planar rupture verified on Section A. Stereographic projection for Kinematic Analysis from Section A: planar and wedge. The pale red zones represent the zones of risk for planar and wedge failures.

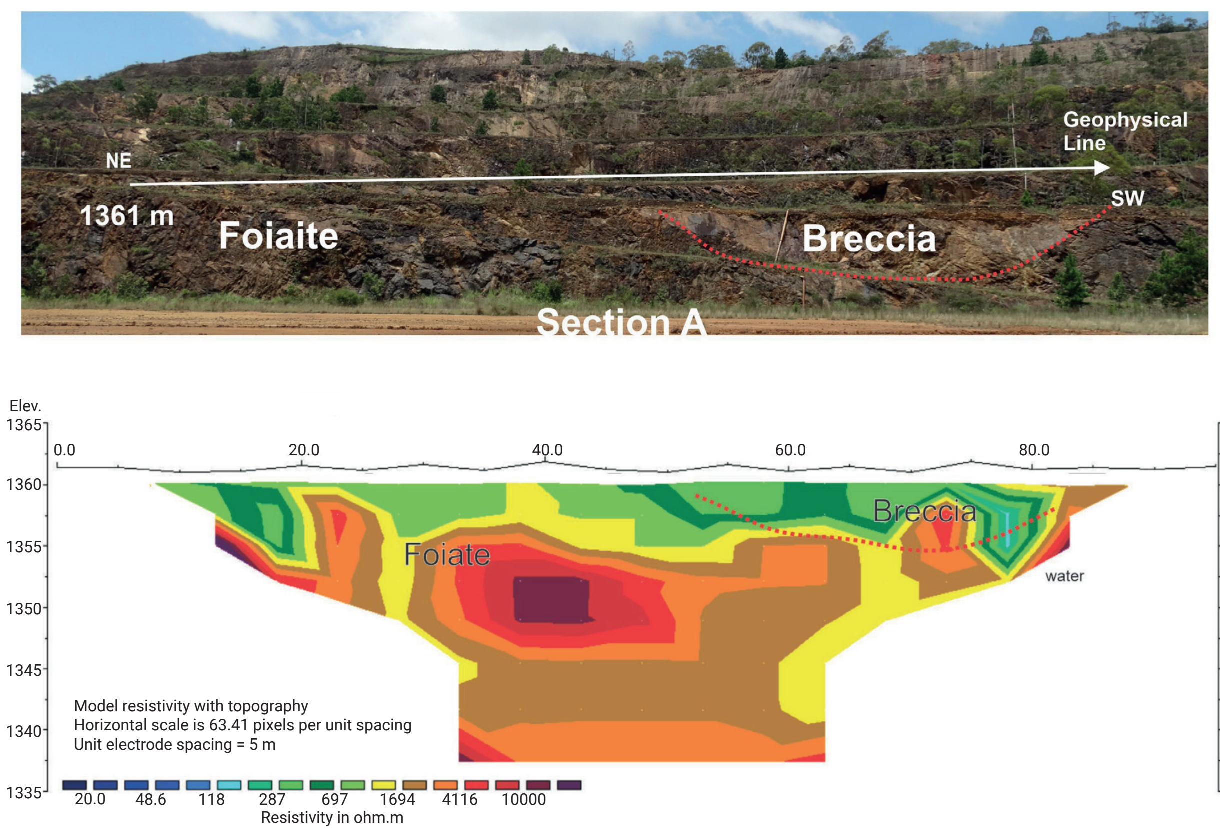

Figure 6. Interpreted geophysical profile of Section A. The red dashed line outlines the plane failure.

