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Original Article

# Technical feasibility study of the exploitation of seabed potassium salts by solution mining

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ABSTRACT

To address Brazil's need for imported saline potassium, a technical feasibility study of the exploitation of seabed potassium salts by solution mining in Brazil was conducted based on a mapped anomaly of the coast of Sergipe. This study involved a technical–scientific partnership between the Federal University of Minas Gerais, and National Agency of Petroleum, Natural Gas and Biofuels. The latter provided the technical data acquired from wells drilled by oil companies, including descriptions of channel samples, composite profiles, drill hole profile, geophysics, gravimetry, and magnetometry. The data were analyzed using petrographic tools to characterize the anomalies in the potassium salts at drilling sites. The profile data was processed to examine the gamma ray, sonic and resistivity, and create a filter to separate potassium salts from other salts. The objective of the study was to build a new route for exploratory research of sedimentary rocks. The seismic interpretation of the results and description of the drill holes were used to develop a geological model of the mineral body with the aim of determining the potential of potassium salts for mine applications. Based on the findings, the optimal exploitation parameters (equipment, pumping rate, mine layout, and mineral recuperation) for possible exploitation of the potassium salts were defined.



## 1. Introduction

Brazil's dependence on imported potassium salts has economic and strategic implications for its trade balance [1], considering that potassium is a primary input for the production of the fertilizers used in the agricultural sector, which accounted for 21.4% of the country's gross domestic product in 2019 [2]. Imported potassium represented 36.9% of the total mineral imports and 39.3% of the total mineral assets of the country in the first half of 2019 [3].

Potassium salts, such as carnallite and sylvite, are referred to as evaporites, which are rocks of sedimentary origin commonly formed in sedimentary environments with low terrestrial sediment input in a dry climate with a high water-evaporation rate [4]. Feijó [5] observed that the evaporitic deposits in

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Brazilian marginal basins are of Aptian age (125 Ma), having been formed by several processes related to the rupture of Gondwana and formation of the South Atlantic Ocean. Evaporite precipitation occurs during the formation of a restricted marine environment, referred to as a gulf (Fig. 1), after an initial rift phase in which the continental environment prevails and a carbonatic marine phase in a shallow sea environment induced the evolution of the South Atlantic basin.

To date, the Muribeca Formation is subdivided into three geological units, namely: Carmópolis, Ibura, and Oiteirinhos. This formation occurs exclusively on a subsurface, and is restricted to the Sergipe sub-basin onshore and offshore. Its thickness varies between 50 and 400 m, and can even reach 600 m. Salt diapirs in drill holes of up to 1600 m in the area are reported. Geological units commonly have thicknesses of 15–200 m with a maximum thickness of 420 m in the Ibura geological unit, which may reflect intrusive salt bodies [6].

The Ibura geological unit contains most of the evaporitic section of the Muribeca Formation. According to PPGG/UFRN [6], this geological unit was produced by several evaporitic cycles initiated by the deposition of carbonates and sulfates (anhydrite), followed by the precipitation of halite and mixed deposits of halite–sylvite, called sylvinite. Some of the cycle formations have evolved under conditions of extreme aridity with the deposition of rare and extremely soluble salts, such as carnallite and tachyhydrite.

With the aim of ending the dependence of Brazil on imported potassium salts, the present study was conducted to develop a technical procedure for the exploration and exploitation of potassium salts in a marine environment. Particularly, this study was based on a potassium salt anomaly detected by the Company of Research of Mineral Resources (CPRM) along the Sergipe coast [7]. Specifically, the study objectives are twofold: modelling the mineral anomaly to facilitate mine design, and defining the technical mining parameters and process routes. To facilitate this, a bibliographic review of evaporite rocks, evaporate formation environments, geomechanics of evaporite rocks, solution mining, and brine processing were included in this research. This work seeks to follow the research work previously carried out by Feijó [5] in order to make the exploitation of a new mineral body viable of potassium salt.

## 2. Methods

This study involved a technical–scientific partnership between the Federal University of Minas Gerais, and National Agency of Petroleum, Natural Gas and Biofuels (ANP) with the latter providing technical data acquired from wells drilled by oil companies.

The geological, seismic, and petrophysical data used in this study were as follows:

- Regional-level geological data from the oil and gas industry.
- Three-dimensional (3D) and two-dimensional seismic data, namely 0223_BAIXO_MOSQUEIRO_5A and 0068_SERGIPE _ALAGOAS_4[a], respectively.

