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Assessing structural challenges in potash mining: Perspectives from Yara solution mining, Dallol Depression, Northern Afar, Ethiopia

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Abstract

The Dallol Depression, located in the northern Danakil Depression, has a complex geological history shaped by Afar rifting, containing approximately 1.7 km of evaporite deposits. These deposits, heavily influenced by volcanic activity and extensional tectonic faulting, exhibit significant structural variability. This research focuses on the potash-bearing section of the salt sequence, which consists of several distinct layers including the marker bed, sylvinite member, upper carnallitite member, bischofitite member, lower carnallitite member, and kainitite member. Employing satellite imagery (Landsat Thematic Mapper), geological and structural mapping, borehole data, and seismic analysis, this study characterizes the sub-surface features of the evaporites and estimates their reserves. The RockWorks software facilitated the development of a subsurface stratigraphic map and a three-dimensional fence diagram for enhanced interpretation. Seismic data indicate that while the upper layers of the evaporite deposits are largely horizontal and undeformed, deeper layers exhibit considerable tectonic disturbance. Thickness variations were observed, with evaporite and alluvial deposits being thinner at the southeastern rim and thicker in the eastern concession center. The total potash reserve is estimated at approximately 2.96 billion tons, of which 877.76 million tons (29.60%) remain unexploited. Current borehole designs restrict the company's extraction capacity to 24.64%. This study recommends revising mining strategies, incorporating updated borehole designs and advanced geophysical methods to improve potash recovery and promote sustainable practices in the Dallol region.

1. Introduction

The Danakil Depression, specifically, and the Afar Depression, generally, are regions where oceanic plate formation is progressing, marked by active volcanic activity and seafloor spreading [1]. The northern Afar depression, commonly referred to as the Danakil depression, was formed by oblique to orthogonal extensional tectonics, which resulted in a depression that was eventually filled with sediments and evaporite deposits. Huge deposits of potash, sulfur, manganese, and rock salt have been accumulated since the Miocene period, as well as epithermal gold within the Pliocene-Holocene volcanic rocks [2]. This region is strongly affected by volcanic activity and extensional tectonic faulting [3], resulting in the displacement and folding of stratigraphic units and affecting the deposit structure and homogeneity. The potash and sulfur deposits of the Danakil depression are the two resources that have been explored for the past 100 years. However, because of the low level of mining knowledge in the country and the hostile nature of the depression, these resources remained unexploited for almost a century. Extensive

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potash mineral deposits formed at various locations around the world during the Paleozoic and Mesozoic eras, due to the differing seawater chemistry compared to modern oceans [4]. Producing potash fertilizer, an essential macronutrient for plant growth and development is among the most significant economic activities [5].

To sustain most of the world's population, modern agricultural production heavily relies on the quantity and quality of chemical fertilizers required to enhance grain and horticultural yields [6]; [7]. Due to rising demand in Southeast Asia, potash production has increased by 9% during the last decade [8]. Growing production in China, Canada, Russia, and Belarus increased potash production worldwide. The need for fertilizer minerals like potash has risen due to a growing global population, shifting dietary patterns, and dwindling arable land [9]. This provides an opportunity to increase exploration and exploitation activities all over the globe. Potash solution mining is a method used to extract potassium salts from underground deposits, and it has become increasingly important in meeting global agricultural demands. It is one of the mega-project developmental activities in Ethiopia. The Yara Solution Mining Project, operated by Yara International, is a significant initiative in this region, aiming to harness the rich potash deposits. These deposits cover a total area of around 80 km^2 and aim to extract potash resources in the Musley Mining license area (MMLA, 10 km^2), Musley north exploration license area (MNELA, 20 km^2), and crescent exploration License area (CELA, 50 km^2) in the Dallol region.

The increasing demand for resources, driven by human needs and the pursuit of foreign investment, has attracted significant interest from mining companies in the Dallol depression. Favorable policies have further incentivized the exploration of this region, known for its immense potash reserves. However, solution mining in Dallol is confronted with substantial structural and environmental challenges. Key issues include geological instability such as faults, as well as the movement of high-temperature hydrothermal fluids through evaporite deposits, extreme heat, and logistical constraints associated with the harsh environment. Addressing these challenges is critical to ensuring the success and sustainability of potash extraction operations. This study assesses structural challenges such as faults that pose significant risks to solution mining operations.

These challenges can lead to operational inefficiencies, instability, and leakage, threatening both productivity and safety. The study proposes mitigation strategies that include advanced geological mapping, real-time monitoring systems, and the use of engineered barriers to counteract structural disruptions. These measures aim to enhance mining efficiency, while ensuring long-term safety in a geologically active and environmentally demanding setting. Existing research on tectonic and volcanic processes in the Dallol area provides essential context, highlighting the complex interplay between tectonic activity, rifting, and hydrothermal processes that have shaped the region. This dynamic environment features extensive fault networks, salt domes, and significant thermal instability, presenting unique challenges for mining. Incorporating these insights into mining strategies strengthens the geological foundation needed for sustainable operations. Additionally, a historical perspective on challenges in the Danakil Depression—such as extreme salinity, high temperatures, and ground instability—underscores the importance of resilient and adaptive approaches to mining in this unique setting. By addressing these issues, this study contributes to the advancement of safer, more efficient, and sustainable potash extraction practices in the region.

2. Tectonic Setting and Regional Geology

2.1. East African rift system

The largest active continental rift on Earth [10], which illustrates the early stage of continental plate fragmentation [11] consists of several extensional basins, two large plateaus, and numerous volcanic formations of varying spatial extent [12]. According to [13], [14], [15], [16,17] and other sources, the EARS is a tectonic structure confined to the African continental lithosphere, consisting of two branches: East and West, along with an emerging South-West continuity through the Okavango rift zone. Stretching roughly 4000 km from the southern Red Sea in the north, the East African Rift System (EARS) is a remarkable tectonic phenomenon on Earth. It passes through the Afar Depression, the Kenyan Rift, and ends in central Mozambique [18], and references therein. The evolution of the East African Rift System (EARS) is a narrow, deep rift in regions with weak lithospheres, like the Main Ethiopian Rift, and a wide, diffused rift in areas with cold cratons, like the Kenyan Rifts, suggests that pre-rift deformation features that are inherent to the region, rather than rheological layering, maybe the primary control on the architecture of extension in these continental rifts [19]. According to [1], and references therein, the EARS covers a wide range of rift evolution, from strongly magmatic rift segments in the Afar Depression (incipient seafloor spreading) to partly magmatic rift segments in Tanzania (a less evolved rift segment).

