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DEVELOPMENT OF SUSTAINABLE TECHNOLOGIES FOR THE LOCAL PRODUCTIVE CLUSTER OF KAOLIN FROM PEGMATITES RN/PB

F.W.H. VIDAL[1], K. M. ALMEIDA, A. P. F. SOUSA, N. F. CASTRO
Centro de Tecnologia Mineral – CETEM/MCTI[1]
ORCID ID: https://orcid.org/0009-0004-8368-3982[1]
fwhollanda@gmail.com[1]

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ABSTRACT

The Seridó region, located in northeastern Brazil, in the states of Paraíba and Rio Grande do Norte, is known for its vast reserves of kaolin from pegmatites. Small companies mine and process ore. However, these operations are precarious, lacking mining planning and processing studies. Consequently, the recovery rates are only 25%, and mining accidents happen. Within a Ministry of Science and Technology work project named Associated Entities, the Centre for Mineral Technology and the Federal University of Campina Grande carried out integrated research, technology and innovation actions to add value to the mineral production chain in the Seridó region. After elaborating on a working plan, the partners collected information on the area, which they used to construct geological maps and computerized mine models. In addition, a kaolin processing plant with a hydrocyclone, aiming to increase the ore's recovery, was studied. This project results were two pit design scenarios with distinct geometric characteristics for the mine planning stage. The first scenario presented better results than the second, with a higher ore tonnage recovery and a lower waste/ore ratio. In the processing stage, the hydrocyclone tested plant led to a concentrate with high kaolinite percentages. The mining and processing project showed the possibility of extracting and processing the kaolin ore in a safer and more economically viable way for small producers.

KEYWORDS: Kaolin, hydrocyclone, beneficiation, Seridó.

DESENVOLVIMENTO DE TECNOLOGIAS SUSTENTÁVEIS PARA O ARRANJO PRODUTIVO LOCAL DE CAULIM NOS PEGMATITOS RN/PB

RESUMO

A região do Seridó, situada no Nordeste brasileiro, nos estados da Paraíba e do Rio Grande do Norte, é conhecida por suas vastas reservas de caulim oriundas de pegmatitos. Pequenas empresas fazem o processo de extração e beneficiamento do minério. No entanto, essas operações são precárias. A falta de planejamento na lavra e no processo de beneficiamento faz com que os pequenos produtores de caulim tenham apenas um aproveitamento de 25%, e diversos acidentes causados na etapa de extração. O projeto Entidades Associadas do Centro de Tecnologia Mineral – CETEM/MCTI, em parceria com a Universidade Federal de Campina Grande - UFCG foi criado para desenvolver ações integradas de pesquisa, tecnologias e inovação para agregar valor à cadeia produtiva mineral na região do Seridó. Foi elaborado um plano de trabalho onde se fez o levantamento de informações da área. Foram coletados dados em campo e utilizados na elaboração de mapas e modelos geológicos para cálculo de cubagem, utilizando software computacional. Além disso, foi montada uma planta piloto de beneficiamento de caulim utilizando hidrociclone, visando o aumento de recuperação do mineral minério. Na etapa de planejamento de lavra foram elaborados dois cenários de lavra com características geométricas distintas. O primeiro cenário apresentou resultados melhores que o segundo. A tonelada de minério foi maior e a relação estéril minério menor. No processo de beneficiamento a recuperação de caulim apresentou bom resultado. O concentrado do processo apresentou altas porcentagens de caulinita. O projeto de lavra e beneficiamento mostrou a possibilidade de extrair e tratar um minério de forma mais segura e viável economicamente.

PALAVRAS-CHAVE: Caulim, hidrociclone, beneficiamento, Seridó.

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1 INTRODUCTION

The increasing use of raw mineral materials in different areas of the industry makes the exploitation of reserves by small miners attractive. In recent years, small-scale mining has gradually grown in Brazil, where the mining industry is predominantly formed by micro and small companies (IBRAM, 2020). They serve as a basis for strengthening the production chains of different industrial sectors, exploring deposits of no interest to large companies and boosting local economies (FREITAS *et al*., 2021).

On the other hand, many of these operations are artisanal, with a low technological level, in which the lack of geological knowledge and operations planning, as well as the use of inefficient mining and processing methods, may cause environmental, economic and social damage and represent the main challenges for their development (DE TOMI *et al*., 2021). An example of this is kaolin mining in the Seridó region, located in the Brazilian Northeast, in the states of Paraíba and Rio Grande do Norte.