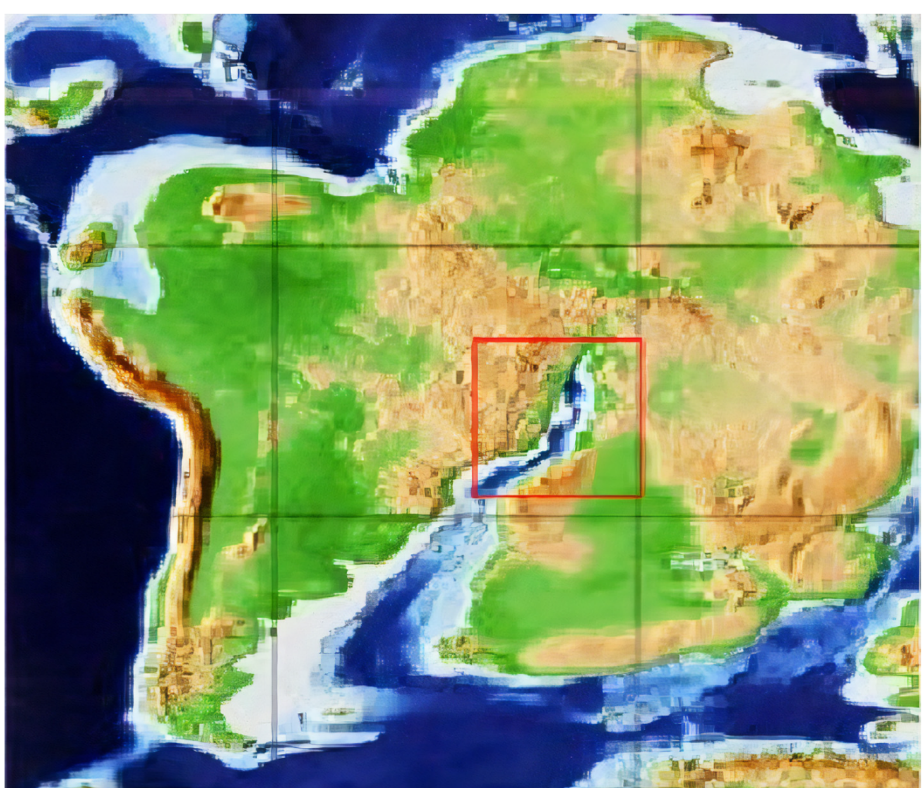

**Fig. 1 – Rift at the beginning of the continental opening. Source: Feijó [6].**

- Lithological profiles of the drill holes in the region, showing the anomalies and descriptions of the drill cutting samples.
- Petrophysical curves, namely sonic speed (DT), gamma ray (GR), and density (RHOB) curves.

This work started from CPRM's mapping of some potassium anomalies in the area; however, the institution cannot provide the source of the data and study associated with the mapping. Thus, the information obtained from CPRM was only used to initiate the present study, while the existence or absence of the mapped anomalies remains uncertain. The obtained data were used to develop a simplified geological model using the software Kingdom, DUG, Micromine, and AutoCAD. The correlation of the seismic, geophysical profiling, and drill cutting samples was conducted using a step-by-step process using the Kingdom software, as shown in Fig. 2.

The acquisition of seismic data on the high seas involves the use of equipment with cables (streamers), hydrophones, geophones, and receivers positioned at varying depths to acquire data with a higher frequency and resolution. Subsequently, the acquired seismic data are processed and prepared and are referred to as post-stacks. Using the post-stack data, the interpreter constructs their model using previous geological–structural knowledge of the area. In this study, Kingdom and DUG software were used for the modeling. The post-stack data was used together with the data acquired from the drill holes (e.g., tops and geophysical profiles) to generate the formation tops and horizons. Finally, the generated formation tops and horizons were used to construct a geological model.

Using the Micromine software, the interpreted seismic lines were transformed into horizons at the top and bottom of the Ibura geological unit. Owing to the low resolutions of the seismic data at depths of 2500 and 3500 m in bodies with a thickness of 1–10 m, it is not possible to map the potassium salt bodies only. Conversely, because the geological unit had a thickness of 100–420 m in the same region, its mapping could be easily performed.

## 3. Discussions

The mechanical behaviors of rocks should be examined for studies on the technical feasibility of mineral exploitation. Further, this is important for evaporites because their geomechanical behavior cannot be explained by elastic models proposed for other rock types.

From a geomechanical viewpoint [8], saline rocks in the field are highly ductile and exhibit a viscoplastic behavior. They have a relatively low resistance, and exhibit properties in the transition area between soft and hard rocks. In addition, they exhibit high mobility due to their viscous behavior.