2.2. Afar depression

The Afar depression is part of and genetically linked to the entire Afro-Arabian rift system. It is a unique location on Earth, where active rift processes can be directly observed, and it is nearly on the verge of continental breakup [20]. The Red Sea, the Gulf of Aden, and the main Ethiopian rift radiate from the Afar depression, an area of active extensional deformation and basaltic volcanism. The Afar depression displays three structurally distinct trends in terms of geometry: (1) a NNW trend that aligns with the Red Sea rift; (2) an almost E-W trend, extending from the Aden Gulf onto the land; and (3) an NNE trend observed in the main Ethiopian rift. At the triple junction of the Nubian, Somali, and Arabian plates, situated atop the developing Danakil microplate that is driving the continental breakup of Africa, lies the Afar Depression, an incipient seafloor-spreading center (e.g. [21]; [22]; [23]; [3]; [24]; [25]). The main Ethiopian rift funnels out and merges with the central Afar depression, known as the Afar triangle [26]. The Gulf of Aden, the Red Sea, and the Ethiopian rift systems radiate from the Afar triangle, a region characterized by active extensional tectonics and basaltic magmatism.

At the western edge of the rift, Neoproterozoic basement rocks, mainly of the meta-volcanic and meta-sedimentary types, are exposed, outlining the region's geological setting [1]. The deposition of shallow-water limestones, marine clays, and evaporites suggests that marine environments once covered a significant portion of the Danakil Depression for at least some of the Miocene.

2.3. Danakil depression

One of the world- class examples of active rifting and the birth of a new ocean is the Danakil depression, which is situated in the northern section of the Afar rift [27]. The geological history of the Danakil depression is linked to the rifting processes of the Afar-region and thus strongly influenced by volcanic activity and extensional tectonic faulting [3], leading to the displacement and folding of stratigraphic units. The approximately 300 km-wide Afar depression [28] merges southward with the NE striking main Ethiopian rift and eastward with the ENE striking Gulf of Aden, bordered by the Ethiopian Plateau to the west [3]. The Danakil Depression, with an average elevation of 200 m, is characterized by axial volcanic ranges [1], followed by a thick pile of evaporate deposits. The Danakil (or Danakhil) depression, located in the northern region of the Afar depression (also referred to as the Afar triangle), is well-known for its natural resources, which are mostly salt rocks including potash, sulfur, manganese, bentonite, gold, and light and heavy hydrocarbon deposits [29], and for its potentially advantageous geothermal energy sources ([30]; [31]; [32,33]).

A salt pan known as the Dallol salt flat [34] dominates the northern side of the Danakil depression. It is the deepest portion of the depression, reaching a depth of 120 meters below sea level. The basin is infilled with a series of Quaternary evaporites that may underlie the depression and is covered by volcanic successions in the southern part [27]. The majority of geophysical surveys and drilling operations have taken place in the northwestern region, close to Mount Dallol, where economically viable potash deposits two thick halite layers, the lower and upper rock salt formations, are separated by the potash-bearing Houston formation. The sequences of kainitite, carnallite, bishofite, and sylvinite complete the succession of evaporites, which is at least 970 m thick. Their depth varies from 38 to 190 meters near Dallol are found [35], and from 683 to 930 meters to the east [36]. The Danakil depression, or Danakil Graben, runs NNW-SSE with an extension of more than 200 km from Lake Badda in the north to Lake Acori in the southeast [37].

2.4. Geology of the Dallol area

The studied area, Dallol potash deposit is found in the northern Danakil depression, a salt-encrusted desert area in northern Ethiopia, close to the Eritrean border (Figure 1).

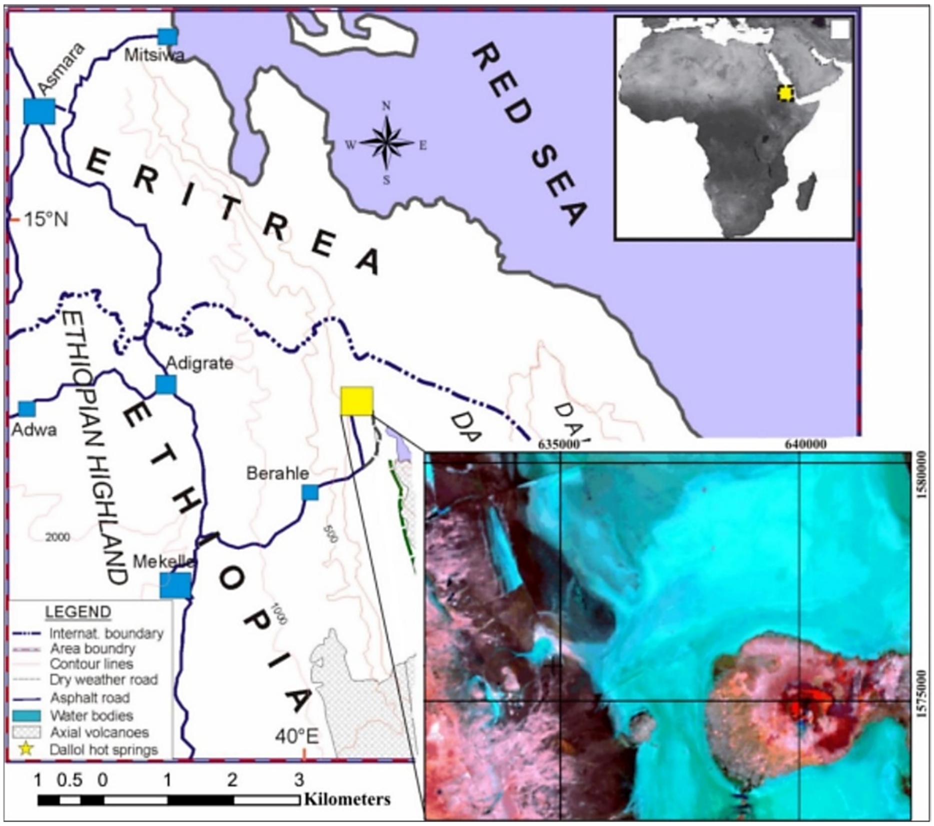

Figure 1. Location map of the studied area with reference to Africa and the Middle East. The composite satellite map represents the studied area.

The surface geology of the studied area is characterized by: (1) lower sandstone "Adigrat sandstone unit", (2) carbonate rocks "Antalo limestone unit", (3) volcanic rocks, (4) evaporates, and young sediment deposits, which consist of mainly salt deposits (halite and potash), mud, and sulfur, especially on Mount Dallol and its vicinities, and (5) gently dipping quaternary alluvial deposits from older to younger (Figure 2). The entire succession of Mesozoic sedimentary strata covers the western edge of the Afar depression. The Mekelle-Wukro outlier contains a portion of the Mesozoic succession that is down-thrown by 2000 m to the Afar depression. In most of the outcrops, the blocks show flexural slip faulting and folding. In general, the rocks are tilted by ~35^0 towards the east.

