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TARGET SEAM SELECTION AND RESERVOIR MODELING IN SOLUTION MINING – FIELD APPLICATIONS FROM BEYPAZARI, TÜRKIYE

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Abstract

This study aims to evaluate the cavern planning strategy (one horizontal and two vertical wells) applied in solution mining operations at the Beypazarı, Türkiye natural soda ash (trona) deposit, focusing on target seam selection and reservoir management. Key factors considered in seam selection include dissolution performance, mineral content within trona, inter-seam fracture networks, and solution flow behavior. The upward migration of the solvent into overlying seams was observed on site and incorporated into the cavern and reservoir model to conduct reserve estimations. The cavern and reservoir model are both presented in this study to provide an overview of the solution mining methods applied at the trona deposit in Beypazarı, Türkiye.

The reservoir model was constructed based on the coalescence of previously mined caverns. Based on the developed reservoir model, the production (AK) well concept was designed to produce saturated solution from the reservoir while controlling solution flow within the reservoir. The drilling plans for AK wells were optimized and fully integrated into reservoir calculations. The study also addresses the determination of cavern direction and inter-well spacing, design modifications in response to operational challenges during drilling, and the impact of trona ore characteristics on cavern behavior. All findings are derived from over 20 years of field-based experience and operational data. Accordingly, the study presents field-tested engineering insights and practical approaches to enhance solution mining performance, offering transferable strategies for solution mining performance in similar deposits.

Key words: Solution mining, Trona, Cavern planning, Target seam selection, Reservoir modeling, Production wells, Field experience, Drilling engineering, Mineral composition

1 - Introduction

The molecular formula of the chemical compound known as “soda ash” is Na2CO3. Soda ash is produced from natural soda ore (trona) or synthetically with rock salt and limestone as raw materials. Trona is the natural form of sodium sesquicarbonate (Na2CO3•NaHCO3•2H2O), also referred to as a hydrated sodium bicarbonate, a naturally occurring precipitate mineral generally forming in shallow, non-marine alkaline lakes co-forming with other sodium carbonate, sulfate, and chloride minerals. Precipitation is believed to be influenced by semi-arid conditions and the leaching and weathering of alkali igneous rocks. It is classified as a buried deposit (Kogel et al. 2006) versus a surface playa lake deposit.

Continental calcium and magnesium-depleted brines (non-marine type) with excess bicarbonate, which are selectively combined with sodium to form sodium carbonate minerals such as trona, natron, thermonatrite, and nahcolite precipitate, are typically associated with shortite and dawsonite. This lacustrine depositional environment is typical of other major commercial trona deposits, including the Wilkins Peak Member of the

Eocene Green River Formation in the Green River Basin in the United States of America (USA), the Eocene Wulldui Formation in the Wucheng Basin of China, and the Eocene Mülk Formation in the Kazan Basin of Turkey.

Large, extensive, and economic deposits, as seen in Turkey and Wyoming, USA, are Tertiary Eocene in age. They exhibit seasonal and cyclic deposition/precipitation separated by varves, sedimentary beds representing the end of a cycle. In Turkey, these clastic units are oil shale and dolomites indicative of a continental shallow organic-rich depositional environment.

The Beypazarı trona deposit in central Turkey is one of the largest known trona deposits in the world. The principal sodium carbonate minerals are trona ($Na_2CO_3.NaHCO_3.2H_2O$) with minor nahcolite ($NaHCO_3$). Trace amounts of pirrsonite ($Na_2CO_3.CaCO_3.2H_2O$) and thermonatrite ($Na_2CO_3.H_2O$) have been reported. Trona occurs in laminated bedded layers; it is crystalline, prismatic to massive, white to gray to honey colored. Nahcolite is present as thinly laminated, lensoid with short prismatic crystals. It's color may be khaki, white, or translucent.

The deposit is currently mined using solution mining techniques, and the operator, Eti Soda (part of the WE Soda group), has significantly expanded the understanding of the geology and mineability of the deposit over the past decade. Eti Soda has actively solution mined trona since 2009 with over 130 caverns developed and more than 500 exploration and production wells drilled.

Total alkalinity (TA) or equivalent soda ash content of a seam, molecular water, and insolubles altogether are a good measure of the ore's solution mineability. Eti Soda extracts all water-soluble sodium compounds from underground deposits using the solution mining technique, leaving the insoluble gangue material behind. In doing so, the underground drilled wells are utilized either as injection wells or as recovery wells. For each injection or recovery well, Eti Soda closely monitors flow rate, flow pressure, fluid density, fluid temperature, Na_2CO_3 and $NaHCO_3$ concentrations.