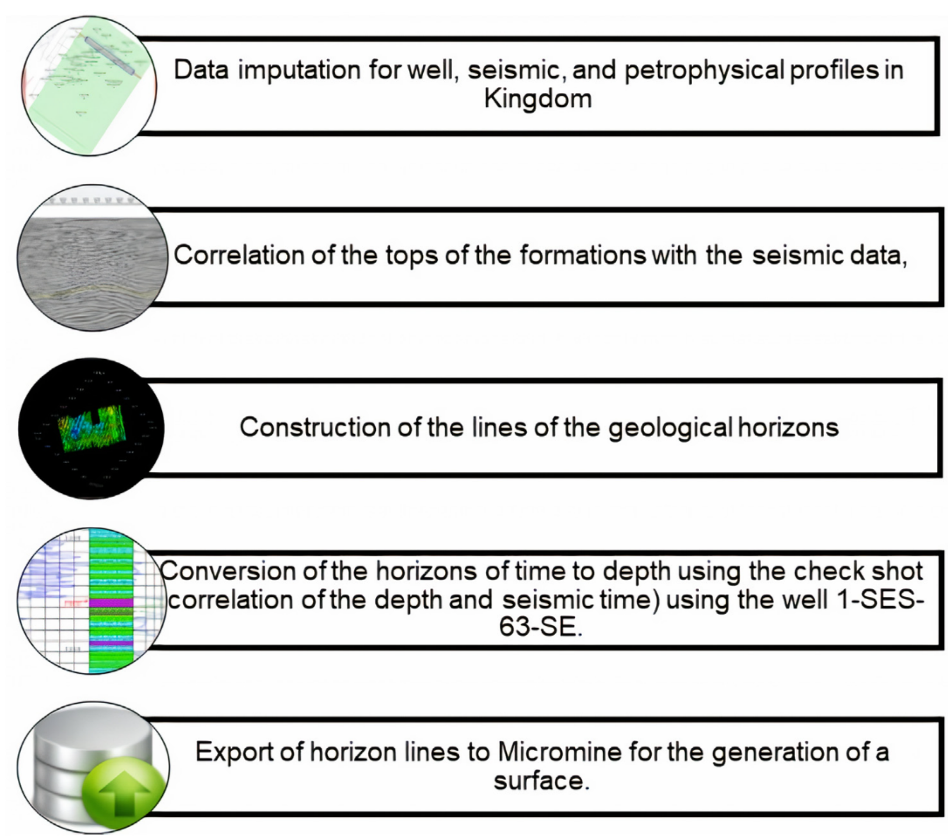


**Fig. 2 – Step-by-step data correlation process using the Kingdom software.**

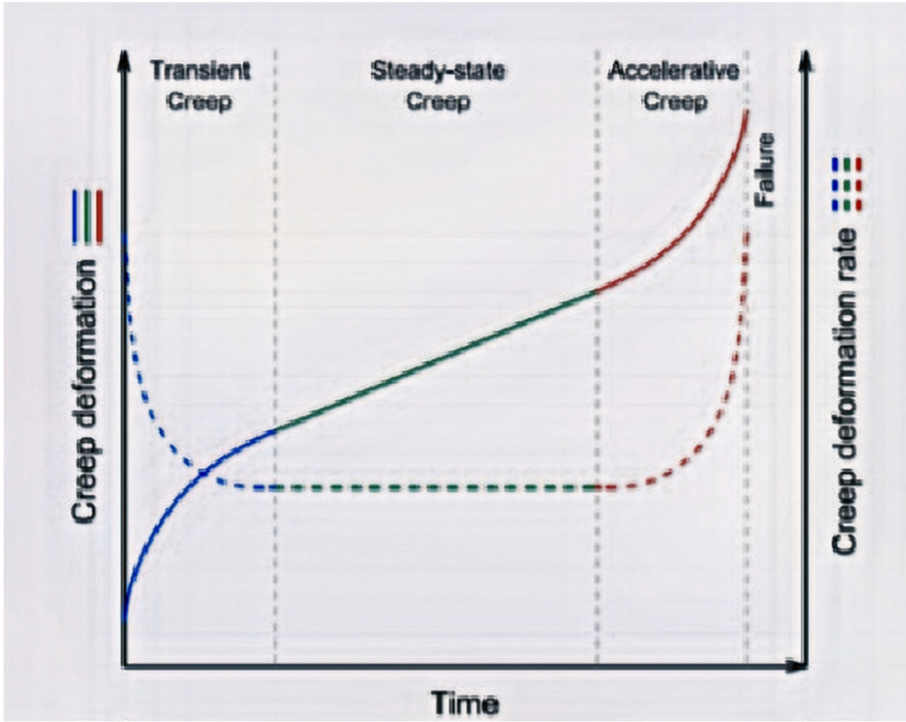


**Fig. 3 — Generic creep curve and deformation rate. Source: Pinto [9].**

The creep phenomenon of saline rocks involves progressive viscoplastic deformation under constant stress and elevated temperatures. According to Baar [8], in situ saline rocks are elasto–viscoplastic and highly ductile. This causes viscoplastic deformation by creep until a new deformability limit is established. Depending on the deformation level and duration, cracking damage may occur. According to Pinto [9], the positive and 3D von Mises stress is used in the equations for analyzing mechanical creep.

