

## Quantitative Assessment of Calcite Scaling of a Vapour-Dominated Well

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**ABSTRACT** - Geothermal scaling is a prevalent issue that significantly impacts the efficiency of thermal energy production, drawing considerable attention in the field. Scaling formation is attributed to multiple factors, including variations in pressure and temperature. In this field, scaling deposits have been associated with an observed production decline of approximately 3.2%, posing a substantial challenge to maintaining optimal operational efficiency. This study aims to quantitatively assess the potential for calcite scaling in selected production wells and to estimate scaling growth rates as a basis for determining appropriate well-cleaning intervals. Geochemical data from produced fluids were analyzed to evaluate calcite and silica saturation using saturation indices derived from simplified thermodynamic relationships. Calcite scaling potential was assessed using the calcite saturation index (CSI), while silica scaling was evaluated using the silica saturation index (SSI). The growth rate of calcite deposits was estimated using a kinetic-based Calcite scaling thickness (CST) approach. The results indicate that one production well exhibits calcite supersaturation, while silica scaling is not expected under the analyzed conditions. Based on the applied assumptions, the estimated calcite scaling growth rate suggests that periodic well-cleaning interventions are required to maintain production performance. However, the calculations rely on simplified geochemical assumptions, including the use of concentration-based approximations and empirical kinetic parameters. Therefore, the results should be interpreted as an operational estimate rather than a definitive prediction, and further validation using activity-based geochemical modeling and direct scale characterization is recommended. This study provides an operationally oriented framework for linking geochemical indicators to well-maintenance planning in vapour-dominated geothermal fields.

**Keywords:** calcite scaling, geothermal system, scaling growth, geochemical

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**INTRODUCTION**

Geothermal energy is a renewable resource that can be harnessed as a source of power. In Indonesia, the total potential amount of installed geothermal resources is 2.74 GW, which has enabled the country to surpass the Philippines and secure the second position globally. To support the achievement of the Renewable Energy target of 23% by 2025, the government has issued special regulations, namely Law No. 21 of 2014 concerning Geothermal and Government Regulation No. 7 of 2017 regarding Geothermal for Indirect Utilization, and other technical regulations. Geothermal energy is also utilized due to its system that emphasizes heat sources, reservoirs, faults, and overburden. In this context, the heated thermal fluid in the reservoir serves as a power source to generate electricity, utilizing a steam turbine. The heat source also emphasizes the magma channel and plays a role in heating the accumulated geothermal fluid, which is contained in a rock structure, namely the reservoir. Additionally, a clay cap is an impermeable rock layer that maintains and manages the fluid in the reservoir, while the fault serves as a geological medium that allows for the drainage of thermal flow.

Generally, produced geothermal fluids often contain associated minerals, whose concentration in water exceeds their solubility, resulting in the formation of solid substances. This condition poses a significant challenge during the exploitation of geothermal wells. The occurrence is also due to the reservoir containing various characteristics perceived from the concentration of chemical compounds, rock types, and types of geothermal fluids. Scaling is a common issue when working with geothermal fluids. Thermodynamic theory states that the solubility of minerals varies with temperature and pressure. (Atkinson et al., 1991) said that when fluids are over-saturated with particular minerals, the minerals will precipitate

and block boreholes or pipelines. The most common depositions at various points in the production process include silica, calcite, and mineral scales that contain iron. During the initial stage of boiling, calcite scale forms, and then, during the outflow of wastewater, silica scale forms. According to Arnórsson et al., (1982), volcanic gas in a geothermal system is often associated with a Fe-bearing mineral scale. The composition of the deep fluid and the geochemical events from the reservoir to the wellhead significantly impact the type of scale that will form. Several studies report that silica scaling frequently occurs in high-temperature geothermal fields, although its occurrence depends on fluid composition and operational conditions (Kaypakoğlu et al., 2012; Quinao et al., 2017; Sigfusson et al., 2011; Villaseñor & Calibugan 2011). Scaling tendency assessments based on saturation and solubility indices have long been applied as practical screening tools in subsurface and production systems. Index-based approaches have been widely used to evaluate mineral precipitation risks under varying temperature, pressure, and water chemistry conditions, particularly for calcium-based scales. For example, Makmur (2007) demonstrated that solubility and saturation indices can be used to assess relative scaling tendencies of calcium sulfate and calcium carbonate under varying thermodynamic conditions. These findings support the use of simplified index-based methods as a practical initial screening approach when detailed data are limited.