In the Borborema/Seridó Pegmatite Province, the production of kaolin is carried out with considerable intensity, constituting a significant hub within the mineral industry. However, this production process also generates a considerable amount of waste, a byproduct of kaolin extraction and processing (PEREIRA, 2022). Managing these residues becomes a critical point for the industry's sustainability, demanding effective waste handling measures and, ideally, strategies aimed at reusing or recycling this material. These approaches seek to mitigate environmental impacts while maximizing the efficiency of the kaolin production cycle in the region. Innovative strategies for utilizing these residues could not only reduce potential adverse environmental impacts but also pave the way for new applications and economic opportunities (LEANDRO, 2017).

This region is known for its vast reserves of kaolin from pegmatites. Kaolin is a hydrated aluminium silicate composed of Al_2O_3, SiO_2 and H_2O (SOUSA *et al*., 2005). It occurs in two types of geological deposits: primary and secondary (LUZ; CHAVES, 2000). Kaolin's primary deposits result from pegmatitic rocks alteration by weathering. The secondary deposits, in turn, are formed by the deposition of kaolin transported by water currents over time. The Seridó kaolin deposits are primary. The natural properties of kaolin, such as fine grain size, whiteness, little abrasion and chemical stability, help make it one of the most used clays in the world (REZENDE, 2008). It is widely used in white ceramics, plastics, paints, refractories, and particularly paper (LUZ *et al*., 2008).

Kaolin extraction in the Seridó region concentrates in the municipalities of Juazeirinho, Assunção, Tenório, and Junco do Seridó, in the state of Paraíba-PB, and the municipality of Ecuador, in the state of Rio Grande do Norte-RN. These municipalities are in the domains or close to the Borborema Pegmatitic Province (VIDAL *et al*., 2017). Several small companies extract and process kaolin ore in the Seridó region. The mining method and kaolin processing are carried out in a rudimentary way (SILVA *et al*., 2010). Mine planning studies for the opening of the deposits are not usual. There is a large volume of waste generated by companies in the region, which indicates the use of inefficient kaolin production techniques. According to Rezende (2013), approximately 75% of the kaolin extracted and processed becomes waste. The characterization of

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the residue shows that a significant percentage of kaolin, approximately 30%, is still discarded (ALMEIDA *et al*., 2016).

In micro and small enterprises, kaolin mineral deposits are mined with superficial geological knowledge and low mechanization levels. Also, inappropriate techniques in mining and processing are used. In addition, the qualification of human resources on the mining fronts and processing units is low. Mining is rudimentary, with most kaolin extraction carried out by *garimpeiros* (artisanal miners). The most experienced ones dig underground tunnels to remove the kaolin without planning or studying geotechnical stability. As a result, the region has a high rate of fatal accidents. There is also a lack of financial resources, commercialization structure and enormous difficulty in maintaining the legalization of areas already required for extraction (VIDAL *et al*., 2017). According to Silva and Lima (2016), block sizing and modelling is an alternative to solve the problems with irregular kaolin extraction in northeastern Brazil.

To minimize this situation, the project: "Integration of research and technological development aimed at the rational and sustainable use of pegmatite minerals and quartzite rocks" was executed. The Ministry of Science, Technology and Innovation funded that project through the Associated Entities Program of the Centre for Mineral Technology – CETEM with the Federal University of Campina Grande - UFCG. The project's overall objective was to develop and implement integrated research, technology development and innovation actions to add value to the mineral production chain and enable the sustainable use of small mineral deposits in the Pegmatitic Province of Borborema/Seridó. The aim was to contribute to minimizing or eradicating the severe problems that inhibit the development of kaolin mining activities, which are important for the regional economy, and to strengthen the Local Productive Cluster (APL) of Pegmatites RN/PB.

Among the various actions established in the work plan, the partners designed and developed a pilot project in areas already formalized by small mining cooperatives, such as the Cooperative of Mineral and Agricultural Workers of Equador and Seridó - COOTMAES, located in Equador-RN. That pilot project, developed and carried out by a team coordinated by Marinésio Pinheiro Lima, professor at the Federal University of Pernambuco - UFPE, and Francisco Wilson Hollanda Vidal, coordinator of the CETEM’s Associated Entities program, consisted of technological actions in the mining and processing stages in an area called Galo Branco which is mined for kaolin. The project's purpose at the mine was to collect the necessary data for its planning and thus propose a viable scenario for the extraction activities. In processing, the objective was to study other technologies by adding new equipment, a hydrocyclone separator. The pilot project sought the creation of a sustainable plan for all stages of kaolin mining.