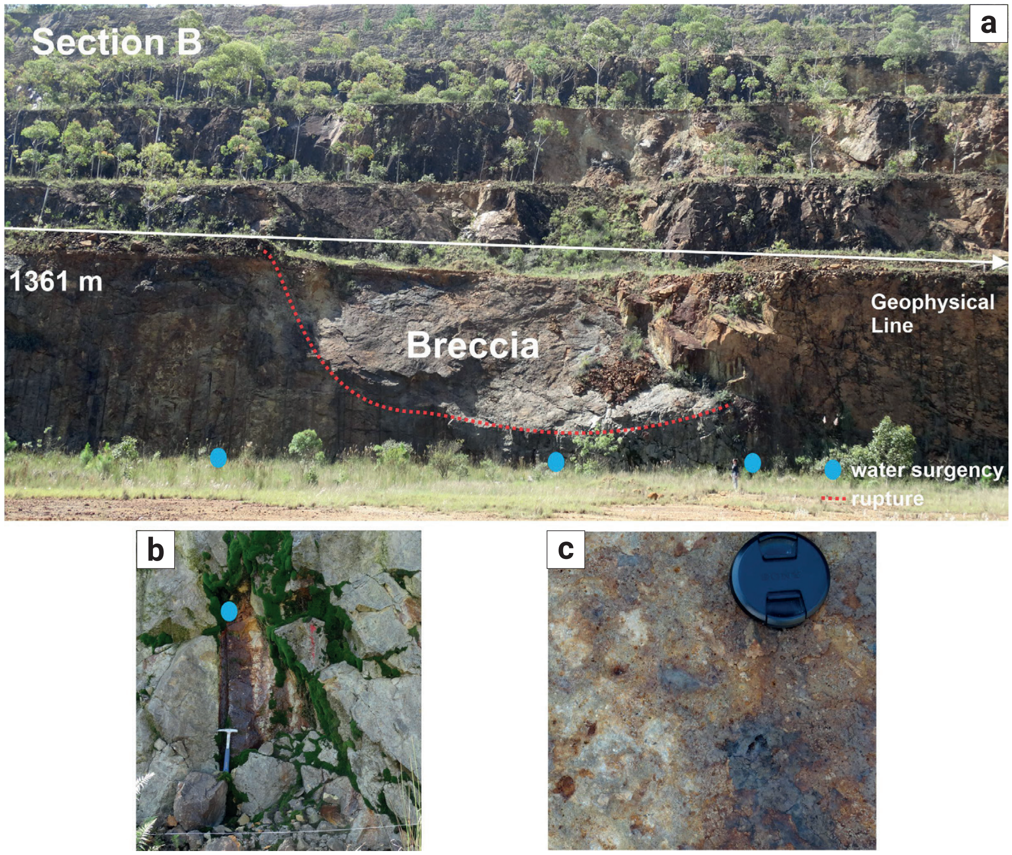

Figure 7. Conditions of the slope face from section B.