A geothermal system consists of a heat source, a reservoir, fluid pathways, and a cap rock. Thermal fluids circulating within the reservoir commonly transport dissolved minerals whose solubility is strongly controlled by pressure, temperature, pH, and gas content. During production, changes in these parameters, particularly pressure reduction and CO<sub>2</sub> degassing, can shift the fluid from equilibrium to supersaturation, inducing mineral

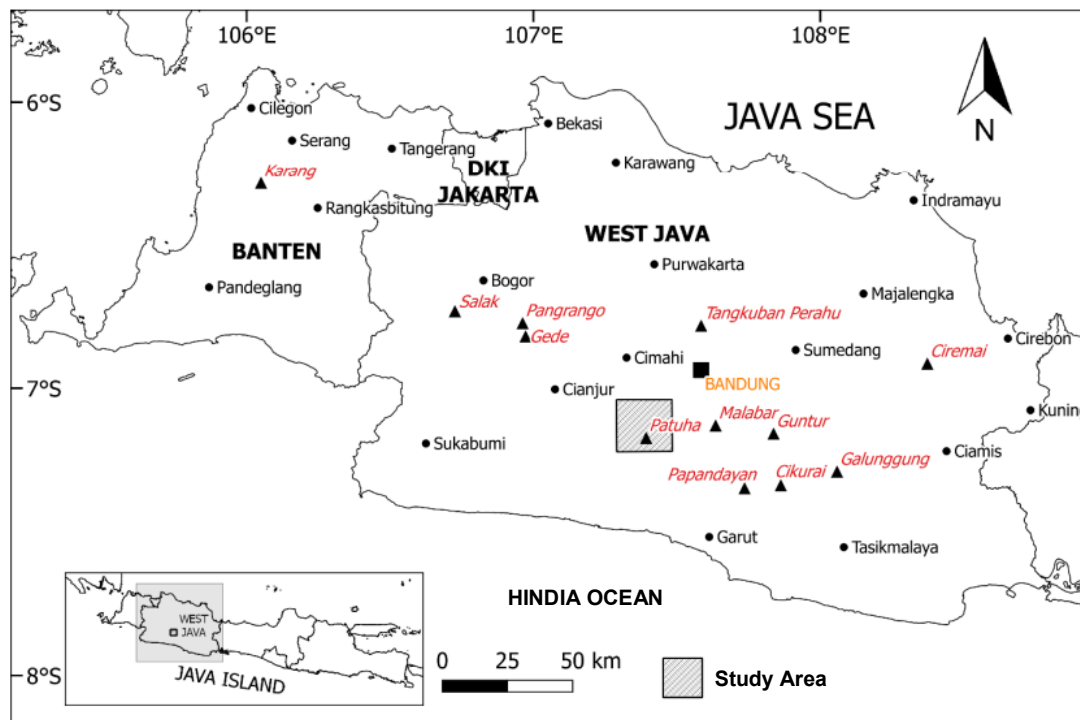


Figure 1. General location and geological context of the studied vapour-dominated geothermal field (Suryantini et al., 2017)

precipitation. This phenomenon, commonly referred to as scaling, represents a persistent operational challenge because mineral deposits can reduce effective wellbore diameter, increase pressure losses, and ultimately decrease production performance. As observed in the Dieng field, this problem can occur in the production well and the geothermal fluid pipe, where it can form and clog, reducing the flow rate. In this case, the formulated silica scaling clogs the pipe leading to the injection well, enabling the less optimal performance of the geothermal fluid flow process (Wahyudityo et al., 2013).

From this context, scaling is a problem encountered during the production process, due to the formation of deposits or solids in the reservoir or geothermal flow pipe. Changes in pressure, temperature, and pH parameters often cause this solid formation. The type of scaling formed is also different according to the chemical composition of the liquid (Ciptadi & Patangke 2001).

The formed solids or scaling can cause various problems, specifically reducing the production rate. This is because the deposited solids can block the flow of geothermal fluid in production wells and pipes, affecting the reduction of manufacturing rates. When deposits form in the production well,

flow restriction near the feed zone may occur due to the proximity of scaling to the feed zone. According to a previous report, a decrease in production rate was observed at a rate of 3.2% per year (internal field monitoring data).

This study addresses this gap by providing a quantitative, operational assessment of calcite scaling potential in selected production wells from a vapour-dominated geothermal field. By combining saturation index evaluation with a kinetic-based estimate of calcite scaling thickness, this work aims to establish a link between geochemical indicators and well cleaning strategies. While simplified geochemical assumptions are employed, the results are intended to support operational decision-making and to highlight the need for further validation using activity-based geochemical modeling and direct scale characterization.

## GEOLOGICAL SETTING

The Indonesian archipelago is a geologically complex region situated at the southeastern fringes of Southeast Asia's Sunda Shelf continental core. This region is surrounded by a highly dynamic zone, characterized by frequent seismic activity and volcanic phenomena, due to the ongoing subduction

of tectonic plates. From this context, the subduction process, which commenced around 45 million years ago (Hall 2012), occurs between three expansive plates: Eurasian, Indian-Australian, and Pacific. The subduction of the Indian-Australian plate beneath the Eurasian layer also commonly causes a volcanic belt stretching from the late Tertiary period to the Quaternary era along Java Island, hosting a multitude of active volcanoes (Sriwana et al., 2000). This volcanic region encompasses the field studied, which is located 37 km southwest of Bandung City (Figure 1). The field also represents a vibrant geothermal region with substantial potential to address the escalating energy demands.