2 MATERIALS AND METHODS

The activities started with the topographic mapping of the target areas of study. There were already rudimentary kaolin mining operations at the site, most of which were carried out by artisanal miners. Then, the area of interest was selected, and a detailed study was carried out collecting specific elevation points through topographic profiling using a high-precision millimetre

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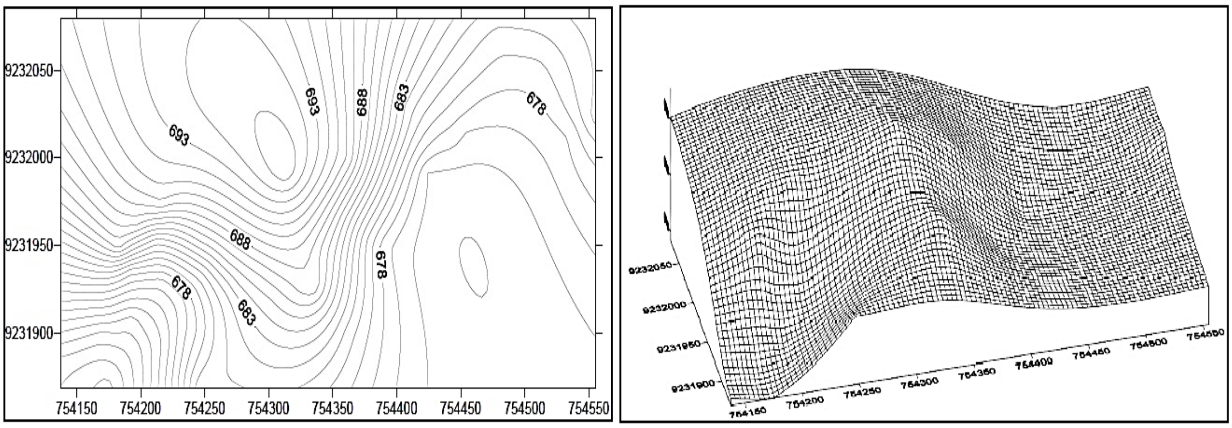
GPS. With the information collected, it was possible to create a database with various information on the topography of the place. The data contributed to the execution of the kriging process to establish the surface characteristics of the area. The final collection helped create a topographic surface in 2D and 3D, illustrated in Figure 1.



a) b)

Figure 1: Topographical surface of the area proposed for kaolin mining; a) 2D Map; b) 3D Wireframe.

Geological and geotechnical mapping of the areas of interest was carried out by observing old kaolin extraction wells excavated by miners in the region, collected samples, and prior geological reconnaissance for detailing the observed geological features. This information enabled identifying and characterising the entire kaolin mineralised body. The model was graphically represented so the 3D interpretation could be performed, as shown in Figure 2.

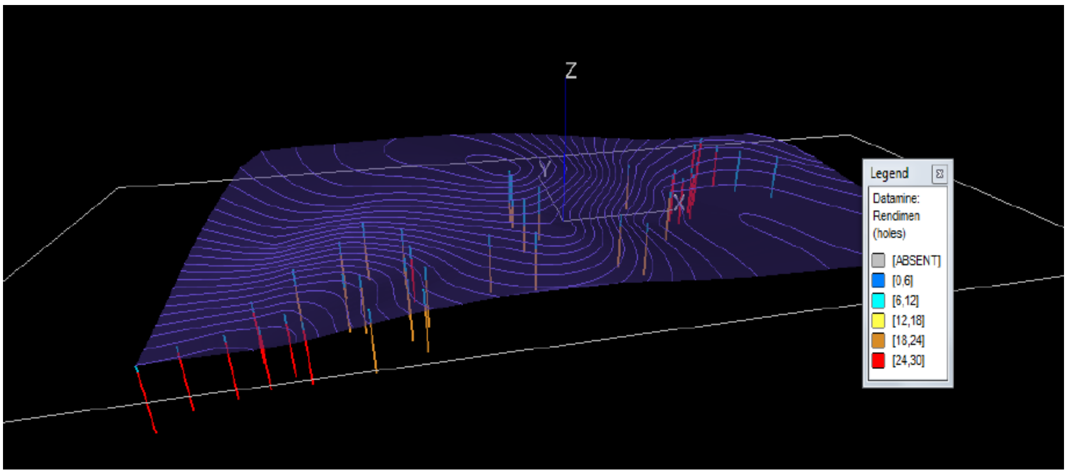


Figure 2: Wells data and topography three-dimensional representation.