2.5. Sub-surface geology of evaporite deposits

The sub-surface geology of the evaporites is highly complicated and variable. Drilling and geophysical explorations indicate that the maximum thickness of the evaporate formation exceeds 1400 m. The potash-bearing section of the salt sequence (Houston formation), directly underlain by the lower rock salt and overlain by the clastic overburden and upper rock salt, consist of marker beds, sylvinite, upper carnallite, bischofitite, lower carnallite, and kainitite from top to bottom (Figures 4, 5, and 6).

3. Methods

Digital image processing techniques were employed to create base maps as well as detailed surface geological and structural maps of the Dallol region. Enhanced thematic satellite imagery facilitated the identification of tectonic lineaments and other significant geological features. To model the subsurface, data from five seismic profiles and sixteen boreholes were analyzed, enabling the mapping of potash horizon continuity across the Dallol area and revealing the structural framework of the deposit. The study extensively utilized Rockworks, ArcGIS, and the CorelDraw software for data acquisition, processing, and visualization.

The processing of borehole data and seismic profiles followed a rigorous methodology:

1. Data Input and sub-surface modeling**:** Borehole parameters including depth, thickness, elevation, easting, northing, and inclination were entered into Rockworks to model the subsurface geology of the evaporite deposits.

2. Visualization and Geological mapping**:** The input data facilitated the generation of outputs such as lithological and stratigraphic logs, geological maps, cross-sections, borehole location maps, 3D models, and fence diagrams for the concession area.
3. Seismic data integration**:** Seismic profiles were analyzed to trace sub-surface structures, which were then overlaid onto geological cross-sections associated with specific boreholes.
4. Composite Structural Mapping**:** Using CorelDraw, sub-surface structural maps were produced by integrating geological and seismic data, ensuring an accurate depiction of stratigraphic and structural elements.
5. Sub-division of concession areas**:** The three concession polygons (MMLA, MNELA, and CELA) were sub-divided into smaller polygons using the nearest neighbor method in ArcGIS based on borehole locations. The area of each polygon was calculated using the same software.
6. Reserve estimation**:** Potash reserves and fault-bounded potash blocks were quantified using the formula:

$$Reserves = A \times T \times D \times F$$

where, A is the area, T is the thickness, D is the density, and F is the grade factor, as outlined by [38].

This comprehensive methodology allowed for the accurate characterization of the structural and stratigraphic framework of the Dallol region. By integrating seismic, borehole, and satellite data, the study provided critical insights into the geological continuity of potash deposits, paving the way for more efficient and sustainable mining strategies.

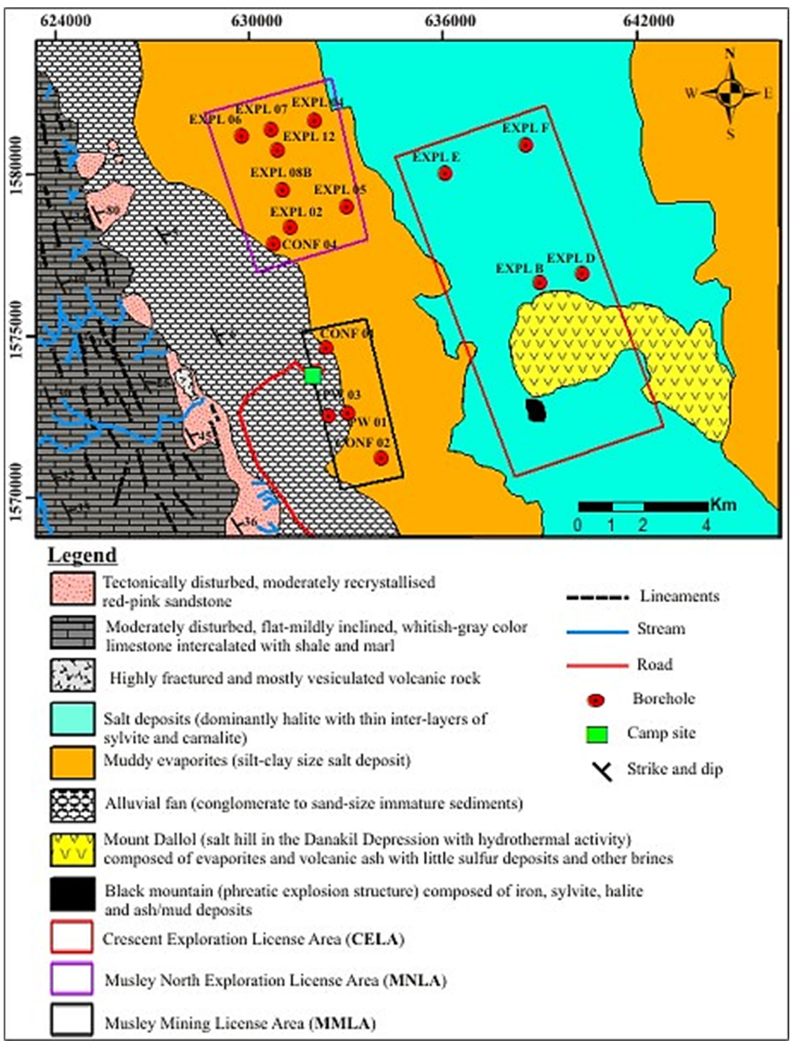

Figure 2. Geological map of the Dallol area prepared based on field observation and interpretation of Landsat -5 ETM^{+}.

4. Results

4.1. Geophysical Profile

In total, twelve seismic profiles of approximately 90 km were completed by the company through the use of vibriosis as an energy source, but seven of them are used for this study. The general orientation of the rift axis is the NNW-SSE direction, and most of the seismic profiles are running orthogonal to the rift axis. The results of the interpreted seismic sections in correlation with the borehole data and subsurface geological maps generated from the selected borehole data were exemplarily shown in Figures 9 and 10.

4.2. Sub-surface structures of studied area

The Dallol depression is one of the tectonically active areas of the East African rift system that is rapidly expanding. Consequently, the extensional structures extensively dissect the Dallol evaporite deposits. Understanding the nature of geological structures is one of the most important parameters in determining the overall behavior of potash deposits and production. The presence of geological structures such as faults or related geologic features may lead to shifts in the potash beds. By carefully investigating the geological data, it is often possible to explain and trace the density and location/orientation of the faults within the potash deposits.

Major fault structures have been identified in the seismic sections, but plentiful localized smaller-scale faults are present, mainly in the MNELA and CELA seismic sections (Figures 9 and 10). The dominant tectonic structure within the studied area are the major fault zones identified from the 2D seismic survey and anomalous deposit development that separates a relatively shallow Houston formation of the graben shoulder (Musley mining license area and Musley north exploration license area) from a deep Houston formation in the graben center (crescent exploration license area), visible also in the seismic cross sections (Figure 9 and 10). Based on the seismic sections and the anomalous deposit development, the NNW-SSE strike typical for the graben structure faults has been recognized.