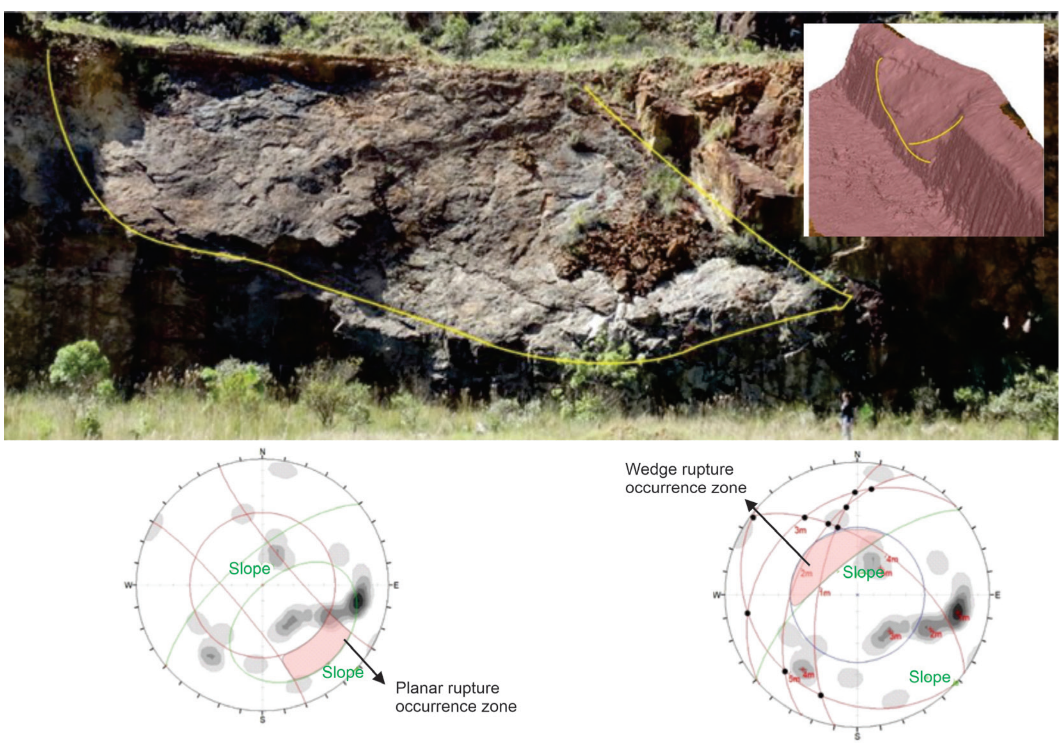

Figure 8. Stereographic projection for kinematic analysis for Section B: planar (left) and wedge (right). The pale red zones represent the zones of risk for planar and wedge failures. Detail of a large wedge failure in Section B. Note the irregular and wavy character of the failure surface.

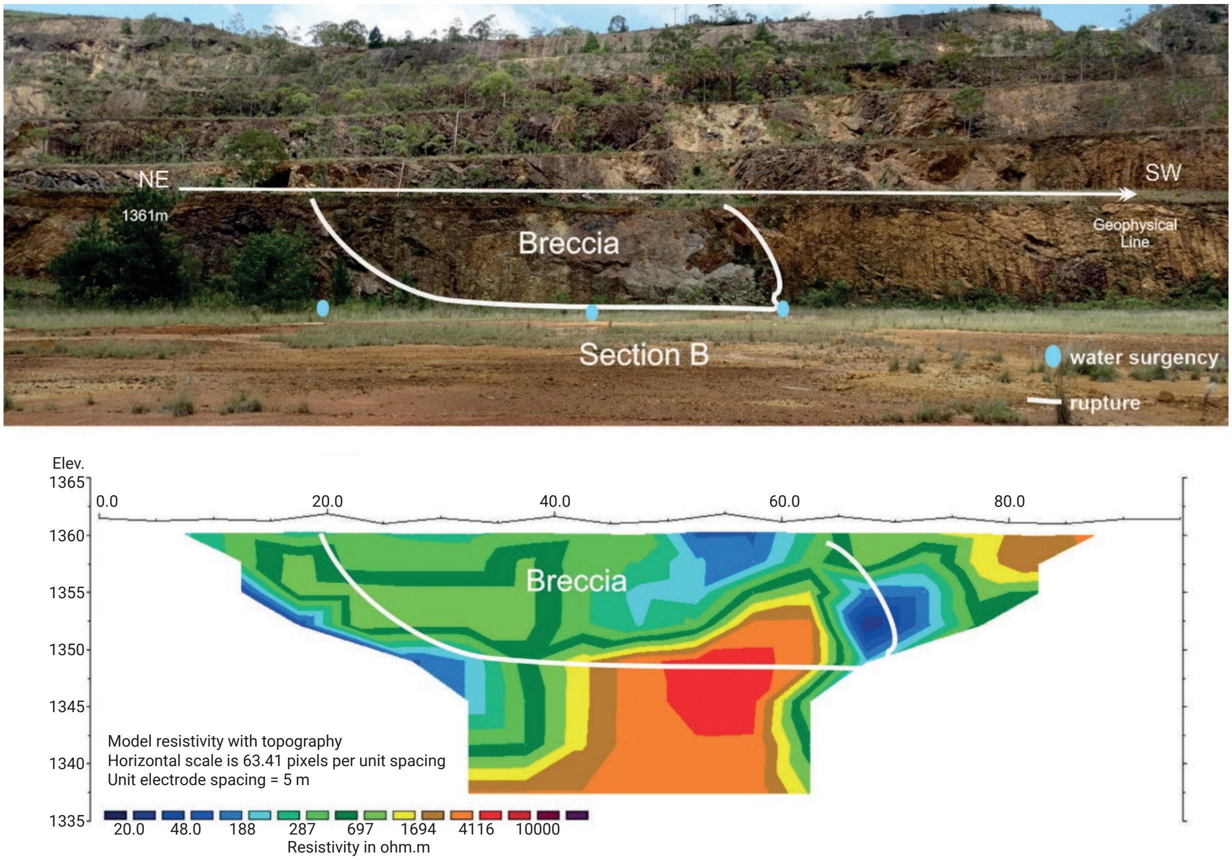

Figure 9. Correlation between geophysical interpretation and analysis from section B.

widespred all over the slope indicating a high rock mass quality. There are no evidences to breccia lithology. The fractures present in the section C belong to the same family and therefore the kinematic analyses show the marginally possibility of occurrence only to planar rupture (Figure 10).