In this field, the estimated power generation capacity within the productive 9 km<sup>2</sup> area ranges from 120 to 200 MW. At a total extension of 35 km<sup>2</sup>, encompassing the productive sector and featuring thirteen production wells, this sustainable contribution is expected to persist for over three decades (Swandaru 2006). The field system also encompasses a vapour-dominated or two-phase reservoir, characterized by two volcanic chimneys carrying magmatic waters (Raharjo et al., 2016). In this context, deep wells drilled to depths ranging from 905 to 2,351 m have confirmed a vapor-dominated

layer approximately 0.5 km thick. This layer is located at a depth of 1 km, exhibiting temperatures ranging from 200 to 240°C (Hochstein & Sudarman 2008).

As a youthful volcanic complex, the field studied is also enveloped by several older volcanoes (Figure 2). Furthermore, the geothermal system is governed by late-stage volcanic vents distributed along the western to northwestern axis, due to being primarily composed of late Pliocene to Quaternary pyroclastic material and andesitic lavas (Layman & Soemanrinda 2003). An active volcano is also observed, whose degassing activities are considered to have created the crater lake, acidic and warm, with a sizable extension of approximately 55,000 m<sup>2</sup> (Hochstein & Sudarman 2008; Pambudi, 2018).

The field studied exhibits a diverse range of fifteen lithologic types, as depicted in Figure 1. In this context, the basement comprises Tertiary volcanic rocks with microdiorite as a prominent component. An epidote-rich zone, developed through silicification and propylitization processes, also indicates significant hydrothermal alteration at temperatures of 200°C or higher, with an elevation of approximately 1,200 m above sea level (a.s.l.). Moreover, the geologic structure of the field is

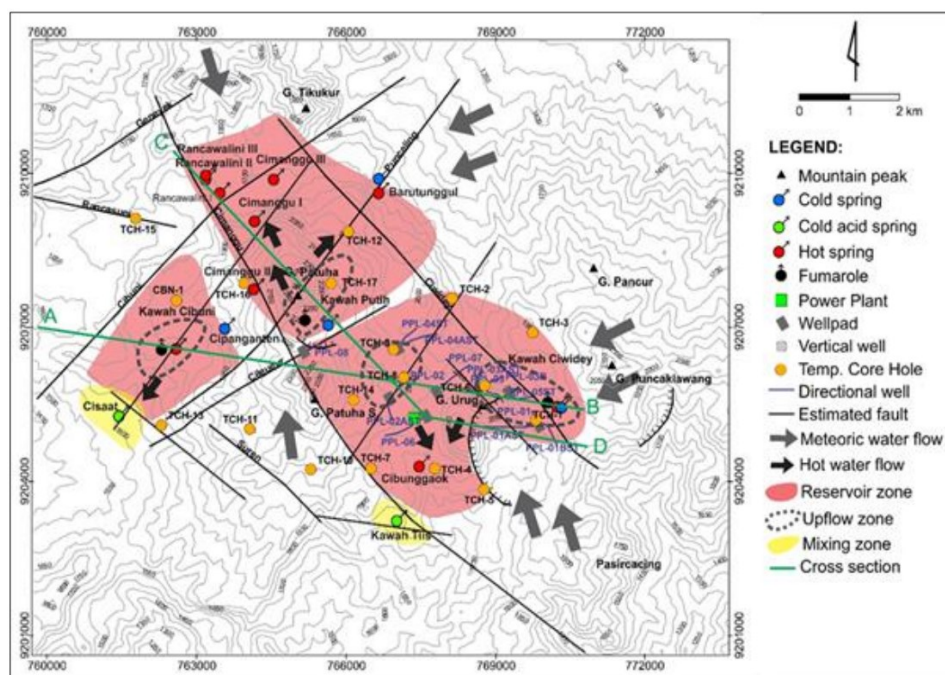


Figure 2. Conceptual lateral fluid flow pattern within the studied vapour-dominated geothermal field, illustrating the inferred pathways of geothermal fluids controlled by geological structures (Ashat & Pratama 2017)

influenced by the Bandung depression zone (Bemmelen 1949).

Based on the depression, a series of normal faults often predominantly trend in the NW–SE and NE–SW directions, forming part of a larger transverse zone. In this case, nine major faults are distributed along the lower slopes and eruption points, where small waterfalls and geothermal manifestations are found. These manifestations include fumaroles, hot springs, cold gas discharges, mudpools, cool, acidic water, and steaming ground areas.