To maximize resource recovery and optimize cavern placement in the Beypazarı deposit, a detailed knowledge of trona zones and seams is necessary, as is precise cavern building into the right seam.

2 – Seam Selection Process

There are 26 trona beds, 13 of which are considered to be of economic grade and thickness. Significant thicknesses of trona occur in 14 seams within the lower Miocene Hırka Formation, separated by 20 to 25 meters (m) (65 to 80 geet [ft]) of interburden into 7 upper units (U1 to U6) and 7 lower units (L1 to L6). A seventh upper bed is designated as UX, located between U3 and U4. A bed designated as L2-1 represents local splitting of a trona bed. Depth to the orebody is from 200 to 500 m (650 to 1,640 ft). It was not deemed feasible to dissolve this ore and obtain brine of the desired quality solely through the drilling of vertical wells. As a solution, the vertical wells were interconnected with an additional horizontal well within the target ore seam, with the aim of increasing the surface area of the dissolution environment. In general, caverns consist of two vertical wells and one horizontal well. However, factors such as local wildlife, surface topography, ore characteristics, and seam inclination have led to variations in cavern configurations in the field, including the use of a different number of vertical or horizontal wells. Figure 1 illustrates the different cavern types developed by Eti Soda over the years. Because cavern design is closely linked to seam characteristics, these factors make the selection of the target seam one of the most critical stages in the solution mining operations conducted in the field. An incorrectly chosen seam, one unsuitable for horizontal drilling, or seams with low TA content fail to deliver the desired production performance, and limited cavern development is observed.