The geotechnical mapping was carried out to determine the discontinuities strike and dip direction on the outcrops and the host rock, in this case, the quartzite found in the region. The collected data were gathered to propose a suitable mining method for the conditions of the existing deposits in the region. They were grouped in TXT files in Excel spreadsheets with the following information: location of existing wells, depth of wells, apparent overburden and kaolin yield. The files were imported and graphically represented to carry out the geological

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interpretation. With the subsurface information, the geological interpretation was made through straight segments (strings) of the kaolin body's contour in vertical sections along the body. The mineralised thickness was interpolated for each section. Each resulting rendering was projected perpendicularly to the body volume extending to the next section. Thus, joining the sections, the total deposit volume was estimated. After all the sections' interpretation, the 3D model of the kaolin body shown in Figure 3 was constructed.

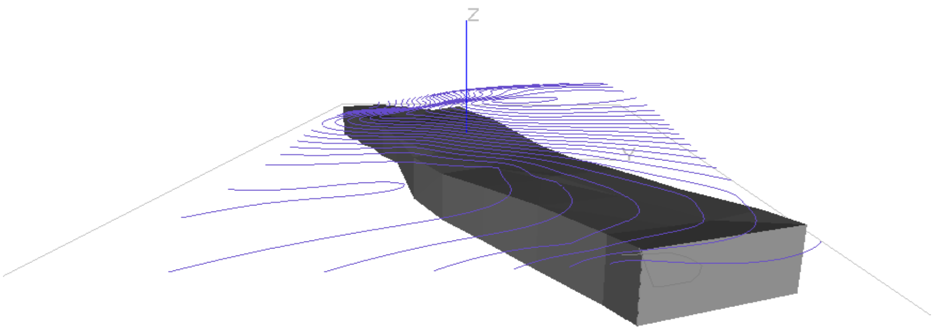

Figure 3: Kaolin body's 3D model.

The interpreted data were rearranged in a block model. The Inverse of the Square of the Distance (IDQ) was used for its representation. In it, the ore of interest was represented together with the host rock of the mineralised body (Figure 4). The three-dimensional representation helps to quantify the geological and technical-economic aspects.

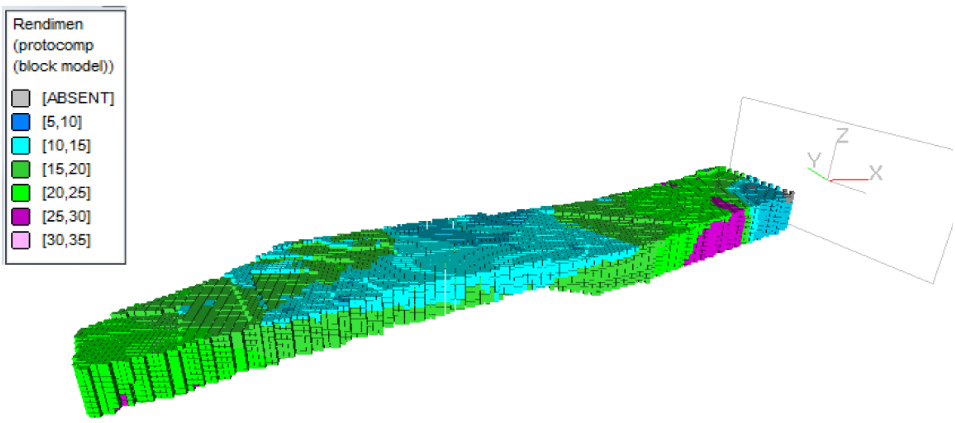

Figure 4: 3D Block model of kaolin's mineralised body.

2.1 First proposed mining scenario

With all the information collected, interpreted and modelled, two possible scenarios were then analyzed for opening pits for kaolin extraction. The first scenario foresaw the ore recovery up to 658 m level, totalling four 5.0 m height and width benches, with a spiral ramps system. Table 1 details the geometric parameters of the proposed pit for the first scenario.

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Table 1: Geometric parameters of the first mining model.