## METHODOLOGY

This study aims to evaluate the mineral scaling potential and estimate the relative calcite scaling growth rates in production wells from a vapor-dominated geothermal field using geochemical screening and simplified kinetic approaches. The methodology combines geochemical screening using saturation indices with a simplified kinetic-based approach to estimate the relative thickness of calcite scaling. The applied methods are intended to support operational assessment rather than to provide a fully rigorous thermodynamic description of the system.

Geochemical data were obtained from produced fluid samples collected at selected production wells during routine field monitoring. The analyzed parameters include temperature, pH, calcium concentration, bicarbonate concentration, and dissolved silica concentration. All concentrations are reported in parts per million. The sampling and laboratory analyses were conducted in accordance with standard operational procedures used in geothermal field monitoring. However, detailed analytical uncertainty and replicate measurements were not available for this study and are acknowledged as a limitation.

The Oddo and Tomson (Oddo & Tomson, 1982, 1994) method was applied as a screening tool to evaluate carbonate scaling tendency, while classical indices such as Stiff and Davis (Stiff & Davis 1952) and Ryznar (Ryznar 1944) were used for comparative assessment. The dissolved gas content in geothermal fluids, which occurred during the removal process, led to changes in

conditions. These changes were primarily caused by decreased pressure and increased temperature (Vetter & Kandarpa 1982).

Based on the Oddo-Tomson method, the tendency estimation of calcium carbonate scaling formation was determined regarding the CSI value through the following conditions, i) The saturation of water with calcium carbonate was observed due to a negative CSI value, and scaling was unlikely formed, ii) The water was above calcium carbonate saturation due to a positive CSI value, indicating the formation of scaling, and iii) The water was at the point of saturation when  $CSI = 0$ , with no scaling expected.

To determine the CSI value, the following calculation formula is used based on the analyzed experiment of,

$$CSI = \log \frac{IAP}{K_{sp}} \quad (1)$$

where, CSI is Calcite Saturation Index, IAP is the ion activity product of calcium and carbonate species, and  $K_{sp}$  is the solubility product of calcite at the relevant temperature. Determining the solubility product ( $K_{sp}$ ) value in each well was necessary to calculate the Calcite Saturation Index. The CSI values were interpreted as follows. CSI values greater than zero indicate supersaturation and a potential for calcite precipitation. CSI equal to zero represents equilibrium conditions, while CSI values less than zero indicate undersaturation and an absence of calcite scaling tendency.  $K_{sp}$  values were obtained from published temperature-dependent thermodynamic data.

To predict the potential formation of silica scaling, saturation index values were also adjusted to the Fournier and Rowe (Fournier & Rowe 1977) equation. This equation compared the actual and amorphous silica concentration, with Equation 2,

$$SSI = \frac{\text{Silica Concentration Solution}}{\text{Amorphous Silica Concentration Solution}} \quad (2)$$

the value of amorphous silica concentration was also determined by using a proposed formula to measure silica scaling in the Lahendong geothermal field (Ciptadi & Patangke, 2001),

$$\text{Log } C = 4.52 - (731/T) \quad (3)$$

where  $C$  is the amorphous silica concentration, and  $T$  is the absolute temperature of the fluid (K). Furthermore, the occurrence of silica scaling was determined regarding the SSI value. SSI values greater than one indicate supersaturation and potential silica scaling, whereas SSI values less than one indicate undersaturation. This approach provides a first-order screening of silica scaling potential and does not explicitly account for kinetic inhibition or phase transformation effects. To determine the growth rate of calcite, scaling was also determined by the Zhang CST (calcite scaling thickness) method, which analyzed kinetic properties (Zhang et al., 2001). This method implementation was previously carried out in the Kangding field, China (Yiman 2017), through Equation 4,

$$CST = R_L * (\text{day in second}) \quad (4)$$

where,  $R_L$  Growth rate (m/s), with the value subsequently determined using Equation 5,

$$R_L = K_p * (S^{0.5} - 1)^2 \quad (5)$$

where  $S$  is the Saturation Ratio, and  $K_p$  is the Empirical rate constant. Based on this formula, the empirical formulation proposed by Zhang et al. (2001) was used to estimate the kinetic rate constant,  $K_p$ , based on fluid temperature, pH, and ionic strength. This expression was adopted directly from the literature and was not recalibrated using field-specific kinetic data through Equation 6,

$$\log K_p = 0.123 * (I)^{0.5} - \frac{2400}{T} - 0.34 * pH - 0.222 \quad (6)$$

where  $I$  is Ionic Strength,  $T$  is Geothermal Fluid Temperature, and  $pH$  is Water Acidity. The calculated CSI values were used to indicate calcite supersaturation, while the saturation ratio,  $S$ , served as input for the kinetic-based CST estimation, providing a relative indicator of scaling growth severity.

The precipitation rate was calculated as a function of saturation ratio and an empirical rate constant. The resulting rate, expressed in meters per second, was converted to an equivalent

monthly thickness assuming continuous deposition over time. This conversion provides an operational indicator of relative scaling severity rather than an absolute prediction of deposit thickness.