Based on the well-known solution mining technique, the high solubility of saline rocks in water is another notable parameter that is fundamental to the new evaporite mining method proposed in this article. When a drill hole, tunnel, or gallery is dug in a saline material by removing the material, the surrounding rock is not confined. Hence, there are changes in the state of tension of the bedrock, thereby triggering creep. Although creep cannot be controlled, it can be managed, implying that structures are dimensioned for work under creep's effects. Hence, even with the fluidity of the material during the useful life of the structure, the risks are minimized.

Creep phenomenon is traditionally represented by three phases: primary creep (transient creep), secondary creep (stationary, permanent, or steady state creep), and tertiary (accelerative creep) (Fig. 3). There are several physical creep mechanisms that explain the behavior of saline materials. However, the pressure and temperature conditions normally observed in evaporite excavations occur in regions with no defined physical deformation mechanisms. Nevertheless, several empirical equations have been proposed for the deformations observed under these conditions [10].

## 4. Results

### 4.1. *Petrophysics of evaporites*

The present study focused on three petrophysical parameters: GR, RHOB, and DT. In geological context, these parameters are briefly described as follows.

- According to Stevanato [11], the GR petrophysical curve represents the natural radioactivity emitted by unstable elements $^{238}U$, $^{232}Th$, and $^{4}K$, whereas the spectral profile of the GR represents the three radioactive elements separately.
- Stevanato [11] noted that the formation RHOB profile (density log) is a continuous record of the bulk density of the entire formation. Geologically, this is a function of the density of the rock-forming minerals, namely the matrix and fluid within the pores.
- The DT profile is used to calculate the porosity of the formation. In addition, it assists in the seismic interpretation by providing the speed range and profile, and can be calibrated based on the seismic section.

In the present study, the authors used the same principles described by Jackson et al. [12], in which GR, RHOB, and DT

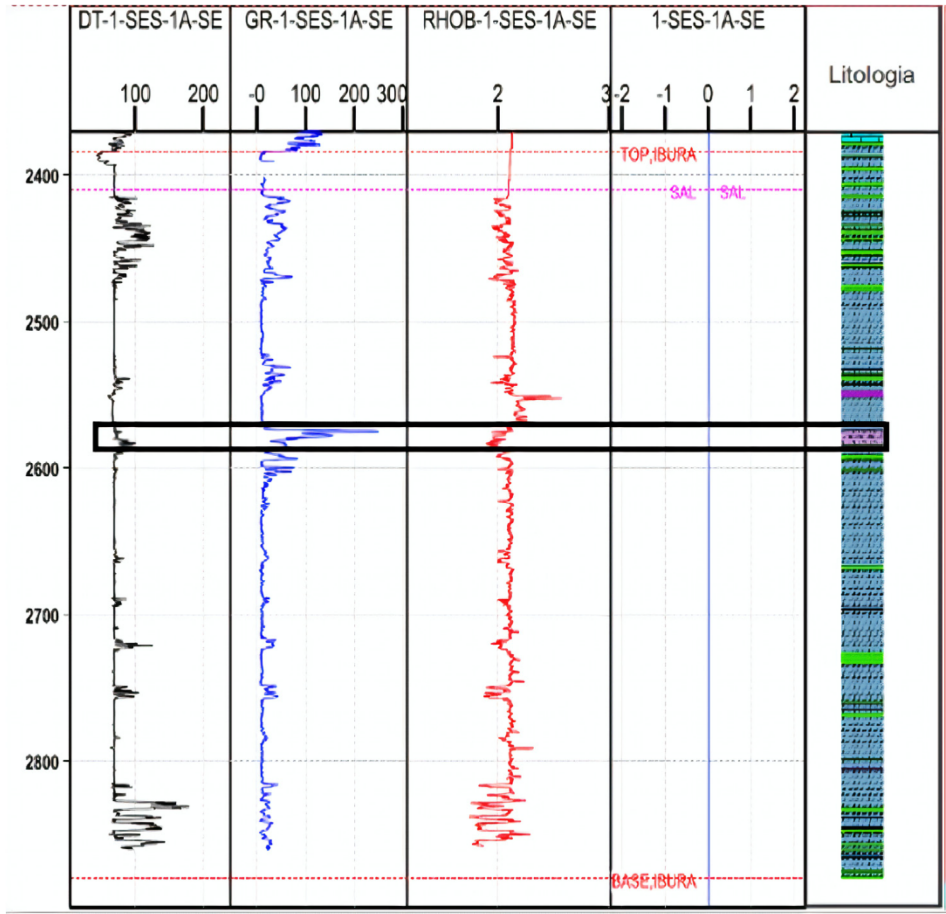


**Fig. 4 – Schematic profile of the drill hole 1-SES-1A-SE, showing the behavior of the sonic speed (DT). gamma ray (GR), and density (RHOB) curves in the presence of potassium salt bodies.**