4.3. Borehole results

In total, sixteen drill hole data points, along with a seismic profile, were utilized in this study (Figure 3). However, three boreholes, PW 03 found at a shallow depth, EXPL 04 found at an intermediate depth, and EXPL D found at a higher depth, were selected to represent all the boreholes.

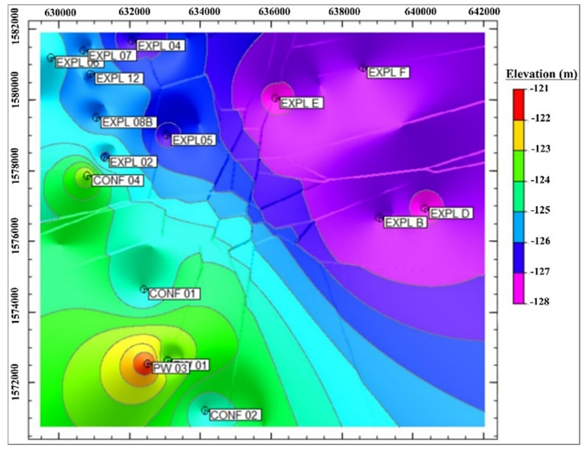

Figure 3. 2D borehole location map of the concession areas, most of the boreholes are concentrated on the northwestern part of the mapped area.

4.3.1. Borehole PW 03

The borehole was drilled to a depth of 59.6 meters at 90^0 inclinations, where the deposit was found at shallow depths. According to the lithological description of the hole, the encountered rocks were identified as clastic overburden, upper rock salt, marker beds, sylvinite member, kainitite member, and the upper lower rock salt layers (Figure 4).

4.3.2. Borehole EXPL04

The borehole was drilled to a depth of 480.1 meters at 90^0 inclinations, where the deposit was found at intermediate depth. According to the lithological description in the hole, the encountered rocks were identified as clastic overburden, upper rock salt, marker beds, sylvinite member, upper carnallite, bischofitite, lower carnallite, and the kainitite member (Figure 5).

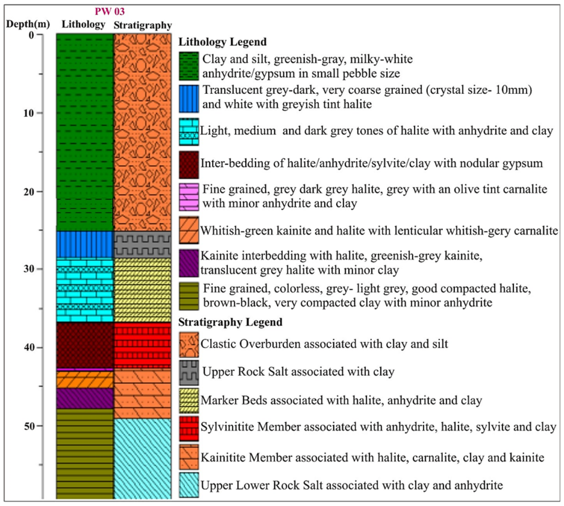

Figure 4. Lithological and stratigraphical column for borehole log PW 03.

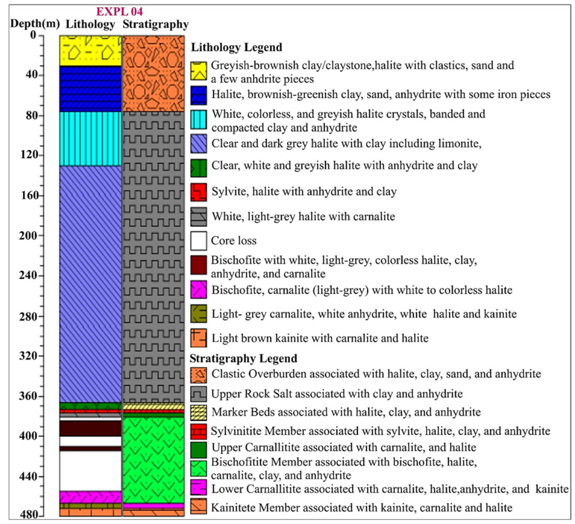

Figure 5. Lithological and stratigraphical column for borehole log EXPL 04.

4.3.3. Borehole EXPL D

The borehole was drilled to a depth of 804.6 meters at 90^0 inclinations, where the deposit was found at a higher depth According to the lithological description in the hole, the encountered rocks were identified as clastic overburden, upper rock salt, marker beds, sylvinite member, upper carnallitite, lower carnallitite, kainitite member, upper lower rock salt, and the lower lower rock salt (Figure 6). The thickness of the sylvinite layer is not more than 1m.

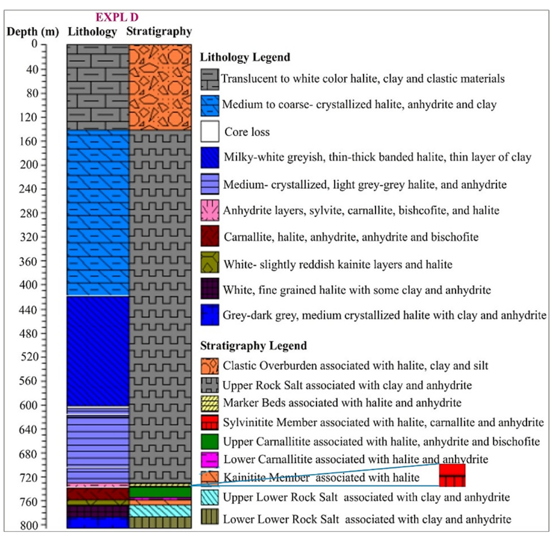

Figure 6. Lithological and stratigraphical column for borehole log EXPL D.

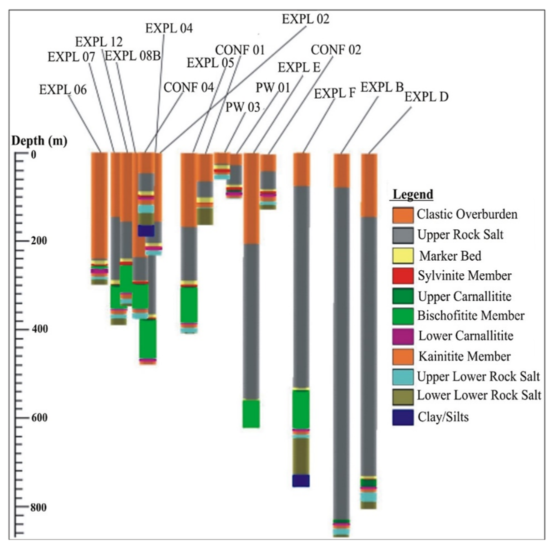

Figure 7. 3D view of the multiple logs of all boreholes of the area. The borehole log was prepared using Rock Works 15 Software.