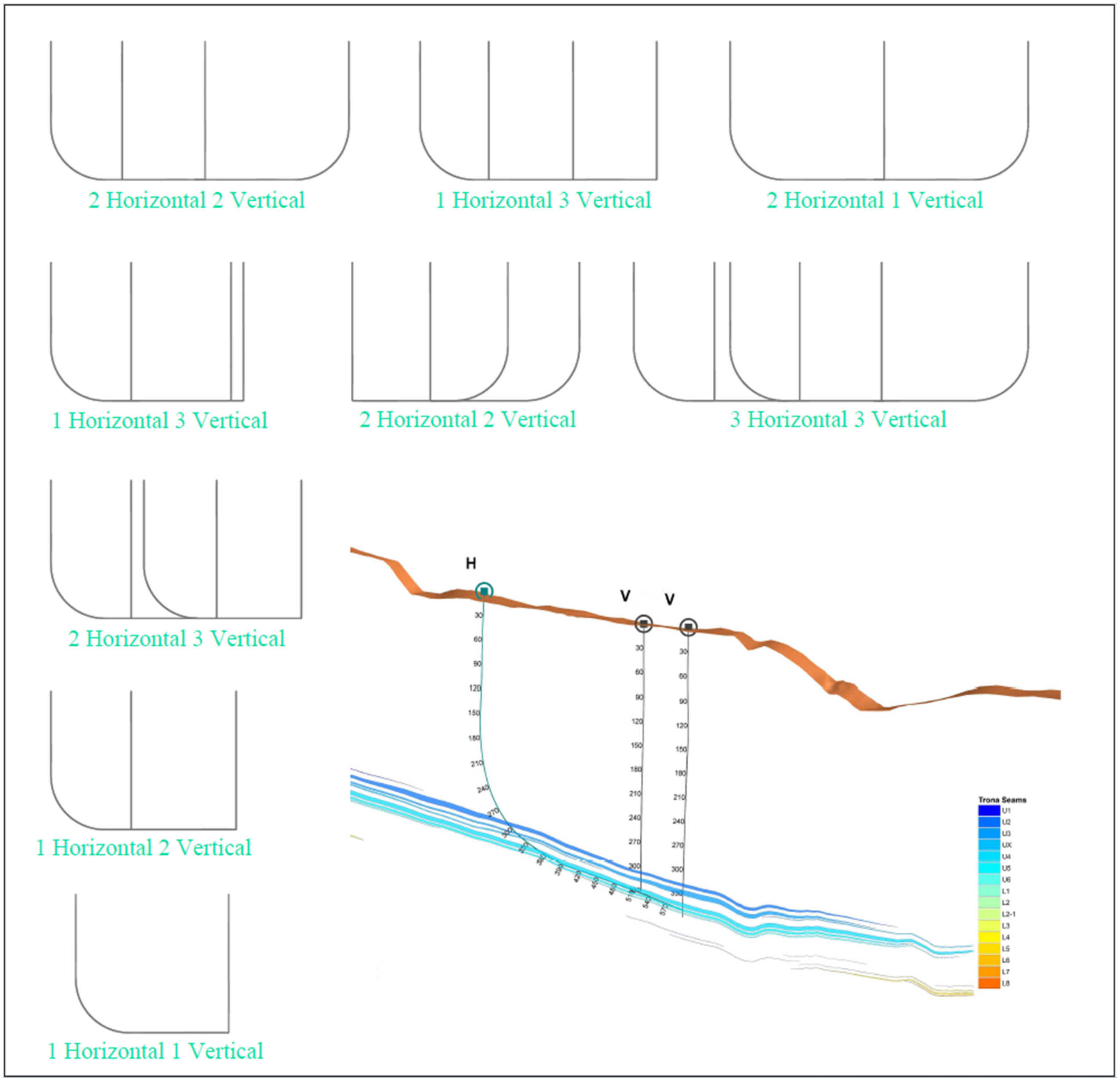

Figure 1: Different Cavern Types Developed by Eti Soda Over the Years (modified from Agapito Associates Inc., 2019)

The Beypazarı deposit is composed of multiple tabular, sub-horizontal trona beds separated by clay-rich interbeds. Trona occurs as discrete beds labeled U1 to U6 in the Upper Zone (UZ) and L1 to L8 in the Lower Zone (LZ), with a characteristic interburden separating the two zones. The trona mineralization exhibits lensoid and podal distributions in some units (e.g., UX), while other beds, such as U4, are laterally extensive and high grade. The UZ hosts approximately 70% of the total resource, while the LZ hosts 30%.

On average, trona beds in the Upper Zone are thicker than those in the Lower Zone, and some of the thickest and most laterally continuous seams are found within the UZ. By contrast, many of the thinner seams are present in both zones, limiting their potential for solution mining.

The most used parameter for grade at Eti Soda is total alkalinity (TA%). Total Alkalinity (TA) is the equivalent of sodium carbonate in the combined sodium/sodium carbonate in the trona. One unit of sodium bicarbonate contains 0.631 units of sodium carbonate. Calculated percent trona is also reported and is a calculated value based on the percent molecular weight of Na2CO3, NaHCO3, and water. Global weighted average percent trona for the entire resource is 60.06%. Since all sodium-containing compounds dissolve and are brought to the surface through the production wells, it has been adopted to calculate the extracted or to-be-extracted ore in terms of TA, with the acceptance that all non-trona minerals are also considered as ore. This approach was chosen to obtain more realistic production data.

The selection of the optimal seam bed for cavern development plays a critical role in ensuring efficient dissolution, stable cavern growth, and maximum resource recovery. The following key criteria, derived from operational experience at Eti Soda, have been established to guide seam selection.

- The total trona bed thickness in the upper trona zone is much thicker than the thickness in the lower trona zone.
- There is a greater number and thickness of interbed separations between the trona beds in the lower trona zone than in the upper trona zone.
- Cavern development in a thin trona bed usually takes longer than in a thicker trona bed to leach out enough cavern surface area for dissolution.
- When selecting the target seam for the cavern, the minimum seam thickness to be followed during horizontal well drilling must be 0.8 m. This figure is one of the most critical parameters in drilling operations in the field. Therefore, the seam at the greatest depth where the cavern will be constructed must have a thickness of 0.8 m.
- Based on the cut-off values, a minimum total ore thickness of 2.3 m above the target seam is required for the development of a cavern.
- Throughout the cavern, the behavior of all seams is determined by geophysical e-logs obtained from within the well during and after drilling. Thickness and relative quality are then evaluated based on this data, and their consistency with 3D mining software models is verified.
- For a cavern to be developed in either the UZ or the LZ, the total ore thickness within the target zone must exceed 30% of the target zone's total thickness, including interbeds.
- Caverns in the lower trona zone will need to grow through thick interbeds, which will affect the cavern performance.
- The ratio of the total trona bed thickness to the total interbed thickness in caverns built in the lower zones is only 0.38 compared to 1.02 for caverns in the upper zones. The lower ratio of trona bed thickness to interbed thickness indicates that growing caverns from the lower trona zone will take a significant time for solution mining to reach the thick and rich trona beds in the upper trona zone. It is possible that the horizontal wells may become blocked as the thick interbeds cave into the opening leached out in the startup bed.