First scenario: proposed pit geometric parameters	
Minimum elevation	658 m
Number of benches	4
Bench height	5 m
Berm width	5 m
Overall slope angle	45°
Bench-face inclination	80°
Ramps system	Espiral
Ramps inclination	10%
Ramps width	5 m

2.2 Second proposed mining scenario

The second scenario foresaw the ore recovery up to the 660 m level, with five 5.0 m high and wide benches and a zig-zag ramp system. Table 2 details the geometric parameters of the second scenario proposed pit.

Table 2: Geometric parameters of the second mining model.

Second scenario: proposed pit geometric parameters	
Minimum elevation	Minimum elevation
Number of benches	Number of benches
Bench height	Bench height
Berm width	Berm width
Overall slope angle	Overall slope angle
Bench-face inclination	Bench-face inclination
Ramps system	Ramps system
Ramps inclination	Ramps inclination
Ramps width	Ramps width

2.3 Kaolin Beneficiation Process proposal

Concomitantly with the mining project, a study was carried out to improve the processing of kaolin using the hydrocyclone separator. Samples of kaolin ore were collected from two companies for technological tests and hydrocyclone separation. The material was disaggregated and sieved, and with the fraction < 0.84 mm, a pulp with 20% solids was prepared for the hydrocyclone process with a pressure of 10 psi. The best parameters for processing kaolin in the region were determined based on the results obtained from the granulometric, mineralogical and chemical analyses and the preliminary classification tests in the hydrocyclone. Then, continuing the research, a pilot plant was set up using the AKW JC 91 model cyclone, with a vortex of 1 ½ apex opening of 10 mm and slurry feeding with an open valve (Figure 5). The feed granulometry was kept constant.

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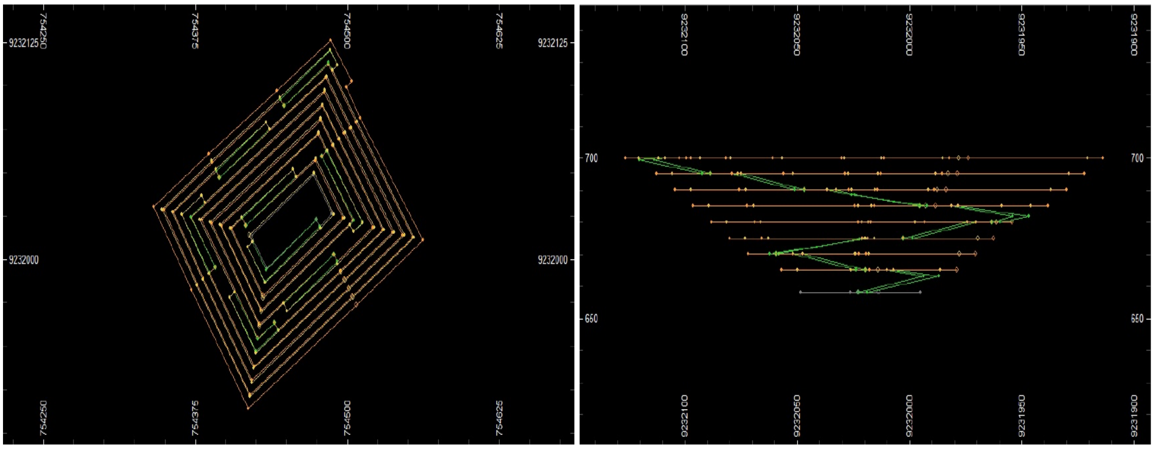
Figure 5: Hydrocyclone test for kaolin processing.

3 RESULTS AND DISCUSSION

For the pit designs, the place with less overburden and where the block model showed the best yield (25 to 30%) was selected. Two pit design scenarios were then built for this location. The most conservative parameters concerning the final inclination of the slopes were considered.

3.1 First mining scenario

For the first design scenario of the pit, the base elevation of 658 m was chosen, from which the following levels were designed until extrapolating the topography. The levels are interconnected with a 5 m wide spiral ramp with a 10% inclination, initially obeying an overall slope angle of 45°. Figure 6 shows the top and profile view of the project.



a) b)

Figure 6: Design of the first proposed mining scenario, spiral ramp; a) plan view; b) profile view north-south.

The final pit was obtained by intersecting the pit design with the topography, which allowed the total volume estimation (Figure 7a). Next, the kaolin body block model was inserted to determine the ore and waste volumes (Figure 7b).