Several simplifying assumptions were applied in this study. Ion activities were approximated by measured concentrations, and pressure-dependent speciation,  $CO_2$  degassing dynamics, and gas-liquid interactions were not explicitly modeled. The kinetic parameters were adopted from published studies and were not calibrated specifically for the investigated field. Consequently, the calculated CSI and CST values should be interpreted as indicative metrics for operational planning rather than precise thermodynamic or kinetic predictions.

## RESULT AND DISCUSSION

Fluid samples from selected production wells in a vapour-dominated geothermal field were analyzed to assess their geochemical characteristics and scaling tendencies. The measured parameters include temperature, pH, calcium concentration, bicarbonate concentration, and dissolved silica concentration.

Table 1 summarizes the geochemical properties of the analyzed wells. All geochemical parameters used in this study were measured at surface conditions during routine field monitoring. The analyzed samples represent liquid-dominated produced fluids. No back-calculation to in-situ reservoir conditions was performed, and the effects of  $CO_2$  degassing, pressure changes, and phase separation were not explicitly modeled. These factors are acknowledged as limitations of the applied screening approach.

Table 1. Geochemical content of the vapour-dominated production wells

Variable	P well	R well	D well
Temp	190.30°C	177.12°C	178.36°C
pH	8.51	5.95	5.35
Ca	5.56 ppm	0.3 ppm	1.25 ppm
SiO <sub>2</sub>	98.52 ppm	14.7 ppm	9.6 ppm
HCO <sub>3</sub>	26.93 ppm	7.32 ppm	3.6 ppm



Table 2. Calcite saturation index (CSI) and Silica saturation (SSI) values in P, R, and D wells

Variable	CSI	SSI
P	3.25	0.11
R	-0.579	0.018
D	-0.267	0.012

However, during the production period, scaling problems occurred. This could result in a decrease in production rate, with the potential for the formed scale to be analyzed for accompanying minerals carried by geothermal fluids. The following mineral content is presented based on data from wells P, R, and D.

The measured fluid temperatures range from approximately 177 °C to 190 °C. The pH values exhibit notable variability between wells, with one well displaying alkaline conditions, while the others show mildly acidic to near-neutral conditions. Calcium and bicarbonate concentrations are also higher in the alkaline well compared to the other wells, suggesting a greater potential for carbonate mineral supersaturation under production conditions. Calcite was the first mineral to be analyzed to determine the CSI value, with the results presented in Table 2.

Table 2 presents the evaluation of calcite scaling tendency using the Calcite Saturation Index, calculated according to the previously described methodology. CSI values greater than zero indicate supersaturation with respect to calcite, while CSI values less than zero indicate undersaturation. Table 2 shows that there is no silica scaling formation in the P, R, and D wells. This was supported by the provisions of the SSI value limit, where SSI less than one emphasized the non-formation of silica scaling.

The results of this study indicate that calcite scaling potential varies significantly between production wells within the investigated vapour-dominated geothermal field. Only one well exhibits calcite supersaturation based on the calculated CSI values, while the remaining wells remain undersaturated. This finding highlights the importance of site-specific geochemical evaluation, as scaling risk cannot be inferred solely from field-wide temperature or reservoir type. The observed

association between alkaline pH, elevated calcium and bicarbonate concentrations, and positive CSI values is consistent with established carbonate precipitation mechanisms in geothermal systems. During production, pressure reduction and CO<sub>2</sub> degassing may increase pH and promote calcite supersaturation.

Silica scaling was not identified as a significant operational concern in the investigated wells, as indicated by SSI values below unity. Although silica scaling is frequently reported in high-temperature geothermal systems, its occurrence depends on dissolved silica concentration, cooling history, and phase separation. In vapour-dominated systems with limited liquid transport and relatively low dissolved silica concentrations, silica precipitation may be kinetically inhibited or operationally insignificant. The present results are therefore consistent with studies that report minimal silica scaling under similar production conditions. The estimated calcite scaling growth rate derived using the simplified kinetic approach provides an indication of potential deposit accumulation over time. Given the assumptions applied in the calculation, including concentration-based approximations and empirical kinetic parameters, the estimated growth rate should be interpreted as a relative indicator rather than a precise prediction. Nonetheless, even gradual accumulation of calcite over extended production periods may contribute to increased flow resistance and pressure losses, particularly in near-feed zones or restricted wellbore sections.

Scaling in the production wells, specifically calcite formation in the P well, is shown in Figure 3. This led to various issues, including a decrease in production rate, which is consistent with the presence of calcite scaling. The CST value was calculated to determine the calcite growth rate in the production well.