4.4. Construction of fence diagram

At this level of analysis, it has been tried to understand the 3D model of the evaporite-bearing zones of the Dallol Depression. The fence diagram below is constructed based on eight borehole logs. This diagram helps to give clues about the lateral and temporal variations of the deposits since they are not homogeneous throughout the concession areas. From the boundary fence diagram (Figure 8b), thick deposits of alluvial sediments are found on the peripheral part of the depression, and thick deposits of upper rock salt, and bischofitite towards the rift axis. The general shallowing of the potash-bearing layers is found towards, the southwestern part of the concession area (Figure 8b).

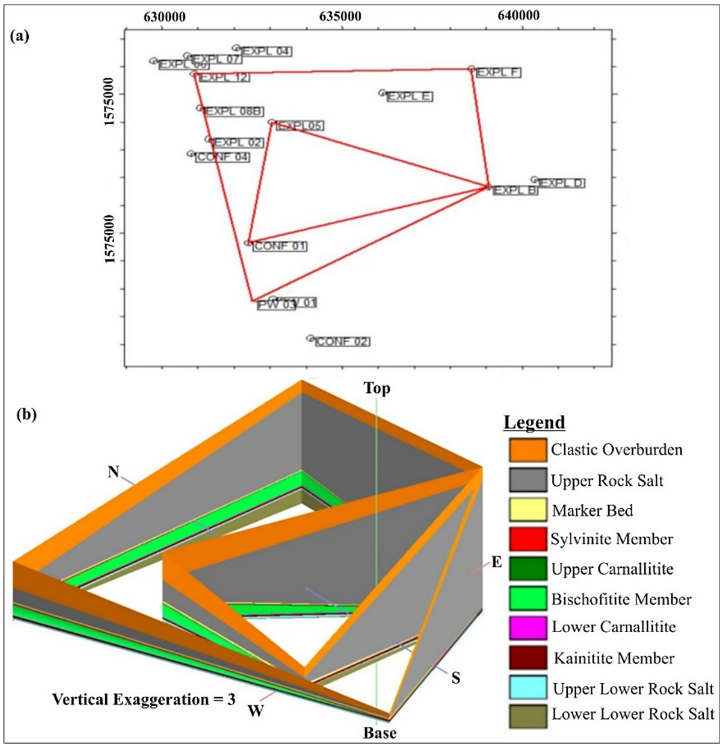

Figure 8. 3D fence diagram illustrating stratigraphic layers with a reference map showing the locations of the fence panels above (a).

4.5. Overlay analysis of geophysical and borehole data

Seismic imaging is a top technique for visualizing layered features in subsurface formations, widely used in various exploration activities. In total, seven seismic profiles were conducted, but five representative profile sections have been analyzed and interpreted for this study along with the borehole log data. Out of the five representative profile sections (CONF 01-EXPL D, CONF 04-EXPL F, EXPL 06-EXPL 04, EXPL 07-CONF 02, and PW 03-PW 01) combined with borehole data, two illustrative profile sections (CONF 01-EXPL D and CONF 04-EXPL F) were presented in this paper. The maximum depth of the seismic profile reaches 1750 meters, while the borehole depth is limited to 867.60 meters in the upper layer, with the analysis focused on their intersection. This helped to understand the intensity and geometry of faults and the nature or shape of the horizontally-laying evaporite deposits. Along each profile section, a minimum of two and a maximum of six boreholes were drilled, and this overlap helps in understanding the overall subsurface characteristics of the area.

As it is interpreted in Figure 9, the continuity of the potash-bearing layers is interrupted by six visible faults forming seven independent blocks. These blocks vary in size and depth down warping towards the east. Among the seven blocks, three of them (areas 1, 2, and 3) do not have any connection with the boreholes and this will have a negative impact during extraction of the deposits.

Similarly, as shown in Figure 10, the continuity of the potash-bearing layers is disrupted by ten visible faults, creating fourteen separate blocks. Among the fourteen blocks, six of them (areas 1, 2, 3, 4, 5, and 6) lack any connection to the boreholes, which will adversely affect the extraction of the deposits.

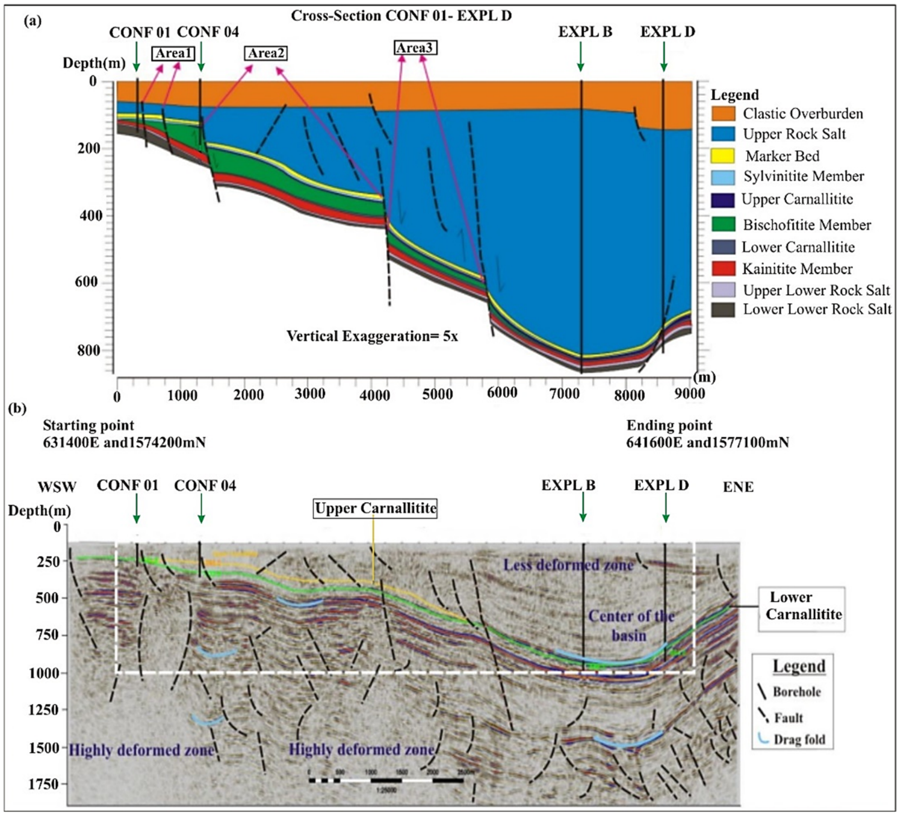

Figure 9. (a) Cross-section from borehole CONF 01 to EXPL D shows the subsurface geological distribution, continuity, demarcation of the overburden, inter-burden and potash zones, and subsurface structures traced from the seismic data survey provided. (b) A seismic data survey taken along WSW- ENE of the Dallol Depression that detected up to 1750 m below surface with many sub-surface structures and four drilled boreholes (CONF 01, CONF 04, EXPL B, and EXPL D).