were compared to distinguish potassium salts from other salts (Fig. 4). As shown in Fig. 4, a lower RHOB, higher DT, and stronger GR are observed in the profile regions where carnallite or sylvinite occurs. This can be attributed to lower density than other salts and the higher sonic speed and natural radioactivity of potassium salts. Thus, the combined use of these three parameters allows the improved distinction of potassium salts from other salts. Similar schemes were developed for drill holes 1-SES-3-SE and 1-SES-8-SE, which contain potassium salts.

### 4.2. *Geological model*

To construct the geological model, the interpreted lines of the 3D seismic data were imported into Micromine [13] and processed using the Kingdom software. In Micromine, the lines were interpolated using the least curvature algorithm, as described by Birhanu [14], which offers computational ease and a good illustration of the structural tendencies indicated by geophysics. Further, it considers the thickness of the layer in the geological model. The outputs of the process were the top and bottom of the Ibura geological unit, as illustrated in Fig. 5.

As most of the drillholes did not cut the Ibura geological unit containing the potassium salt, the control points, shown in Fig. 6, were used to create the top surface of the geological unit through the formula:

$$D_T = Z_S - Z_P \quad (1)$$

where $D_T$ is the distance to the top surface in meters, $Z_S$ is the Z coordinate of the hitting point on the surface, and $Z_P$ is the real Z coordinate of the point.

This algorithm is referred to as “thin plate”. The thin plate algorithm uses multi-square functions to interpolate the surface with the aid of the input information. The top and bottom surfaces were created by subtracting the seismic grid and $D_T$ grid. For each interpolated cell within the grid, the x and y coordinates of both surfaces (seismic and interpolated distance grid) coincided, with only the Z coordinate differing, as follows:

$$Z_R = Z_S - Z_T \quad (2)$$

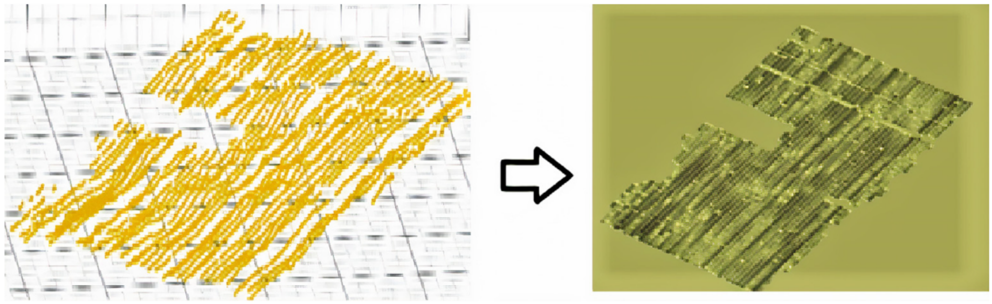

Fig. 5 — Top view of the seismic grid of the Ibura geological unit. Source: Nader/Micromine [15].

where $Z_R$ is the top Z coordinate of the resulting base, $Z_S$ is the Z coordinate of the seismic grid, and $Z_T$ is the Z coordinate of the distance grid. The results are shown in Fig. 7.

Using the top and bottom horizons of the Ibura geological unit, the maximum anomaly range was defined based on the holes that intercepted the unit, as indicated by the light blue lines in Fig. 8. Subsequently, a solid body was created between the top and bottom of the unit, and used to estimate the volume of the rock material in the geological unit.

### 4.3. *Estimation of the bulk volume*

The volumetric factor was determined by dividing the total thickness percentage of the saline layer corresponding to the potassium salts (no differentiation was made between sylvinite and carnallite in this study) by the total thickness of the saline layer in the composite profile of the three drill holes (1-SES-1A-SE, 1-SES-3-SE, and 1-SES-8-SE) that cut through the potassium salts Only the vertical variations were considered because these are more relevant in the volume estimation of sedimentary deposits [4]. The average volumetric factor was determined to be 2.728%, which represented the volume of the Ibura geological unit containing potassium ore. However, the potassium salt in the ore bodies should still be determined.