3 – Cavern Model (Primary Solution Mining)

Solution mining at Eti Soda's Beypazarı mine starts with primary mining and each solution mining cavern is designed to operate as an independent mining area. Primary mining progresses as the injected solvent dissolves the trona deposits surrounding the injection well. Eti Soda has experimented with several different cavern designs (Figure 1). Based on these operational experiences, the most effective design was determined to be the "one-horizontal two-vertical well" model. This layout consists of a horizontal well intersecting two vertical wells. Injection alternates between the horizontal well and vertical wells, resulting in a symmetrical cavern shape resembling a peanut (Figure 2). Ensuring symmetrical growth from each injection point before the cavern merges with other caverns (before transitioning of caverns to the reservoir model) enhances overall efficiency and allows for a more controlled and uniform cavern development.

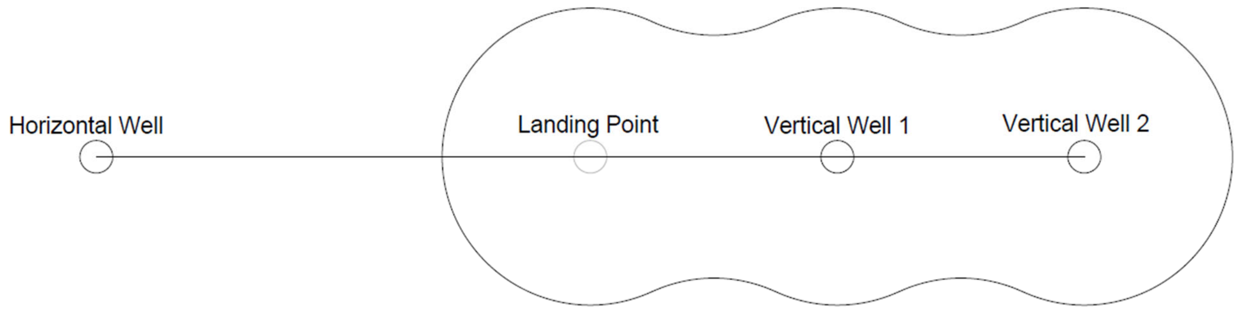

Figure 2: Peanut Shape Cavern Footprint

Because no diesel or oil blanket is used, leaching the target trona bed often causes the cavern roof to collapse as the cavern roof span grows. Then, the upper trona deposits are accessed by injection solvent and dissolved (Figure 3). This approach enables the extraction of the upper trona beds at the top of the cavern.

Geophysical logs from the two vertical wells will provide valuable information for designing the horizontal well. These logs help determine the optimal locations of the kickoff and landing points (Figures 4), which are essential for defining the well trajectory. The kickoff point is the point in the wellbore where drilling deviates from the vertical section and begins its curve toward the horizontal interval within the target seam, while the landing point is where the horizontal well reaches the target zone. The horizontal well stays open hole from landing point to the final target vertical well. This enables cavern growth, with the landing point serving as an injection well. Brine is recovered from each of the vertical wells. An additional vertical well will be drilled midway between the production well and the landing point to optimize resource recovery. This intermediate well provides access to resources in the middle section of the cavern.

Cavern design principles below are used to direct these activities and provide the safe and effective extraction of the resources.

- Horizontal wells are used for cavern connection and injection, and vertical wells spaced 75–100 m (245-330 ft) apart are used for injection and recovery.
- Cavern width is designed to be about 90 m (295 ft).
- The thickness of the target trona bed needs to be 0.8 m (2.6 ft) or more.
- The planned cavern leaching boundaries need to be at least 50 m (165 ft) away from known major faults.
- Caverns are planned along local strikes to maximize resource recovery.
- All trona layers above the target trona bed are considered mineable.
- If the cavern axis is aligned with an inclined ore seam, it should be positioned in the direction opposite to the dip by 180 degrees.