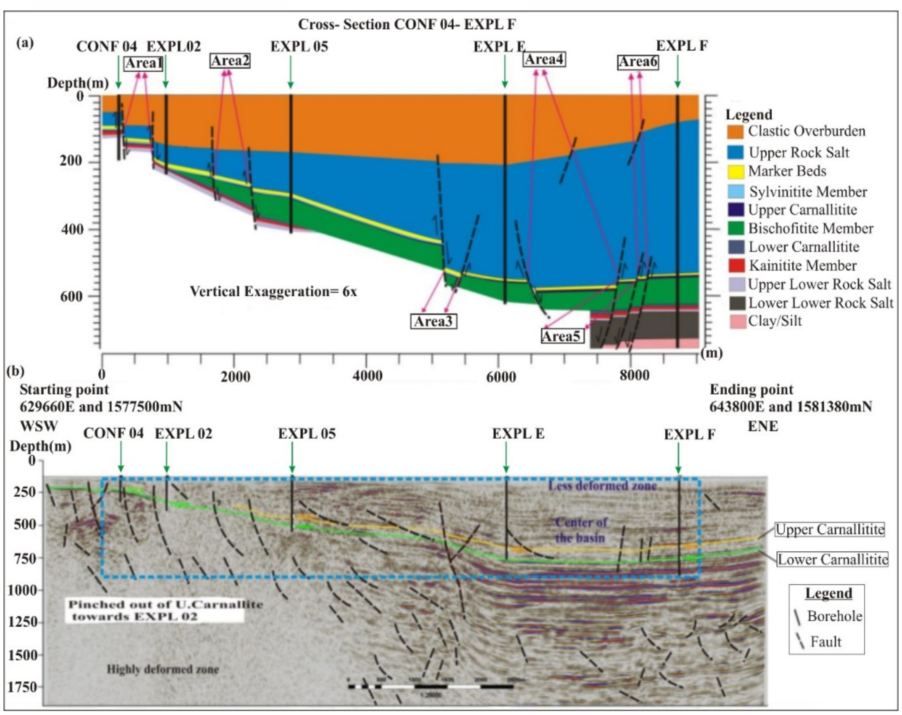

Figure 10. (a) Cross-section from borehole CONF 04 to EXPL F shows the sub-surface geological distribution, continuity, nature of the overburden, inter-burden and potash zones, and sub-surface structures traced from the seismic data survey. (b) A seismic data survey taken along WSW-ENE of the Dallol depression that detected up to 1750 m below surface with many sub-surface structures and five drilled boreholes (CONF 04, EXPL 02, EXPL 05, EXPL E, and EXPL F).

5. Discussion

One of the most volcanically and tectonically active regions on Earth is the northern Afar depression (Danakil depression), which is located at the nucleus of the great east African rift system [1]. It is a site of volcanism, tectonism, and sedimentation. The Danakil Depression is connected to the rifting processes of the Afar-Depression and therefore, is strongly affected by volcanic activity and extensional tectonics [3], resulting in displacement and folding of stratigraphic units. Lower Miocene to Lower Pliocene (≈20 Ma to □≈5 Ma) syn-rift Red-bed Series sandstones and shales were deposited in a newly forming basin in the Dallol Depression, the northern segment of the Danakil Depression [39].

The Neoproterozoic basement complex, Mesozoic sedimentary succession, and thick Miocene to Quaternary evaporite deposits make up the Afar depression/Dallol area [39]. [39] State that marine clays, limestones, and thick evaporite deposits show that Sea water inundated the Dallol depression in the early Miocene and that the majority of the northern graben submerged below sea level for at least a portion of the Miocene. Though the mode of formation of the depression is not well constrained, from field observations and geophysical measurements, the Danakil depression is the result of dynamic effects strongly supported by both asthenospheric flow and mantle convection. Tectonic grabens such as the Danakil depression, are found 100-125 meters below sea level.

This graben covers the concession area, which comprises salt flats with alluvial fan deposits along the western edge. There are potash deposits in the concession area, according to historical data. The geological condition of the Danakil depression is closely linked to the active rifting process and tectonic faulting, which essentially opens the graben structure, a process that is still ongoing. As a result, the deposit's location in a volcano-tectonically active zone hinders the development of mining in the area. The deposit structure, homogeneity, and continuity of the deposit is strongly affecting by this geological setting.

The potash deposit occurs within this graben in a stratigraphic layer known as the Houston formation, which consists of the mineralized layers sylvinite, upper/lower carnallitite, and kainitite. And hence, mining in such areas needs a detailed understanding of the subsurface geological conditions, and based on that the mining design should be determined. This research work, therefore, focuses on assessing the impact of subsurface structures on deposit structures and solution mining and recommends redesigning the company's current mining design. From the overall analysis, it has been assessed that most of the potash mining companies (Allana Potash/Israel Chemicals Limited, Yara Potash, and Circum Minerals) did not take into account the impact of subsurface structures, which could lead to a significant reduction in potash production. Potash is a multi-mineral deposit. As a result of the strong global demand for potash raw materials, Yara Potash plans to extract sylvinite, carnallitite, and kainitite mineral deposits in their concession areas using solution mining.

The geological, structural, geochemical, and geophysical results, combined with the existing data, have contributed to refining the mining design in the area and understanding to some extent the evolutionary history of the Dallol Depression evaporite deposits. At this level of investigation, borehole, structural, and geophysical data were collected and analyzed to evaluate the structural challenges faced during potash solution mining in the Dallol area.

5.1. Estimation of Potash reserves

Reserve estimation is a vital part of geological exploration, providing the basis for evaluating the economic viability of mineral deposits. Estimates often require recalibration during mining phases as new data refine resource strategies and mining designs. According to Wood et al. (1983), reserve estimation relies on three key parameters: area, thickness, and average ore density. This study employed the RockWorks software, chosen for its suitability for stratabound deposits like potash, to perform geological analyses and visualize subsurface data through 2D and 3D models. Using detailed borehole data including easting, northing, elevation, lithology, stratigraphy, and grade factors, the study focused on estimating reserves and identifying fault-constrained potash blocks unexploited under the current mining plan. Observations confirmed the homogeneity of potash deposits, with their distribution aligning closely with potash-bearing patterns. Using the Polygon Method, reserve calculations assumed consistent grade values within each polygon, multiplying the area of influence by the thickness and grade of the deposit.