Based on the density of a pure salt consisting of carnallite and sylvite, and through abstraction, the main impurity in the potassium salts were determined to be halite, which has a similar solubility to and precipitates within almost the same time as potassium salts. The relative densities of these salts were used to estimate their contents in the present rocks with the aid of the RHOB curve. The percentages were then weighted to the thicknesses of the strata to obtain the average potassium salt content. The average content of potassium salts (sylvite or carnallite) after weighting by the thickness of the strata was 70.12%, implying that each body described as potassium salt based on the present methodology contains 29.88% halite and/or other impurities.

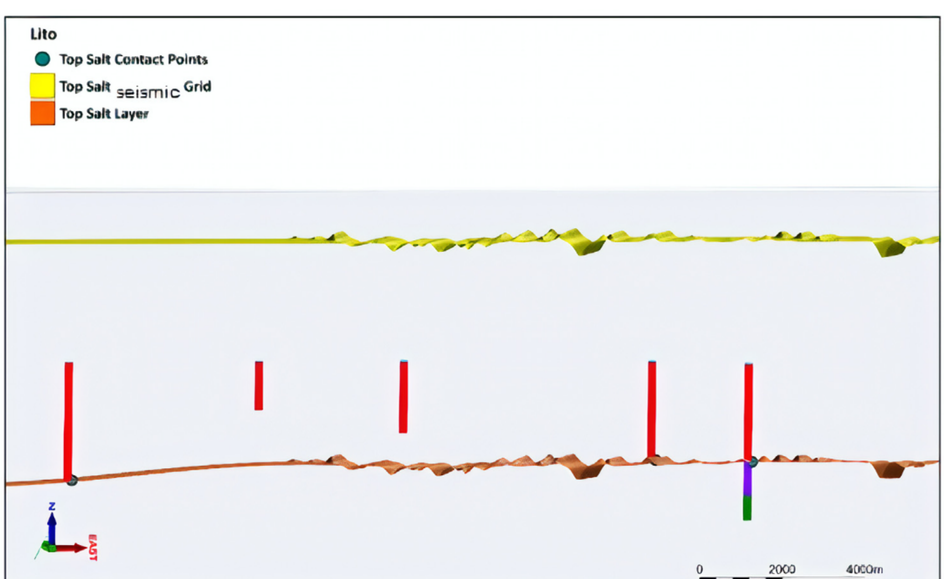


Fig. 6 — Seismic interpretation line of the top and bottom surfaces of the salt contact points. Source: Nader/Micromine [15].

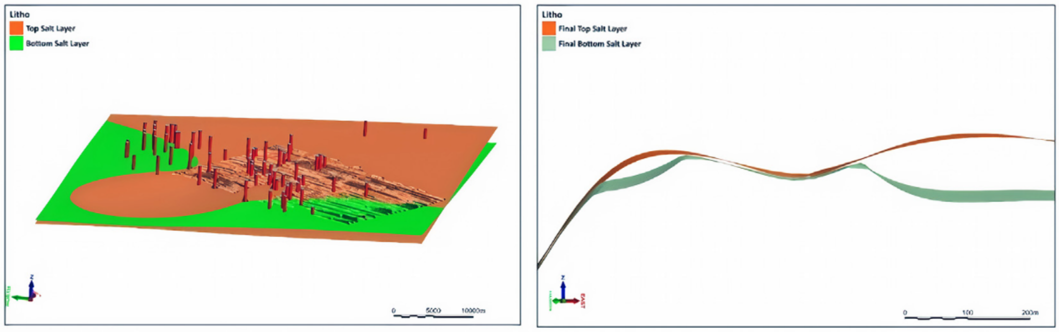


**Fig. 7 – Generated top and bottom profiles. Source: Nader/Micromine [15].**

Therefore, an initial resource estimate should be conducted using a volumetric factor of 2.728% and average potassium salt content of 70.12%. The formula used for this purpose is as follows:

$$V_{potassium} = V_{total} \times 2.728\% \times 70.12\%, \quad (3)$$

where $V_{potassium}$ is the volume of potassium in the mineral body ($m^3$) and $V_{total}$ is the total volume of the stratum, which is the volume of the Ibura geological unit exported from Micromine (100, 018, 165,754 $m^3$). The value of $V_{potassium}$ obtained in this study was 1,913, 221, 088 $m^3$, based on the weighted average density of the mineral body of 1.94 g/cm$^3$ (1.94 t/m$^3$). This indicates the potassium salt content of 3711.65 Mt in the body. The corresponding total amount of gangue minerals, mostly halite, that will be mined together with the ore was 815, 274, 474 $m^3$ or 1769.14 Mt.