The resistivity results of this section indicated the presence of a fractured rock mass with resistivity values between 287 Ω.m and 1694 Ω.m and the presence of water in areas with resistivities lower than 118 Ω.m (Figure 11). However, the fractures were filled with water, the geomechanical conditions, such as, high mechanic resistance and lower alteration degree help prevent the development of ruptures. Furthermore, the inexistence of oxidation film on the rock mass suggests that the seepage water flows quickly, and not be accumulated in the fractures, reducing the chances of ruptures.

5. Conclusions

The integration between the geophysical and structural - geotechnical data allowed us to conclude that although the presence of water in the subsurface is one of the main triggering agents for the ruptures occurrence, this is potentiated when it is found under more porous, altered and consequently less resistant rocks, such as volcanic breccias.

Zones with the presence of other types of rocks such as foiaite and tinguaite, are less susceptible to the development of ruptures and although they may contain water, its flow is faster and the storage capacity is smaller. The geophysical test of DC resistivity proved to be an assertive tool regarding the identification of different subsurface materials, such as water and different lithologies.

Furthermore, the results also reveal the possibility of using geophysical monitoring in slopes of linear works with high traffic, such as highways and railways, where the accumulation of water in fracture planes combined with vibration during the passage of vehicles, can induce geotechnical instabilities.

Whether in cases of mining operations or transport, early diagnosis of groundwater, with possibility of geotechnical instability events can save lives, damage and significantly reduce the costs involved with removing and unblocking access, or even resurfacing works.