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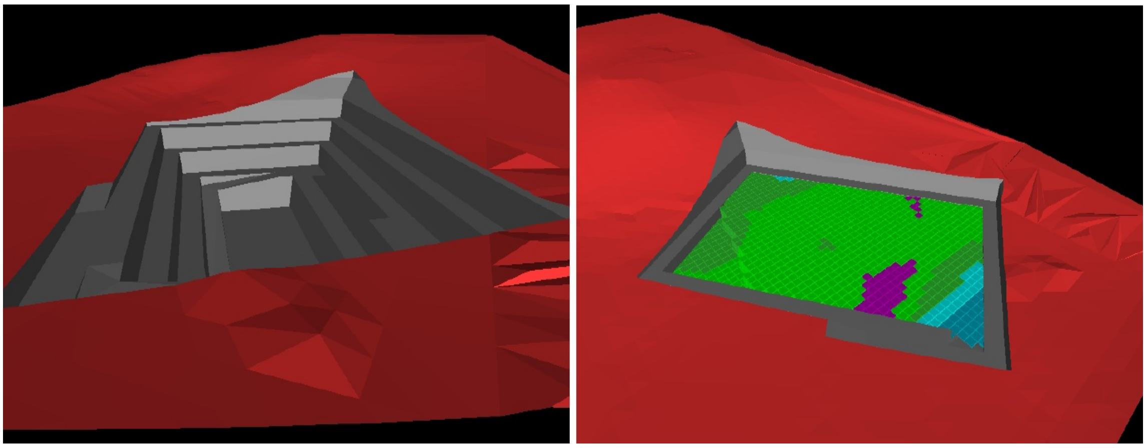

a) b)

Figure 7: First scenario: Mine perspective view - a) pit model; b) pit with kaolin body block model.

Table 3 summarizes the geometric parameters and calculated volumes for the pit first scenario.

Table 3: Mine first scenario results.

Estimated results for the mine first scenario	
Maximum elevation	686.88 m
Minimum elevation	658 m
Number of benches	4
Bench height	5 m
Berm width	5 m
Overall slope angle	45°
Bench-face inclination	80°
Ramp system	Spiral
Ramp inclination	10%
Ramp width	5 m
Waste volume	30,165.78 m^3
Ore volume	56,518.20 m^3
Total volume	86,683.98 m^3
Pit tonnage	225,378.34 t
Ore tonnage	146,947.32 t
Waste tonnage	78,431.03 t
Waste/Ore Ratio	0.53

The block model analysis for the first proposed mining scenario resulted in 146,946.80 t of kaolin, with an average yield of 24.11% (Table 4).

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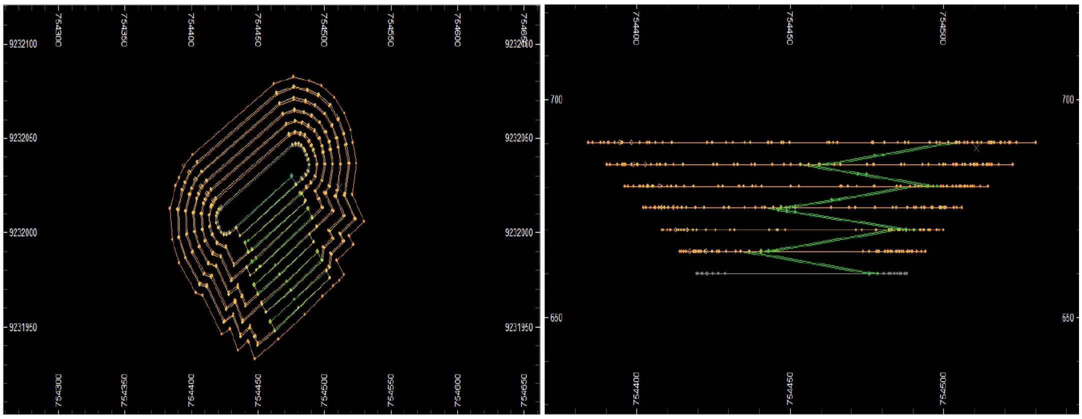
Table 4: Kaolin volumes and yields for the first mining scenario.