Building on these design principles, the drilling and cavern development sequence applies an organized method to progressively grow the cavern while preserving stability and symmetry. The drilling and cavern development sequence is as follows:

1. Vertical wells are drilled and completed at the base of either the upper or lower trona ore zones. These wells are strategically located ‘on-strike’ at the bottom of the upper or lower trona ore zones.
2. Surface pipelines and instrumentation are installed.
3. Single-well solution mining is initiated in each well by injecting water at a temperature of 60–80°C (140-176 °F) down the well tubing and recovering the partially saturated sodium carbonate (Na_2CO_3) and

sodium bicarbonate ($NaHCO_3$) brine through the annular space on the well. This step is continued until a small target cavity is formed at the base of the vertical wells.

4. A horizontal well is strategically located to facilitate connecting the target cavities on-strike.

5. Upon successfully connecting the target cavities with the horizontal borehole, one vertical well is utilized as an injection well and either the horizontal well or the other vertical well is used as a production well as solution mining is initiated. The resulting production fluid is about 15 weight percent (wt%) TA as Na_2CO_3.

6. The well modes are reversed (the injection well is changed to a production well and the production well is changed to an injection well) as needed to ensure the symmetry of the caverns.

7. Each individual cavern will grow vertically until it encounters an interburden layer, which restricts the vertical cavern growth, and the cavern begins to expand horizontally.

8. The cavern continues to expand horizontally until the interburden layer becomes unstable, ultimately collapsing and becoming partially rubblized.

9. After the interburden layer collapses, the cavern again grows vertically until it encounters the next interburden layer.

10. This process continues until the final interburden layer collapses, and the cavern loses integrity.

During later stages of primary mining, the solution mining cavern may develop communication with the adjacent caverns. This communication can limit the ability of the cavern to maintain enough pressure to lift the production brine to the surface. In this instance, a submersible pump is installed in the production well to assist in lifting the production brine to the surface. This situation may require a transition to a more integrated recovery strategy, called the reservoir model or secondary mining.