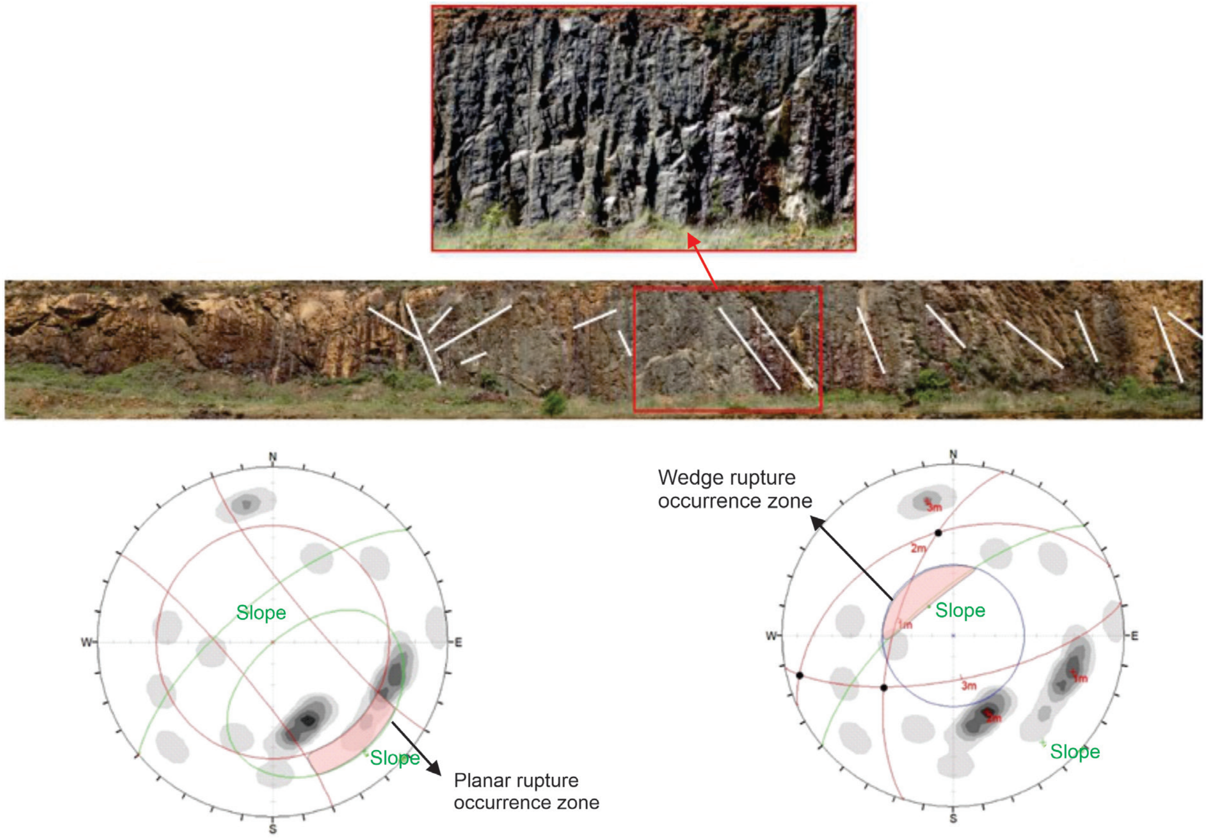

Figure 10. Correlation between visual analysis (tinguaite) and kinematic analysis for planar and wedge ruptures.

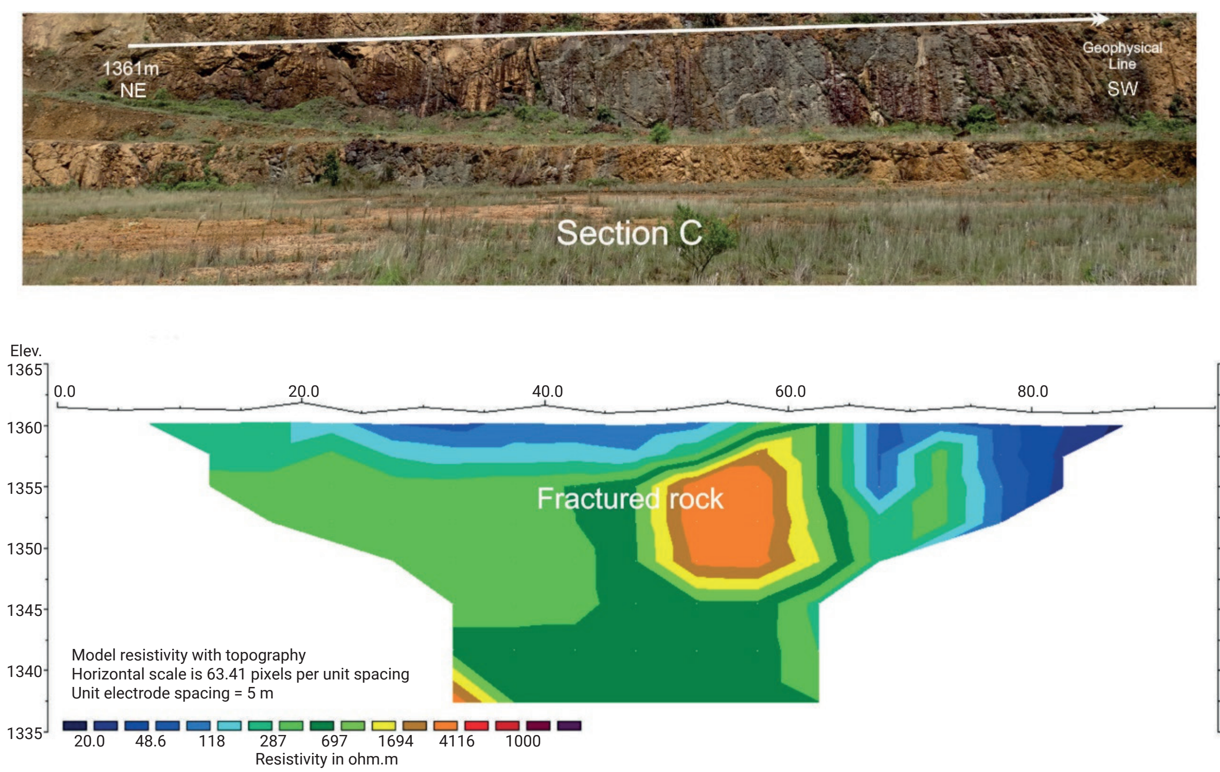

Figure 11. Correlation between geophysical interpretation and analysis from section C.