Yield (%)	Volume (m^3)	Tons	Average yied (%)
5 - 10	256.90	667.94	8.68
10 - 15	631.10	1,640.86	12.78
15 - 20	6,509.30	16,924.18	18.52
20 - 25	21,747.60	56,543.76	23.11
25 - 30	27,373.10	71,170.06	26.63
Total	**56,518.00**	**146,946.80**	**24.11**

3.2 Second mining scenario

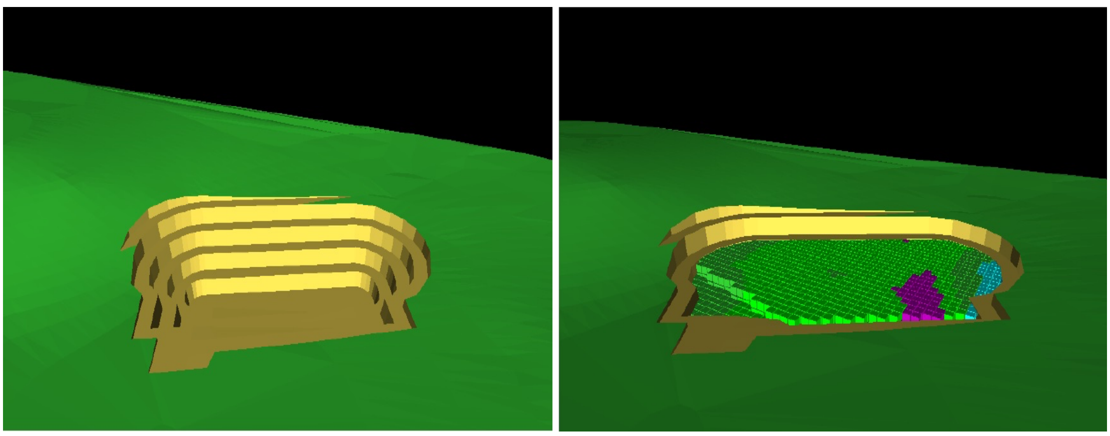
The second pit design scenario starts from the base level of 660 m, and five levels follow up to the surface. The levels are interconnected with a 5 m wide zig-zag ramp with a 12% inclination, initially obeying an overall slope angle of 45°. Figure 8 shows the top and profile view of the project.



a) b)

Figure 8: Design of the second proposed mining scenario, zig-zag ramp; a) plan view; b) profile view east-west.

The pit design incorporated with the topography and the block model resulted in the mine's final geometry and production estimates (Figure 9). Table 5 summarizes the geometric parameters and calculated volumes for the pit second scenario.



a) b)

Figure 9: Second scenario: mine perspective view - a) pit model; b) pit with kaolin body block model.

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Table 5: Mine second scenario results

Estimated results for the mine second scenario	
Maximum elevation	683.13 m
Minimum elevation	660 m
Number of benches	5
Bench height	5 m
Berm width	5 m
Overall slope angle	45°
Bench-face inclination	80°
Ramp system	zig-zag
Ramp inclination	12%
Ramp width	5 m
Waste volume	25,452.26 m^3
Ore volume	41,519.40 m^3
Total volume	66,971.66 m^3
Pit tonnage	174,126.32 t
Ore tonnage	107,950.44 t
Waste tonnage	66,175.87 t
Waste/Ore Ratio	0.61

Table 6 illustrates the block model analysis for the second proposed mining scenario. It resulted in 107,950.44 t of kaolin, with an average yield of 23.96%, which are inferior to the obtained for the first scenario

Table 6: Kaolin volumes and yields for the second mining scenario.

Yield (%)	Volume (m^3)	Tons	Average yied (%)
5 - 10	5.70	14.82	9.21
10 - 15	585.50	1,522.30	13.17
15 - 20	4,740.20	12,324.52	18.45
20 - 25	17,591.60	45,738.16	23.12
25 - 30	18,596.40	48,350.64	26.49
Total	**41,519.40**	**107,950.44**	**23.96**

3.3 Comparison between the two proposed mining scenarios

The proposed mining process considers mechanical removal with average excavation and estimated load productivity of approximately 240 m^3/h. With the parameters delimited, the two projected scenarios can be compared (Table 7).

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Table 7: Comparison between the two proposed mining scenarios.

	1st Scenario	2nd Scenario
Pit (t)	225,378.34	174,126.32
Ore (t)	146,946.80	107,950.44
Waste (t)	78,431.54	66,175.88
Waste/Ore Ratio	0.53	0.61
Mining costs (R$/m3)	5	5
Min. selling price (R$/t)	20	20
Income	2,938,936.00	2,159,008.80
Expenses	433,419.90	334,858.30
Net profit	2,505,516.10	1,824,150.50

The results show the first scenario more advantageous than the second, with higher ore recovery and lower waste/ore ratio (REM). The spiral model presents a greater efficiency of the ramp system for the local design conditions.