### 4.4. *Drilling and drill hole completion for solution mining*

For the proposed new application of solution mining to seabed mining, a drilling technique known as directional drilling is used. According to the American Petroleum Institute [15], directional drilling can be defined as "the art and science that implies the intentional deviation of a hole in a specific direction in order to achieve a predetermined objective that is located underground." After building a drill hole, water is injected into it and then recovered. Salt is quickly dissolved by the water, and a large amount of salt can be produced from the saline dome or salt layer through the simple injection drill hole and another capture drill hole. The roof of the saline cavity dissolves significantly faster than the sidewalls, resulting in solution mining by forming a small cavity at the bottom of the evaporite zone.

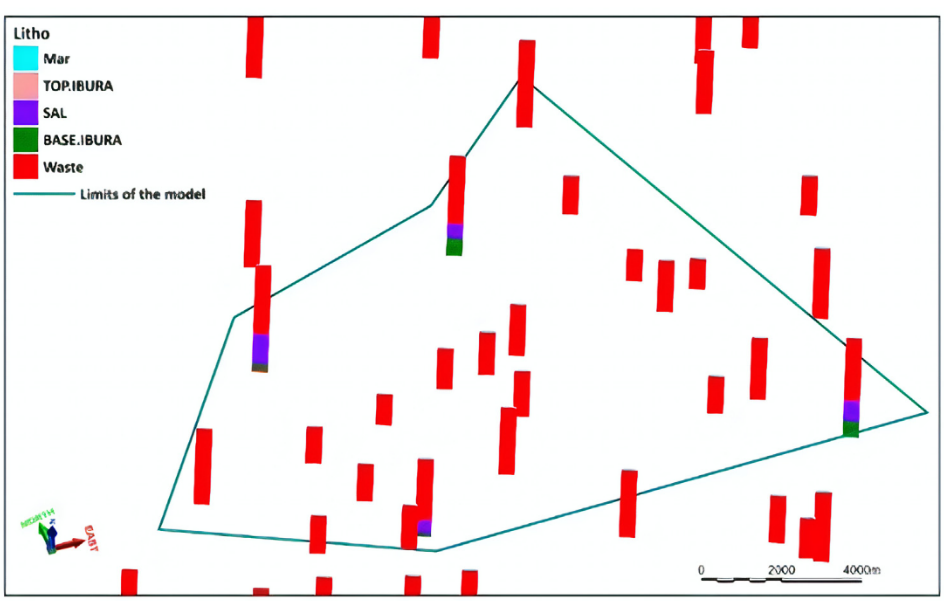


**Fig. 8 – Limits of the generated model for resource estimation, as indicated by the light blue lines. Source: Nader/Micromine [15].**

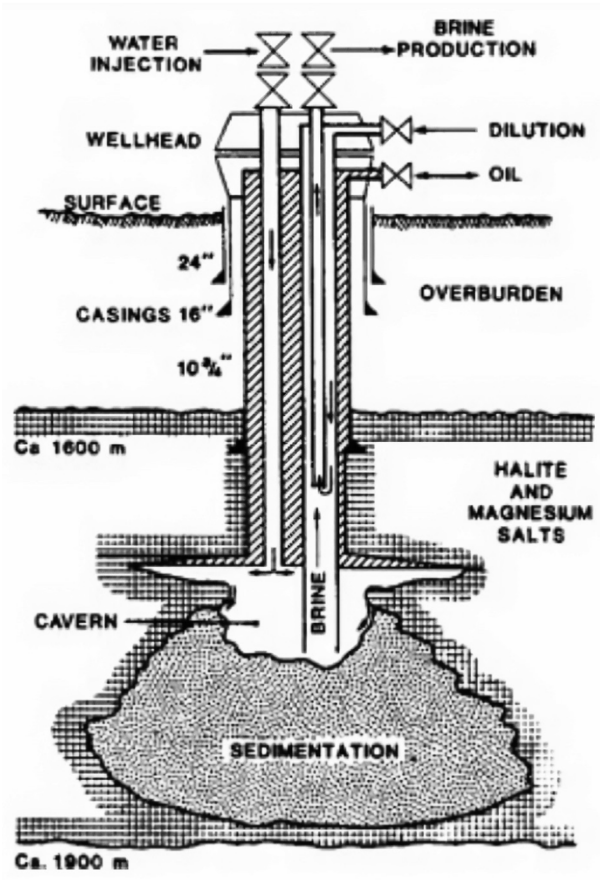


**Fig. 9 – Drill hole configuration for solution mining of impermeable salts. Source: Schlitt and Larson [16].**

The cavity subsequently expands and extends upward. This process separates the non-soluble minerals, which are usually anhydrite, thereby they remain at the bottom of the cavity. Because the generated sediments do not dissolve, they do not interrupt the mining process.