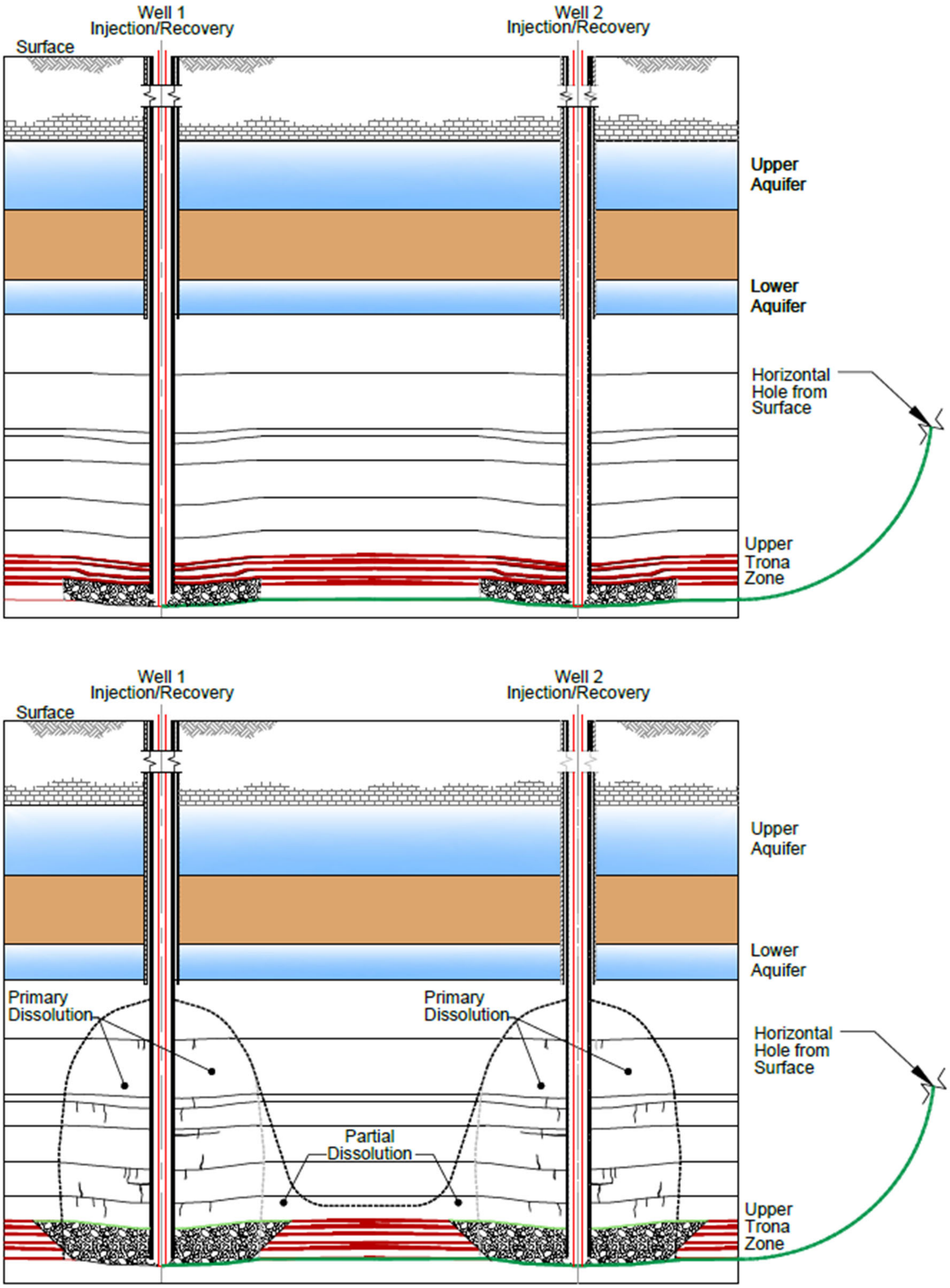

Figure 3: Cavern Bed Roof Collapses and Partial Dissolution (modified from Agapito Associates Inc., 2023)

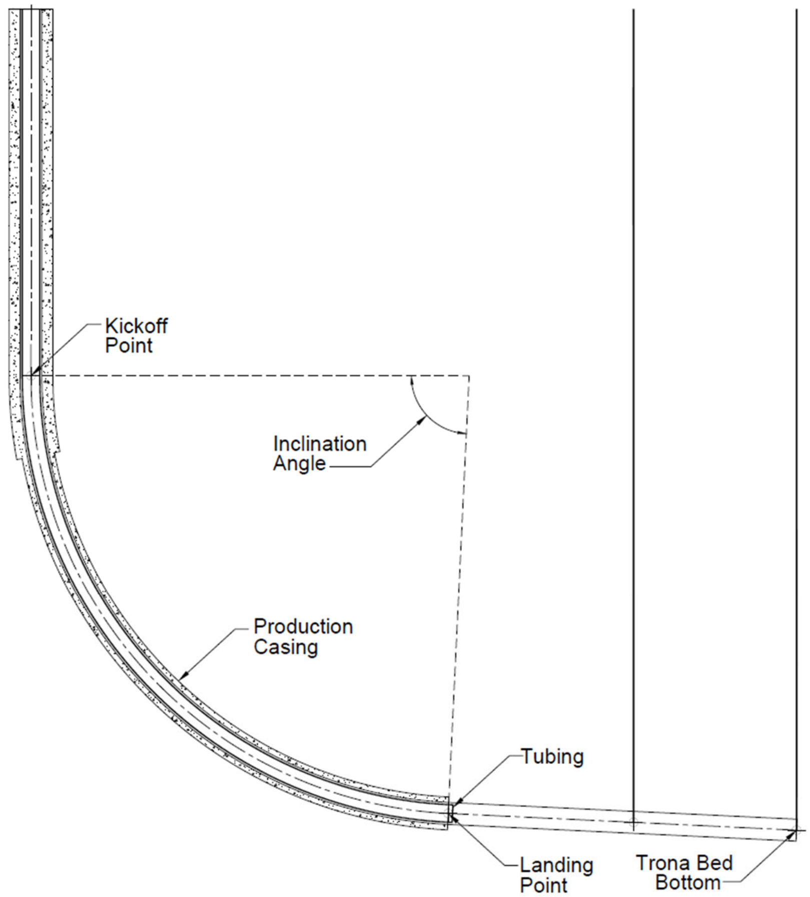

Figure 4: Well Structure Design (modified from Agapito Associates Inc., 2016)

4- Reservoir Model (Secondary Mining)

Secondary mining starts when the caverns are connected with each other, or the cavern radius grows to the designed radius. The goal of secondary mining is to optimize resource recovery after primary mining by properly maintaining and managing the balance of wellfield pressure and leakage, and to avoid abrupt overburden strata movement by distributing solvent injection locations. In secondary mining, additional injection/recovery wells and submersible pumps are constructed or installed to increase brine recovery. Secondary mining is much more complicated than primary mining as the cavern roof collapses and the cavern fills with rubblized material. As caverns are interconnected, the brine flows towards less pressurized areas through the more porous paths.