6. Acknowledgments

The authors are thankful to São Paulo Research Foundation (FAPESP) for the financial support whereby Process Number 20/14647-0 (Regular Project), the Geology Department of UNESP—Rio Claro for the availability of the geophysical equipment and the Brazilian Nuclear Industries (Indústrias Nucleares do Brasil—INB) for providing access to the study area.

7. References

ABEM, Instruments. (2012). Terrameter Lund System-Instruction Manual, Stockholm. 122 pp.

Alegre, D. A. G., Peroni, R. de L., & Aquino, E. da R. (2019). The impact of haulroad geometric parameters on open pit mine strip ratio. *REM-International Engineering Journal*, 72(1), 25–31. doi: https://doi.org/10.1590/0370-44672018720136

Banks, E.W., Simmons, C.T., Love, A.J. (2009). Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). *Hydrogeology Journal*, 17, 1969-1989. doi: https://doi.org/10.1007/s10040-009-0490-7

Barton, N. (1988). *Rock mass classification and tunnel reinforcement using the Q-system*. ASTM International. doi: https://doi.org/10.1520/STP48464S

Casagrande M.F.S, Moreira C.A, Targa D.A. (2020). Study of generation and underground fow of acid mine drainage in waste rock pile in uranium mine using electrical resistivity tomography. *Pure and Applied Geophysics*, 77, 703-721. doi: https://doi.org/10.1007/s00024-019-02351-9

Corrêa, C. V. S., Reis, F. A. G. V., do Carmo Giordano, L., Cabral, V. C., Gramani, M. F., Gabelini, B. M., Duz, G. B. & Veloso, V. Q. (2021). Assessment of the potentiality to the debris-flow occurrence from physiographic and morphometrics parameters: a case study in Santo Antônio Basin (Caraguatatuba, São Paulo State, Brazil). *Anuário do Instituto de Geociências*, 44. doi: https://doi.org/10.11137/1982-3908_2021_44_43313

Edwards, L.S.A. (1977). A modified pseudo section for resistivity and induced polarization. *Geophysics* 42(5), 1020-1036. doi: https://doi.org/10.1190/1.1440762

Fetter, C. W. (2018). *Applied hydrogeology.* Waveland Press.

Fraenkel, M.O.; Santos, R.C.; Loureiro, F.E.V.L.; Muniz, W.S. (1985). Jazida de urânio no Planalto de Poços de Caldas-Minas Gerais. En A. Departamento Nacional da Produção Mineral (Eds.), *Principais depósitos minerais do Brasil.* (pp. 89-103).

Gastmaier Marques, A. C., Moreira, C. A., Stanfoca Casagrande, M. F., & Aldana Arcila, E. J. (2022). Gamma-ray spectrometry applied in the identification of potential acid mine drainage generation zones in waste rock pile with uranium ore and associated sulfides (caldas, Brazil). *Geofísica Internacional*, 61(3), 251-266. doi: https://doi.org/10.22201/igeof.00167169p.2022.61.3.2207

Gomes de Oliveira, V. M., Tavares Ribeiro, L. F., & Rosalino da Silva, M. C. (2014). Hydrogeologic characterization of the abandoned mining site of Castelejo, Portugal by VLF-EM & RMT-R geophysical surveying. *Geofísica Internacional*, 53(2), 135-151. doi: https://doi.org/10.1016/S0016-7169(14)71496-5

Hamdan H, Andronikidis N, Kritikakis G, Economou N, Agioutantis Z, Schilizzi P, Steiakakis C, Papageorgiou C, Tsourlos P, Vargemezis G, Vafidis A. (2014). Contribution of electrical tomography methods in geotechnical investigations at Mavropigi lignite open pit mine, northern Greece. Environmental Earth Sciences, 72(5),1589-1598. doi: https://doi.org/10.1007/s12665-014-3063-6