Based on the applied empirical formulation, the estimated  $K_P$  value, derived from the empirical formulation, was  $1.46 \times 10^{-8}$ , which was then substituted into the  $R_L$  formula for the speed of calcite mineral deposits, yielding  $2.03 \times 10^{-10}$  m/s. By determining the speed of calcite precipitation, the growth rate of the deposits was also calculated

for each month's timespan. Therefore, the value of calcite scaling growth in the well was 0.05 cm/month. This value should be interpreted as an indicative estimate rather than an exact prediction, as it is subject to uncertainties associated with simplified geochemical assumptions and empirical kinetic parameters.

A simplified kinetic-based approach was applied to estimate the relative growth rate of calcite deposits. The resulting estimate provides an order-of-magnitude indication of potential calcite accumulation over time rather than a precise prediction of scaling thickness. When interpreted within these limitations, the results suggest that periodic well-cleaning interventions may be necessary to mitigate the operational impacts of calcite scaling in affected wells. The operational implications of calcite scaling identified in this study are consistent with previous investigations, which show that calcium carbonate precipitation can contribute to plugging and degradation of production and injection performance. Earlier studies emphasize that such scaling-related impacts

highlight the importance of integrating geochemical indicators with operational observations for effective field management (Usman, 2015).

Direct mineralogical validation of calcite scaling, such as X-ray diffraction or scanning electron microscopy, was not available for the investigated wells. Therefore, model validation in this study relies on operational consistency between calculated scaling indicators and observed field behavior. The production well, which exhibited positive CSI values and a higher estimated CST, also required more frequent well-cleaning interventions and showed shorter production recovery periods.

This consistency suggests that the applied geochemical and kinetic indicators effectively capture the relative severity of scaling under operational conditions, although they do not constitute definitive proof of causality. Accordingly, the calculated indices are interpreted as screening-level tools that support operational decision making rather than predictive models of

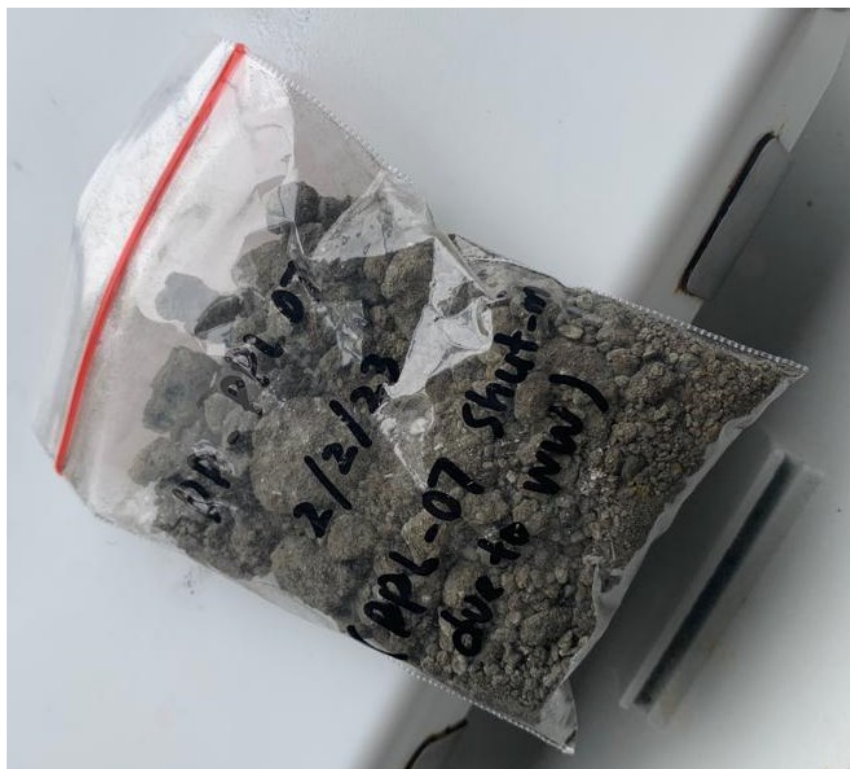


Figure 3. Visual evidence of calcite scale deposits observed in the production well indicates mineral accumulation along the wellbore under production conditions.





Figure 4. Temporal comparison between production performance and estimated calcite scaling growth following the well washing intervention. Production rate and scaling growth are shown as relative trends over time, illustrating short-term production recovery and subsequent decline.

exact scaling rates. In the absence of detailed economic optimization, the selection of a cleaning strategy should therefore consider both scaling severity and operational constraints rather than relying solely on estimated scaling rates.

According to the results, several well intervention methods have been applied in geothermal operations to mitigate calcite scaling, including well washing, coiled tubing cleaning, and mechanical reaming. In the investigated field, these methods exhibit different operational lifetimes and cost implications. Mechanical reaming generally provides the longest period of restored production performance, albeit at a higher operational cost, while coiled tubing offers an intermediate solution. Well washing represents a lower-cost option but may involve operational risks and shorter effectiveness.