Unlike the conventional expectation of caverns forming large, wide voids, often even capable of storing another industrial material like hydrocarbons, such cavern spaces have never been observed in the Eti Soda field to date. This is due to the bed-like structure of the ore, similar to coal; the swelling of interbeds under hot water pressure; and the very low strength of these interbeds, which causes them to collapse onto the dissolved ore. As a result of these conditions, no observations related to conventional cavern growth have been made to date from the existing production wells.

For this kind of mining practice, a reservoir model better simulates the mining process in the wellfield than a peanut model because the peanut model can only simulate an independent cavity. Since the injection and recovery wells' pressure and flow rates are monitored, interconnected wells can be identified. The combined footprint of the connected caverns is considered as a whole in the reservoir model (Figure 5).

For a preliminary reservoir model, it is assumed that dissolution only occurs surrounding the injection area and that brine flows from the injection locations to the lower pressure recovery locations as submersible pumps are installed at these recovery wells. It is also assumed that brine is saturated at the recovery location and, therefore, no dissolution occurs at the recovery location.

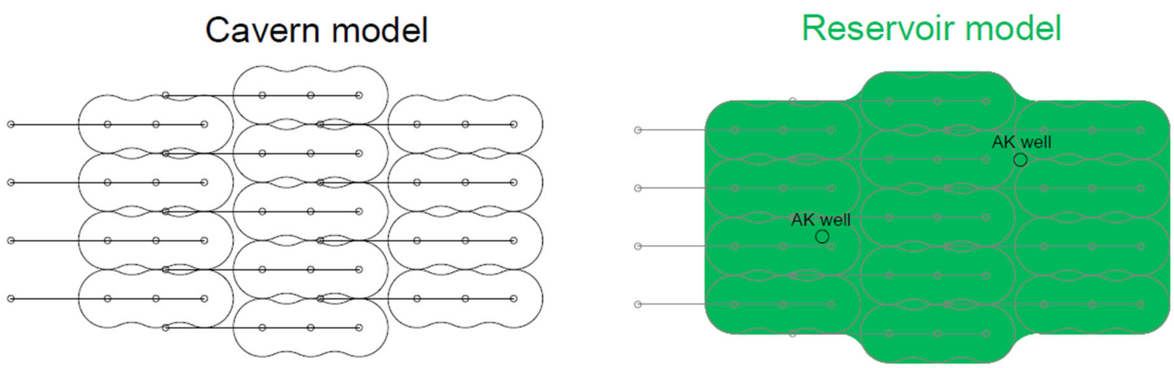

Figure 5: Cavern and Reservoir Model Footprints

Based on these assumptions, additional injection wells should be drilled at the mid-spacing between caverns or in an intact area so that more resource can be recovered. However, additional injection wells should not be drilled in high subsidence areas to ensure subsidence is gradual and to avoid abrupt subsidence. Eti Soda drilled vertical injection wells (I wells) with the aim of dissolving the pillars and integrating the injected water into the reservoir's overall flow system. Nevertheless, it was discovered that these wells were prone to blockage and couldn't be effectively connected to the reservoir flow. Instead, the wells dissolved only the surrounding area and eventually became blocked. Eti Soda intends to implement horizontal injection wells in the upcoming phase to manipulate the dissolution zone and enhance the flow control within the reservoir.

Once the reservoir model is implemented, existing wells are generally converted into production wells or switched to injection mode to continue ore dissolution. During the interconnection process, vertical recovery wells (AK wells) are completed differently from standard production wells, using larger-diameter and screened casing to capture solution flowing through underground channels and other dissolution voids. These screened casings are lowered to cover the entire Upper Zone, or both the Upper and Lower Zones, to collect brine originating from the seams where dissolution occurs. AK wells are typically positioned downdip at locations where the trona is deep and where the highly concentrated brine can be extracted. As a natural result of the underground interconnections, any brine that can no longer reach the surface by natural flow is lifted to the surface with the aid of an ESP in these wells and then fed into the system. Although less common, a similar blockage issue has also been noted in AK wells. However, Eti Soda's experiences have shown it is more economical and time-effective to drill a new AK well next to a blocked one rather than trying to clear the blockage.