Hartwig, M. E. and Moreira, C. A. (2021). Integration of multisources data for quarry slope stability assessment in the Itaoca district (Southeastern Brazil). *Anais da Academia Brasileira de Ciências*, 93(1), e20190322. doi: https://doi.org/10.1590/0001-3765202120190322

Holmes, D. C.; Pitty, A. E.; Noy, D. J. (1992). Geomorphological and hydrogeological features of the Poços de Caldas caldera analogue study sites. *Journal of Geochemical Exploration*, 45(1-3), 215-247. doi: https://doi.org/10.1016/0375-6742(92)90126-S

International Society for Rock Mechanics, ISRM. (1978). Suggested methods for the quantitative description of discontinuities in rock masses. International Journal of Rock Mechanics, Mining Sciences & Geomechanics. Abstracts, 15(6), 319-368.

Jerram, D. & Petford, N. (2012). *The Field Description of Igneous Rocks* (2a ed.). Environmental & Engineering Geoscience.

Kliche, C.A. (1999). *Rock Slope Stability.* Society for *Mining*, Metallurgy, and Exploration, Inc., Littleton.

Kolapo P, Oniyide G.O, Said K.O, Lawal A.I, Onifade M, Munemo P. (2022). An Overview of Slope Failure in Mining Operations. Mining, 2(2), 350-384. doi: https://doi.org/10.3390/mining2020019

Liu, X., Zhang, X., Kong, L., Wang, G., & Lu, J. (2022). Disintegration of granite residual soils with varying degrees of weathering. *Engineering Geology*, 305, 106723. doi: https://doi.org/10.1016/j.enggeo.2022.106723

Marques, E.A.G., Barroso, E. V., Menezes Filho, A.P., Vargas, E. do A. (2010). Weathering zones on metamorphic rocks from Rio de Janeiro-Physical, mineralogical and geomechanical characterization. *Engineering Geology*, 111(1-4), 1-18. doi: https://doi.org/10.1016/j.enggeo.2009.11.001

Martins, A. C., Elis, V., Tomi, G. D., Bettencourt, J., & Marin, T. (2016). Resistivity and induced polarization to support morphological modeling in limestone mining. Geofísica internacional, 55(4), 227-238. doi: https://doi.org/10.22201/igeof.00167169p.2016.55.4.1725

Menezes, D. A., Carneiro, S. R. C., Meireles, B. P. (2019). Map of the potential geotechnical susceptibility for operational pit slopes. *REM-International Engineering Journal*, 72(1). doi: https://doi.org/10.1590/0370-44672018720137

Moreira, C. A., & Innocenti Helene, L. P. (2022). Identification for a favorable area of groundwater exploitation based on structural and geoelectrical data in fractured aquifer in Southern Brazil. *Geofísica internacional*, 61(4), 287-300. doi: **https://doi.org/10.22201/igeof.00167169p.2022.61.4.2045**

Moreira, C. A., Helene, L. P. I., Hartwig, M. E., Lourenço, R., do Nascimento, M. M. P. F., & Targa, D. A. (2021). Geophysical and Structural Survey in the Diagnosis of Leaks at a Fuel Station in a Uranium Mine in Decommissioning Phase (Poços de Caldas, Brazil). *Pure and Applied Geophysics*, 178(9), 3489-3504. doi: **https://doi.org/10.1007/s00024-021-02828-6**

Moreira, C. A., Montenegro Lapola, M. & Carrara, A. (2016). Comparative analyzes among electrical resistivity tomography arrays in the characterization of flow structure in free aquifer. *Geofísica Internacional*, 55(2), 119–129. doi: **https://doi.org/10.22201/igeof.00167169p.2016.55.2.1716**

Nascimento, M. M. P. F., Moreira, C. A., Duz, B. G., & da Silveira, A. J. T. (2022). Geophysical diagnosis of diversion channel infiltration in a uranium waste rock pile. *Mine Water and the Environment*, 41(3), 704-720. doi: **https://doi.org/10.1007/s10230-022-00878-3**

Oliveira, A. F., da Rocha, P. L. F., Carelli, S. C., & Plastino, R. H. (2010). Geophysical investigations for modeling sand ridges at Sepetiba bay, Itaguaí estado do Rio de Janeiro, Brazil. *Anuário do Instituto de Geociências*, 33(1), 44-53. doi: **https://doi.org/10.11137/2010_1_44-53**

Pádua, A. I. D., & Campos, J. E. G. (2020). Estimative of groundwater circulation in fractured aquifers with resistivity and optical borehole logging: case study in Petrolina, PE (Brazil). *Anuario do Instituto de Geociencias* (On), 43(2), 138-150.