3.4 Hydrocyclone processing tests

The hydrocyclone test resulted in an approximately 50% by weight of the overflow, with 80% of material <0.045 mm and 20% > 0.045 mm. The underflow (50% by weight) presented 30% of material under 0.045 mm and 70% over that size. XRD analysis showed an ore mineralogical composition of kaolinite, muscovite, quartz and microcline. The FRX analysis of the hydrocyclone products resulted in a favourable percentage of SiO_2 and Al_2O_3 in the finer fractions. The percentages of SiO_2 and Al_2O_3 in hydrocyclone overflow were 49.42% and 37.51%, respectively. They are the main compounds in the chemical structure of kaolin. Therefore, the bench scale tests in the hydrocyclone showed the possibility of obtaining 86.93% kaolinite concentrates.

3.5 Current panorama

Researchers from UFCG and other institutions continued working on the sustainable development of micro and small mining enterprises in Seridó after completing the CETEM & UFCG Associative Entities Project in 2017. They actuated on the continuity of the social organization and production in the small-scale mining to formalize more mined areas for COOTMAES. Subsequently, new projects were developed to improve the mining methods in the cooperative's already formalized areas.

In addition, a pilot-scale adaptation process is currently being initiated in Equador's processing units of small kaolin producers, aiming to increase ore recovery and reduce waste generation near these units. Furthermore, studies are being carried out for the full use of kaolin residues that are disposed of in piles surrounding these small enterprises.

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In summary, researchers continue to work towards the sustainable development of micro and small mining enterprises in Seridó, with actions to formalize mined areas, improve mining methods and ore recovery, and reduce waste, in addition to studies on the integral use of kaolin residues.

4 CONCLUSION

The Associated Entities Project provided the possibility of working in an economically viable mining scenario for the kaolin producers in the Seridó region. The project results showed that the first proposed mining scenario, with spiral ramps, is the most appropriate, with a calculated reserve of 146,946.80 tons of ore and a waste/ore ratio (REM) is 0.53, which means that it is lower than the obtained in the second mining scenario, resulting in smaller amounts of generated waste. The mining project showed the possibility of extracting the ore in a safer and more economically viable way, contributing to reducing accidents suffered by prospectors.

In the beneficiation process, using hydrocyclones, kaolin recovery showed promising results, with approximately 50% as product with 80% as fine material (<0.045 mm). The process concentrate had 86.93% of kaolinite, which indicates the feasibility of using this tool in the processing plant since companies in the region only recover 25%.

The practices developed by the work show the importance of technological support for small producers. The project allowed small mining enterprises to access innovative and sustainable technologies currently being implemented. Other successful results of this project are the organization of mineral production, the strengthening of cooperatives/associations, and the respect for mineral, environmental, labour and tax legislation.

5 ACKNOWLEDGMENT

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ABOUT THE AUTHORS

F. W. H. VIDAL

Doutor e Mestre em Engenharia Mineral pela Universidade de São Paulo (USP), Graduação em Engenharia de Minas pela Universidade Federal de Pernambuco (UFPE). Pesquisador aposentado do Centro de Tecnologia Mineral (CETEM).
E-mail: fwhollanda@gmail.com
ORCID ID: https://orcid.org/0009-0004-8368-3982

K. M. ALMEIDA

Mestre em Engenharia Metalúrgica e de Materiais, Graduação em Engenharia de Minas pelo Instituto Federal de Educação Ciência e Tecnologia do Espírito Santo (Ifes). Pesquisador no Centro de Tecnologia Mineral (CETEM).
E-mail: kayronemarvila@gmail.com
ORCID ID: https://orcid.org/0000-0001-6140-8358

A. P. F. SOUSA

Mestre de Graduado em Engenharia de Minas pela Universidade Federal da Paraíba (UFPB). Professor titular no curso de Engenharia de Minas na Universidade Federal de Campina Grande (UFCG)
E-mail: apedrogalo@gmail.com
ORCID ID: https://orcid.org/0000-0003-1425-1639

N. F. CASTRO

Doutoranda e Mestre em Geologia pela Universidade Federal do Rio de Janeiro (UFRJ), Graduação em Engenharia de Minas Universidade de São Paulo (USP), Graduação em Engenharia de Minas pela Universidad Politécnica de Madrid (UPM). Pesquisadora titular no Centro de Tecnologia Mineral (CETEM).
E-mail: nutriacastro@gmail.com
ORCID ID: https://orcid.org/0000-0003-3073-5529

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