Therefore, as described under the primary mining section, it is necessary to make an assumption regarding the dissolution processes of the ore left as pillars between caverns. The brine generated from this dissolution is recovered through AK wells, as the production wells can no longer be used as return wells.

5 – Mineral Resource Estimate

In the Eti Soda field, the general geological structure of the ore causes continuous variation in seam thickness, which makes it difficult to accurately estimate the amount of ore to be extracted from a cavern. The main source of data for these calculations and geological assessments is verification drillings. They are carried out to accurately identify the target seam, determine TA content of the beds, evaluate the influence of geological features on the formation, and improve the accuracy of the calculations. As new information becomes available, this method guarantees that estimates of mineral resources are updated continuously. In parallel with these efforts, exploration activities are also underway to find new reserves beyond the current mineralization area, characterize the beds on a larger scale, and take initial steps toward the future extension of the mineralization area.

The cavern model offers the framework for measuring the recoverable trona in order to estimate mineral resources. Eti Soda has collected extensive geologic data, including more than 400 core drillholes with assay data and over 300 production drillholes with geophysical logs. This collective data allows to make assumptions about the TA content within the peanut-shaped of a planned cavern. The estimated recoverable TA is calculated by summing the TA content of the target seam and the overlying seams that are anticipated to be dissolved as the cavern develops. Based on this estimate, operational parameters are determined, such as the amount of brine to be recovered from each production well, the amount of hot water to be injected through each well, the anticipated cavern mine life, and the anticipated timeline for transitioning from the cavern model to the reservoir model. By integrating geological data with well design and operational planning, this integrated approach guarantees that estimates of mineral resources are both realistic and dynamically linked to field practices.

Once the TA quantity projected by the cavern model is reached for a single cavern or a group of caverns, the calculations are transitioned to the reservoir model. At this stage, the total mass of TA-containing ore within the newly transitioned model area is calculated, and the result is obtained. The same principles, particularly those related to dissolution, applied in the cavern model are also applicable to this stage; however, the scale of the calculation expands from individual caverns to the combined footprint of interconnected caverns. In this case, all sodium contained within the former pillar zones and dissolution gaps are taken into account the resource estimate. This highlights the transition from the cavern model calculations to the more complex, field-scale reservoir model.

6- Conclusion

This study presents field-based applications of cavern and reservoir models for solution mining at the Beypazarı trona deposit, supported by extensive drilling data, geophysical logging, and more than 20 years of operational experience. These data and experiences are essential to choose the target seam, define operational limits, develop and operate caverns, and determine cavern configurations. The one-horizontal two-vertical well model has been found to be the most effective in terms of achieving symmetrical cavern growth, stability, and dissolution efficiency among the tested designs.

The transition from cavern model to reservoir model represents the progress of the system from discrete, independent caverns to a collective, field-scale reservoir. Verification drillings play a critical role in this process, serving as the primary source of data for defining target seams, determining TA content, and continuously updating mineral resource estimates. This ensures that both cavern and reservoir models remain dynamically linked to the actual geological conditions of the field.

Operational observations show that cavern development and reservoir performance are significantly influenced by the geological structure of the Beypazarı deposit. In particular, variable seam thicknesses, the collapse of interbeds as seams are dissolved, and the upward migration of dissolution significantly influence cavern growth and reservoir behavior. As a result of these characteristics, caverns in this field differ from conventional solution-mined caverns; instead of developing into wide and stable voids, they evolve into rubblized reservoirs.

Overall, the integration of cavern- and reservoir-scale approaches provides a more complete understanding of the dissolution process and resource recovery potential at the Beypazarı deposit. The lessons learned from these operations not only support more accurate mineral resource estimations for Eti Soda but also offer transferable methodologies for solution mining in other laminate layered deposits worldwide.

7- Recommendations

- For solution mines with ore seam thicknesses between 2-4 m (6.5-13 ft), solution mining is most effective when using the “one-horizontal two-vertical” cavern configuration, as this design enables symmetrical cavern growth and efficient resource recovery.
- In the reservoir model, vertical injection wells (I wells) tend to be prone to blockage, and integrating the injected solution into the reservoir flow remains a significant operational challenge. Horizontal injection wells are recommended to improve connectivity and flow control.
- For recovery wells (AK wells), operational experience shows that when blockage occurs, drilling a new well adjacent to the blocked one is more cost and time efficient than attempting to clear the blocked well.
- Future work should continue to refine reservoir modeling assumptions and applicability of horizontal injection wells (I wells).

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