5.1.1. Area calculation

The Yara Potash deposit is divided into three isolated concession areas: MMLA, MNELA, and CELA. These areas are sub-divided into polygons based on borehole locations using the nearest neighbor method. The area of each polygon was calculated using the ArcGIS software. Each polygon is assumed to have geologically homogeneous conditions, wherein mining technological parameters are considered uniform.

5.1.2. Layer Thickness of Potash

The thickness of the potash-bearing layers was determined from borehole data. Measurements from individual boreholes provided the thickness of potash horizons. Within each polygon, the thickness of a potash-bearing layer is assumed to remain constant for estimation purposes.

5.1.3. Bulk density

The average bulk density of the potash deposit is, 2.06 g/cm^3 (sylvinite member), 1.72 g/cm^3 (upper carnallitite), 2.01 g/cm^3 (lower carnallitite), and 2.12 g/cm^3 (kainitite) (source: Yara potash).

Hence, the potash reserves in the selected concession areas were calculated using the formula below. According to [38], the U.S. Geological Survey the Potash reserves (tons) calculated as follows:

$$\text{Potash reserves (tons)} = \text{Area} * \text{Thickness} * \text{Bulk density}$$

Where

A = Area of each polygon having potash layer (m^2)

T = Thickness of each potash horizon (meter)

ρ = Bulk density of each potash horizon (g/cm^3)

Therefore, based on the formula mentioned above, the potash reserves (sylvinite, upper carnallitite, lower carnallitite, and kainitite) for each concession area (MMLA, MNELA, and CELA) were calculated and presented in Table 1.

Table 1 showing the estimated potash reserves of the three concession areas

Concession areas	Estimated potash reserves (in Million tons/Mt)			
	Sylvinitite	Upper Carnallitite	Lower Carnallitite	Kainitite
MMLA	90.24	26.89	62.48	182.79
MNELA	165.59	77.11	184.26	337.41
CELA	49.76	705.84	411.81	670.77
Sub-total	305.56	809.83	658.54	1,191
Grand total	2 964.93 Mt ≈ 2.96 billion tons			

5.2. Estimated reserves of the fault-bounded potash blocks

It has been reported in the previous sections that all of the potash mine companies in the area did not calculate their reserve in a more scientific and convincing once. Moreover, many mineralized blocks in the concession areas of the Yara potash could not be mined by the existing mining design. Because many faulted blocks are not connected to any of the extraction boreholes (Figures 9 and 10). In this section, a thorough reserve calculation has been conducted for those potash-bearing blocks that could not be mined with the current design. The reserve of fault-bounded potash blocks was determined using the same formula previously employed to calculate the total potash reserve in the concession areas [38]. This includes area calculation, thickness and bulk density.

5.2.1. Area

The areas of the individual fault-bounded potash-bearing blocks in profile sections (Figures 9 and 10) were determined by multiplying the corresponding length and width of the fault-bounded potash layers. Each fault-bounded potash block in the profile sections, from left to right, is denoted as Area (1, 2, 3, 4, 5, and 6). However, the individual areas (1, 2, 3, 4, 5, and 6) were classified based on the density of the fault-bounded potash blocks in the profile sections.

5.2.2. Average thickness:

The average thickness of the nearest boreholes of the individual fault-bounded potash layers was measured from the borehole thickness results.

5.2.3. Bulk density:

The average bulk density of the potash deposit is, 2.06 g/cm^3 (sylvinite member), 1.72 g/cm^3 (upper carnallitite), 2.01 g/cm^3 (lower carnallitite), and 2.12 g/cm^3 (kainitite) (Source: Yara Potash).

$$\text{Fault-bounded potash reserves (tons)} = \text{Area} * \text{Thickness} * \text{Bulk density}$$

Where

A = Area of each fault-bounded potash layer (m^2)

T = Thickness of the fault-bounded potash layer (in meters)

ρ = Bulk density of each potash horizon (g/cm^3)

Putting the values in the above formula, the reserves of each fault-bounded potash block in the individual profile sections of the concession areas were calculated. Therefore, the total fault bounded potash blocks of the five profile sections CONF 01-EXPL D, CONF 04-EXPL F, EXPL 06-EXPL 04, EXPL 07-CONF 02, and PW 03-PW 01 for the Sylvinite, Upper Carnallitite, Lower Carnallitite, and Kainitite were calculated by totaling all reserve values of each profile sections (Table 2).

Table 2. Summarized reserve estimation of the fault-bounded potash layers that could not be mined with the existing mining design

Name of profile Sections	Estimated reserves for the fault-bounded potash layers (in Million tons/Mt)			
	Sylvinitite	Upper Carnallitite	Lower Carnallitite	Kainitite
CONF 0-EXPL D	22.19	186.30	88.49	158.52
CONF 04-EXPL F	13.12	29.12	21.86	36.55
EXPL 06-EXPL 04	21.24	19.21	16.48	23.54
EXPL 07–CONF 02	69.05	30.21	57.00	60.09
PW 03-PW 01	6.66	3.78	7.18	7.17
Sub-total	132.26	268.62	191.01	285.87
Grand total	877.76 Mt			

Three concession areas—MMLA (CONF 01, CONF 02, PW 01, and PW 03), MNELA (EXPL 02, EXPL 04, EXPL 05, EXPL 06, EXPL 07, EXPL 08B, and EXPL 12), and CELA (EXPL B, EXPL D, EXPL E, and EXPL F)—are the primary locations for borehole drilling activities in the study area (Figure 2). From bottom to top, the overall subsurface stratigraphy of the area is composed of clay/silt, lower rock salt, upper lower rock salt, kainitite, lower carnallitite, bischofitite, upper carnallitite, sylvinitite, marker beds, upper rock salt, and overburden. Based on their depth of occurrence, the deposit is mainly divided into three parts: the western part (MMLA) which has a relatively shallow deposit, the central part (MNELA) within the fault zone, with the deposit at an intermediate depth, and the eastern part (CELA) with the deposit at a greater depth. Towards the west of the study area, the potash-bearing rocks come relatively close to the surface and are only covered with alluvial fan sediment that often, were and are, fresh water-bearing. Out of the total reserve of the concession areas, previously calculated as 2 964.93 Mt (Table 1), 877.76 Mt or 30% of the total reserve remains unmined with the current design. Therefore, to accommodate the reserve of the fault-bounded potash deposit into the mining system, additional extraction boreholes need to be carefully chosen and drilled.