In this case, the well washing method was carried out by injecting cold water into wells with calcite scaling problems. The injected water then entered the well through the wing valve, lowering the temperature and reducing the saturation level of calcium carbonate in the feed zone. This process

helped decompose the formed calcite scaling and ensured the removal of the mineral deposits, leaving the well clean. For budgetary reasons, minimal direct operational cost was incurred to implement the approach. Additionally, the Well Washing method at the production well allowed for the maintenance of the production rate before experiencing a decline within one month. Figure 4 shows a growth rate of 0.0016 cm/month.

Figure 4 illustrates an anomaly where the well's production rate rapidly declined at small growth values. This was because the method could not effectively clean the calcite scaling, resulting in a rapid decline of the well, regardless of the small deposit growth value. Furthermore, the coiled tubing method involved injecting high-pressure water using a roto jet.

This tool was inserted into the well up to the cleaning target through the use of coil tubing. In this case, water was pumped at high pressure to clean the calcite deposits formed in the well. Using this method, the calcite deposits formed were appropriately eroded, and the temperature was

reduced. This performance reduced the saturation level of calcium carbonate minerals in the well, with an indicative operational cost of 5 billion rupiahs, based on field-reported experience.

The Coiled Tubing method, carried out at the well, also allowed for the maintenance of the production rate before it declined over a 4-month period, as shown in Figure 5. One of the tasks performed during workover and well service was the mechanical reaming method, which involved using a rig and bit to remove scale deposits formed at a specific depth. This reaming activity was to restore the wellbore diameter affected by the presence of the deposits. During this activity, circulation was also performed to lift the scoured deposits, with an indicative operational cost of 12 billion rupiahs, based on field-reported experience. Additionally, the Mechanical Reaming method carried out on the well enabled maintenance of the production rate for 12 months, as depicted in Figure 6. Overall, the findings demonstrate that simplified geochemical and kinetic indicators can

provide useful guidance for operational decision-making in vapour-dominated geothermal fields. However, the results also highlight the need for integrated validation using activity-based geochemical modeling and direct scale characterization to improve predictive reliability and to support long-term field management strategies. The engineering implications discussed above are intended to provide planning-level insight into the relative trade-offs among well intervention methods and do not constitute a formal optimization or definitive operational recommendation.

## CONCLUSION

This study provides a quantitative, operationally oriented assessment of calcite scaling potential in selected production wells from a vapour-dominated geothermal field. Geochemical screening indicates calcite supersaturation in one production well, while other wells remain undersaturated, highlighting the influence of local fluid chemistry on scaling risk. Silica scaling is not expected to represent a dominant

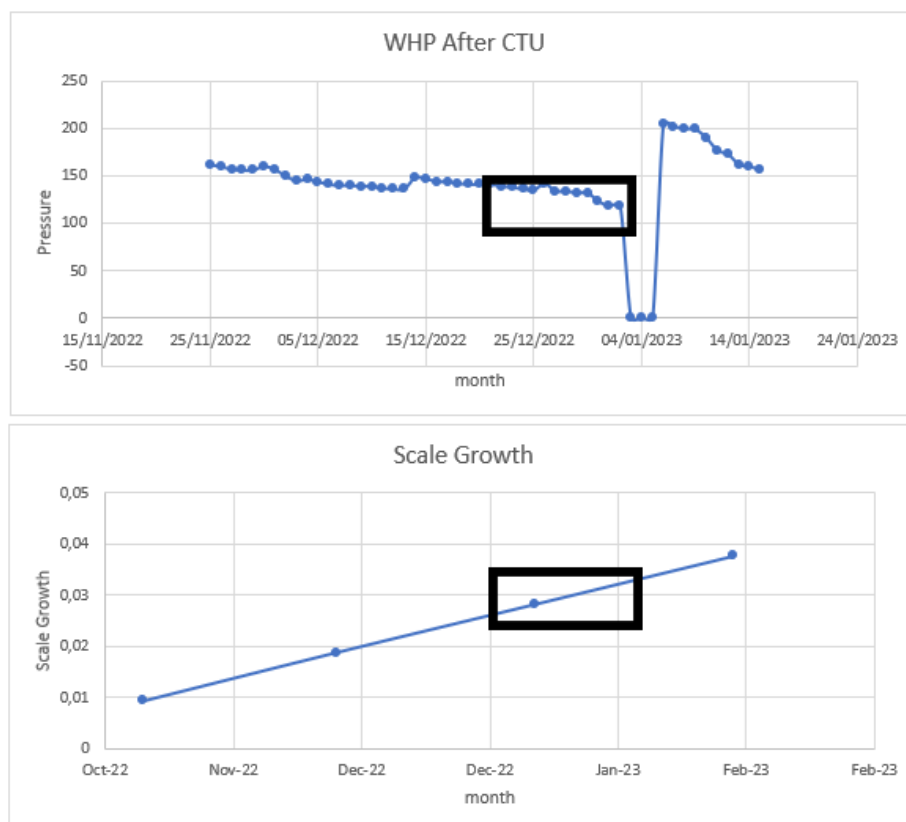


Figure 5. Temporal relationship between production performance and estimated calcite scaling growth after coiled tubing cleaning. The figure highlights the stabilization of intermediate-duration production relative to the estimated scaling accumulation trend.