Palacky, G. (1987). Resistivity Characteristics of Geological Targets. En A. Nabighian.(Ed.), *Electromagnetic Methods in Applied Geophysics-Theory.* (pp. 53-129). Society of Exploration Geophysicists Tulsa, Oklahoma.

Perrone, A.; Vassallo, R.; Lapenna, V.; Di Maio, C. (2008). Pore water pressures and slope stability: a joint geophysical and geotechnical analysis. *Journal of Geophysics and Engineering*, 5(3), 323-337. doi: **https://doi.org/10.1088/1742-2132/5/3/008**

Porsani, J. L., Elis, V. R., & Hiodo, F. Y. (2005). Geophysical investigations for the characterization of fractured rock aquifers in Itu, SE Brazil. *Journal of applied geophysics*, 57(2), 119-128. doi: **https://doi.org/10.1016/j.jappgeo.2004.10.005**

Porto Jr, R., Pires, B. P., Gouveia, G. R., Brandão, V. S., & Coutinho, N. M. (2012). Geological and geotechnical characterization of mass movement occurred between the beaches of Prainha and Grumari, in the city of Rio de Janeiro, RJ. *Anuário do Instituto de Geociências*, 35(2), 5-13. doi: **https://doi.org/10.11137/2012_2_05_13**

Priest, S. D., and J. A. Hudson. (1981). Estimation of discontinuity spacing and trace length using scanline surveys. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 18(3), 183-197. doi: **https://doi.org/10.1016/0148-9062(81)90973-6**

Read, J., and Stacey, P.F. (2009). *Guidelines for Open Pit Design*, CSIRO Publishing.

Singhal B.B.S., Gupta R.P. (2010). *Applied hydrogeology of fractured rocks*. Springer Dordrecht. doi: **https://doi.org/10.1007/978-90-481-8799-7**

Souza, A.M.; Silveira, C.S.; Pereira, R.M. (2013). Contribuições dos metais provenientes das pilhas de rejeito da Mina Osamu Utsumi a drenagens do Complexo Alcalino de Poços de Caldas, Minas Gerais. *Geochimica Brasiliensis*, 27(1), 63-76.

Sun, M.; Yu, J.; Wu, X.; Ding, Y.; Fu, T.; Yang, Y.; Jiang, J. (2021). Mechanical Behavior of Weathered Granite Exposed to Water. *Applied Science*, 11(21). doi: **https://doi.org/10.3390/app112110356**

Telford W.M., Geldart L.P., Sheriff R.E. (2004). Applied Geophysics. Cambridge University Press

Ulbrich, H.H.; Ulbrich, M.N.C. (2000) The lujavrite and khibinite bodies of the Poços de Caldas Massif, southeastern Brazil: a structural and petrographical study. *Revista Brasileira de Geociências*, 30(4), 615-622.

Whiteley JS, Watlet A, Uhlemann S, Wilkinson P, Boyd JP, Jordan C, Kendall JM, Chambers JE. (2021). Rapid characterisation of landslide heterogeneity using unsupervised classification of electrical resistivity and seismic refraction surveys. *Engineering Geology*, 290, 1-15. doi: **https://doi.org/10.1016/j.enggeo.2021.106189**

Wyllie DC and Mah CW. (2004). *Rock slope engineering: civil and mining*. CRC Press. doi: **https://doi.org/10.1201/9781315274980**

Yan, Y.; Yan, Y.; Zhao, G.; Zhou, Y.; Wang, Z. (2022). Combined ERT and GPR Data for Subsurface Characterization of Weathered Hilly Slope: A Case Study in Zhejiang Province, Southeast China. *Sustainability*, 14(13), 7616. doi: **https://doi.org/10.3390/su14137616**