6.3. Socioeconomic benefits of optimized mining operations

Optimizing mining operations in the Dallol depression holds the potential to significantly improve the socioeconomic conditions of the surrounding region. This area, situated within Ethiopia’s Danakil depression, is characterized by economic underdevelopment, limited infrastructure, and high levels of poverty. Enhancing potash extraction practices could yield profound benefits, as outlined below:

6.3.1. Economic Growth

- Increased Revenue: By implementing the recommended borehole design adjustments, resource recovery could increase from the current 24.64% to the targeted 35% extraction rate. For an estimated potash reserve of 2,964.93 million tons, this improvement could translate to an additional recovery of approximately 308 million tons. At a conservative market price of $350 per ton, this would result in an additional $107.8 billion in gross revenue over the life of the mine.
- Boost to National Economy: Enhanced potash production could increase Ethiopia's export earnings and contribute significantly to GDP, positioning the country as a global player in the fertilizer market.

6.3.2. Job creation and skill development

- Employment Opportunities: Optimized mining operations are expected to create additional jobs both directly and indirectly. Direct employment in mining operations could see a 15-20% increase due to the expanded recovery processes. Indirect opportunities in related sectors such as logistics, construction, and trade could amplify this impact further.
- Capacity building: Training programs to meet the technical demands of optimized operations would upskill the local workforce, improving their long-term employability and enabling knowledge transfer within the region.

6.3.3. Infrastructure development

- Mining optimization often requires significant infrastructure investments in roads, power, water, and communication networks. These upgrades, while supporting mining operations, would also benefit local communities by improving access to critical services and reducing isolation.
- Transportation improvements could facilitate the growth of ancillary industries such as agriculture, trade, and tourism, fostering broader economic diversification in the region.

6.3.4. Improved Livelihoods and Social Benefits

- Community Development: Revenues from optimized mining can be reinvested into community development initiatives such as schools, healthcare facilities, and housing projects. This would directly improve living standards for the local population.
- Environmental Management: Sustainable practices tied to optimization would minimize environmental degradation, preserving ecosystems that local communities rely on for subsistence.

Long-term sustainability and regional development

Optimized mining operations can balance economic gains with environmental stewardship, ensuring that potash extraction contributes to long-term sustainable development. By investing in advanced technologies, training local labor, and addressing structural challenges, Yara Potash Mining Company can unlock untapped reserves, boost Ethiopia’s position in the global potash market, and drive socioeconomic progress in the Dallol depression.

6. Conclusions

The Dallol Depression exhibits a complex geological framework with stratigraphic sequences transitioning from older units like the Adigrat Sandstone to carbonate rocks (Antalo Limestone), volcanic deposits, and alluvial fans. At the center of the depression, the graben hosts extensive evaporite deposits comprising halite, potash, muddy salt, and sulfur, particularly concentrated near Mount Dallol. The potash-bearing sequence within these evaporites is distinctly stratified, including lower rock salt, intermediate potash-rich layers, and upper rock salt interspersed with clastic materials. Key potash units include the marker bed, sylvinite member, upper carnallitite member, bischofitite member, lower carnallitite member, and kainitite member. While upper evaporite layers remain horizontal and relatively undeformed, deeper layers are significantly impacted by tectonic deformation. Thickness variations in the evaporite deposits are substantial, ranging from 100 meters at the southwestern rim to 1,700 meters in the central eastern region. Seismic and borehole data reveal sharp depth variations in potash-bearing layers over an 8 km span, with depths varying from 40 meters to 840 meters due to extensional faulting. This faulting creates structural discontinuities, separating shallow formations at the graben margins from deeper ones in the center.

The total estimated potash reserve across the concession area is approximately 2,964.93 million tons, with 877.76 million tons (29.60%) remaining unexploited due to borehole designs that fail to access fault-bounded blocks. Current recovery rates are limited to 24.64%, falling short of the 35% target.

These findings highlight the structural complexities influencing potash distribution and emphasize the need for enhanced extraction strategies. Refining borehole designs to account for geological and structural variations can significantly improve recovery rates while minimizing environmental impacts. Incorporating advanced geophysical methods and real-time monitoring systems can further optimize operations, ensuring both economic viability and sustainability. By leveraging these insights, Yara Potash Mining Company can maximize resource recovery, contribute to regional development, and strengthen Ethiopia’s position in the global potash market.

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ارزیابی چالش‌های ساختاری در استخراج پتاس: دیدگاه‌های استخراج محلول یارا، افسردگی دالول، شمال افار، اتیوپی

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چکیده:

فرورفتگی دالول، واقع در شمال فرورفتگی داناکیل، دارای تاریخچه زمین‌شناسی پیچیده‌ای است که توسط کافت‌زایی آفار شکل گرفته و حاوی تقریباً ۱.۷ کیلومتر رسوبات تبخیری است. این رسوبات، که به شدت تحت تأثیر فعالیت‌های آتشفشانی و گسل‌های تکتونیکی کششی قرار دارند، تنوع ساختاری قابل توجهی را نشان می‌دهند. این تحقیق بر بخش حاوی پتاس از توالی نمکی تمرکز دارد که از چندین لایه مجزا از جمله لایه نشانگر، عضو سیلوینیت، عضو کارنالیتیت بالایی، عضو بیشوفیتیت، عضو کارنالیتیت پایینی و عضو کاینیتیت تشکیل شده است. این مطالعه با استفاده از تصاویر ماهواره‌ای (Landsat Thematic Mapper)، نقشه‌برداری زمین‌شناسی و ساختاری، داده‌های گمانه و تجزیه و تحلیل لرزه‌ای، ویژگی‌های زیرسطحی تبخیری‌ها را مشخص کرده و ذخایر آنها را تخمین می‌زند. نرم‌افزار RockWorks توسعه یک نقشه چینه‌شناسی زیرسطحی و یک نمودار حصار سه‌بعدی را برای تفسیر بهتر تسهیل کرد. داده‌های لرزه‌ای نشان می‌دهد که در حالی که لایه‌های بالایی رسوبات تبخیری عمدتاً افقی و بدون تغییر شکل هستند، لایه‌های عمیق‌تر آشفتگی تکتونیکی قابل توجهی را نشان می‌دهند. تغییرات ضخامت مشاهده شد، به طوری که رسوبات تبخیری و آبرفتی در لبه جنوب شرقی نازک‌تر و در مرکز واگذاری شرقی ضخیم‌تر بودند. کل ذخیره پتاس تقریباً ۲.۹۶ میلیارد تن تخمین زده می‌شود که از این مقدار ۸۷۷.۷۶ میلیون تن (۲۹.۶۰٪) هنوز استخراج نشده است. طرح‌های فعلی گمانه، ظرفیت استخراج شرکت را به ۲۴.۶۴٪ محدود می‌کند. این مطالعه، بازنگری در استراتژی‌های استخراج، ترکیب طرح‌های گمانه به‌روز شده و روش‌های ژئوفیزیکی پیشرفته را برای بهبود بازیابی پتاس و ترویج شیوه‌های پایدار در منطقه دالول توصیه می‌کند.

کلمات کلیدی: دالول، ذخایر پتاس، چالش‌های ساختاری، معدنکاری راه‌حل، معدنکاری پایدار.