When using this method, the rise of the unsaturated brine through the drill hole above the cavity ceiling, which is the desirable for extraction horizon, should be prevented. This is achieved by using a less dense and immiscible blanket fluid, such as petroleum, diesel oil, and pressurized natural gas, which would remain above the brine layer to prevent its direct contact with the ceiling. An sample application of solution mining is illustrated in Fig. 9.

Water is injected into the drill hole and brine is extracted through separate tubes. A small amount of dilution water is added to the brine tube to prevent the freezing of the drill hole due to endothermic salt crystallization. A specific amount of oil is introduced through a fourth tube to avoid the contact of the brine with the rock layer above the salt formation of interest. The tube is gradually raised, resulting in the increase in the cut level of the saline layer and progression of the cavity. The size of the cavity is controlled considering the geomechanical factors of the salt layer to avoid the collapse of the cavity. The diameter of the cavity is usually limited to approximately 150 m. In addition, the pressure of the fluid in the saline cavity should be close to the local lithostatic pressure, rather than the hydrostatic pressure, to prevent collapse of the cavity.

### 4.5. *Mine layout*

Figure 10 shows the possible mine layouts. The figures were prepared using AutoCAD and the layouts assume a square area of 1 $km^2$. The two layouts with different hole spacings were compared in terms of recovery and number of total holes.

### 4.6. *Mining parameters*

The average volumetric recoveries for the cylindrical and elliptical stopes, that is, the function of the pillar size were 50.33% and 54.36%, respectively. The construction of long elliptical stopes requires directional drilling, which could increase the cost of the project. The average recovery gain of 4.03% could not compensate for the increased cost. Moreover, dilution is controlled by a blanket fluid and adjustment of the average brine content, which also makes the method selective.

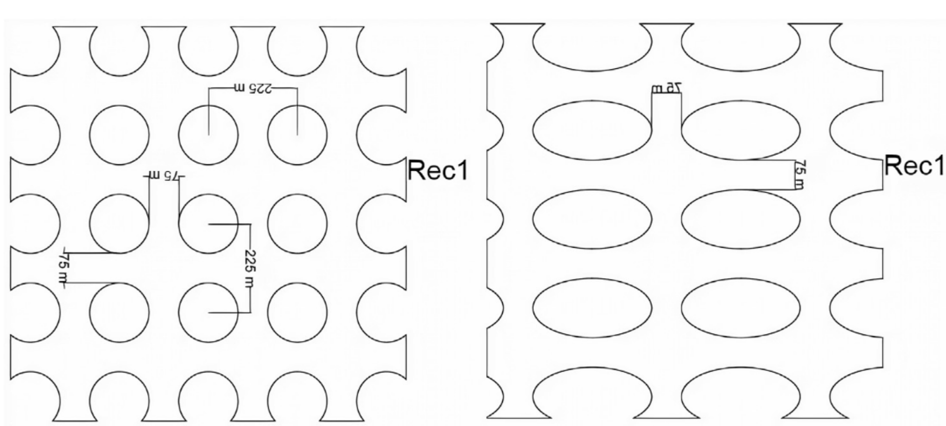


**Fig. 10 – Mine layouts with cylindrical and elliptical stopes. The models were obtained by varying the distance between the stopes, that is, pillar size.**

## 5. Conclusion

The objective of this work was to present solution mining as an economical alternative to conventional open and underground mining for the exploitation of mineral deposits. This involved the use of tools and data that are unfamiliar in the mining industry, such as seismic interpretation, petrophysics, and geological description of drill holes. Particularly, this study represents an innovation for the exploration of evaporites.

This work determined the average potassium salt content to be 70.12% and the total amount of potassium salt to be 1913.22 $Mm^3$ or 3711.65 Mt of the Ibura geological unit. For the mining design and parameters, the average recoveries for cylindrical and elliptical drill holes were 50.33% and 54.36%, respectively. The salt dilution was not analyzed because it is dependent on the rock morphology and mining method. Moreover, there are no dilution data found in the literature for similar situations as that of the present study.

From a technical viewpoint, the combined use of different surface fluid lifting techniques, such as gas injection and high-pressure pumping, may increase the recovery. However, pumping would also increase the operating cost. Further, as the use of either technique depends on the ore body morphology, a detailed investigation is necessary to determine their applicability to specific cases.

By establishing a new route for mineral research not only for potassium salts, but also a route applicable to any sedimentary rock using data and tools from the oil industry, it allows discovering new mineral deposits in a short period of time without wasting a large amount of amount of financial resources; assisting in the geological knowledge of Brazil. Furthermore, the study indicates an area with great potential for potassium salts, which if properly studied in detail could eventually become a mine.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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