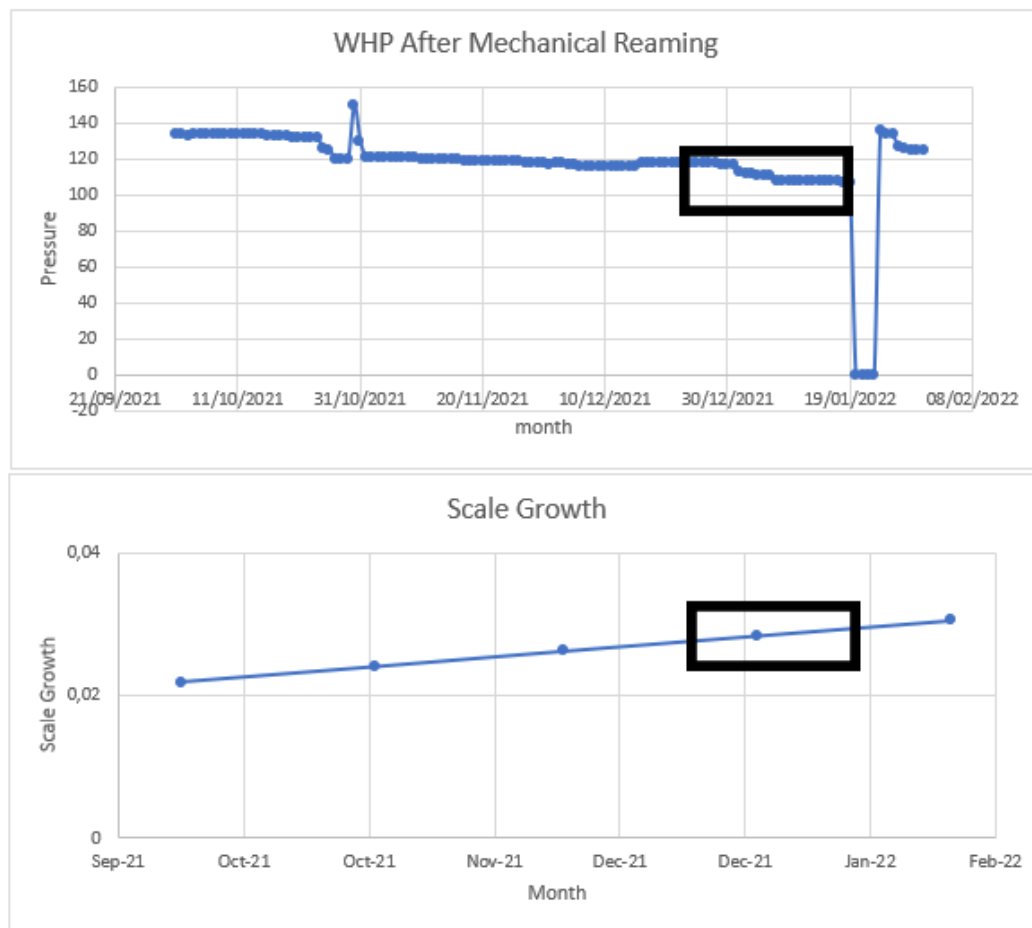


Figure 6. Comparison of production performance and estimated calcite scaling growth following mechanical reaming intervention, showing longer-term production stabilization compared to other cleaning methods.

operational concern under the investigated conditions. A simplified kinetic-based approach was applied to estimate the relative growth rates of calcite scaling. The resulting values represent order-of-magnitude indicators rather than precise predictions, suggesting that periodic well-cleaning interventions may be required in affected wells. Field observations indicate that different well intervention methods provide varying durations of production recovery and involve different cost and risk profiles. Overall, the results demonstrate that simplified geochemical and kinetic indicators, when interpreted in conjunction with operational outcomes, can support preliminary decision-making in vapor-dominated geothermal fields. These findings represent field-specific behavior and should not be interpreted as universal recommendations. Further validation using activity-based geochemical modeling, direct scale characterization, and pressure-loss analysis is

required to improve predictive reliability and support long-term field management.

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### GLOSSARY OF TERM

Symbol	Definition
SSI	Silica Saturation Index
CSI	Calcite Saturation Index
WS	Wackstone
$K_p$	Empirical Rate Constant
IAP	Ion Activity Product
$K_{sp}$	Solubility Product of Calcite
CST	Calcite Scaling Thickness
$R_L$	Growth Rate

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