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ANALYSIS OF POTENTIAL CALCITE SCALE AND SILICATE SCALE PROBLEMS IN DIFFERENT GEOTHERMAL PRODUCTION WELLS IN THE GEOTHERMAL FIELD FLORES INDONESIA

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Article Info

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ABSTRACT:

The Ulumbu Geothermal Power Plant (PLTP) is located at Mount Poco Leok, East Nusa Tenggara, Indonesia, with a capacity of 10 MW. Ulumbu PLTP has three production wells, analysis of potential scaling problems is needed to determine the scaling potential of UL-02 as a production well and planned UL-03 as planned for production well. Results of fluid samples A-03 and scale test results from A-02 samples show differences elemental and mineral dominant. The element that dominates from sample scale of UL-02 is Silicon (Si), that's indicate potential scaling silica problem SiO_2. In contrast to the test results of the UL-03 fluid sample, it shows dominant bicarbonate and indicate potential carbonate scaling problem at wellbore. The differences scaling products due to differences rock types at production zones of UL-02 and UL-03. The production well from UL-03 penetrates to Mudstone-Limestone & Sandstone rocks. The UL-02 well penetrates only volcanic rock, so the scaling product is dominated by silica scaling. The products from UL-03 and UL-02 scaling tend to be different, and detail result show in this paper. Calculations using Silica Saturation Index (SSI) and Larson Index (LI) completed the potential for scaling will occur when the well is produced.

Keywords: Geothermal, Silica Content, Silica Scaling, Silica Saturation Index, Production Optimization Unit.

1. INTRODUCTION

Understanding the characteristics and potential geoindicators of a geothermal field's reservoir through geochemical analysis of geothermal fluid samples is critical for determining the reservoir's water type, the entry of water into the system, and potential formation processes. This type of analysis focuses on the geothermal fluids' chemical composition, encompassing both water and steam, to uncover the fluid's properties and the influencing processes. These processes are relevant both within the reservoir and as the fluid ascends to the surface via production wells, shedding light on the geothermal system's behavior and potential [1]

Scaling, the formation of deposits from dissolved minerals in water, poses significant challenges in geothermal energy extraction. Notably, silica (SiO_2) in brine water is a leading cause of such scaling. The occurrence of scale formation is closely tied to temperature, salinity, and pH levels, with changes in these parameters causing ions to exceed their solubility and precipitate as deposits. Scaling can occur in various parts of the geothermal system, including pipelines, wellhead areas, separators, and reinjection wells, severely impacting the operational efficiency of geothermal energy facilities [2], [3].

The management and mitigation of scaling are crucial for maintaining the efficiency of geothermal energy systems. This involves continuous monitoring and adjustment of the

geothermal fluid's chemical composition to prevent the conditions that lead to scale formation. Advances in technology and chemical treatment methods have been instrumental in addressing these challenges, ensuring the sustainable operation of geothermal energy plants [4].
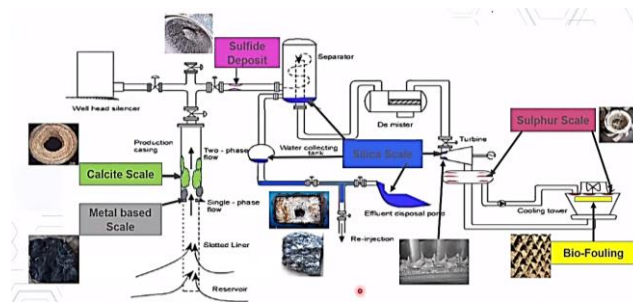

Figure 1. Common typical scale and location in geothermal

Scale deposition within geothermal systems, particularly atop the Slotted Liner Hanger and at the bottom of the production Casing, is a consequence of the physical and chemical changes associated with hot water flashing. The transition from hot water to steam—flashing—increases the concentration of certain solutes, leading to supersaturation and subsequent precipitation of minerals such as calcium carbo , barium sulfate, and silica (Martin & Davies, 2021). This process alters the pH balance exacerbates the scale formation, which can significantly impact the efficiency of heat transfer and fluid flow within the system [5], [6] The geochemical dynamics during flashing are complex, with temperature and pressure decreases playing a central role in promoting the nucleation and growth of scale deposits [7]. These changes are well-documented to occur at the aforementioned critical points in the geothermal system where rapid phase changes induce a shift in the equilibrium state of dissolved minerals [8], as shown in Figure 1.

The issue of scaling in geothermal systems, particularly from minerals such as calcite ($CaCO_3$) and silica (SiO_2), is a significant challenge in the operation of many geothermal systems. In low to medium temperature geothermal systems, the formation of calcite scale has been observed and reported by various researchers. Kristmannsdóttir (1978) noted the presence of calcite scaling in low-temperature geothermal systems in Iceland, where the scaling process is predominantly controlled by the degree of CO_2 degassing and the resultant pH changes that affect the solubility product of calcite ions [9].

Arnorsson (1985) provided a theoretical review of calcite deposition from geothermal waters, elucidating that geothermal fluids in reservoirs across different locales are often saturated with calcite. He also suggested that undersaturation of calcite may occur in some systems due to the lower levels of carbon dioxide which influence the geochemical conditions [10].

The Silica Saturation Index (SSI) serves as an indicator for assessing the potential for silica scaling in geothermal operations. It is a metric calculated by comparing the concentration of silica in a solution to its equilibrium concentration under identical conditions. The SSI provides a relative measure to anticipate the likelihood of silica scale formation, with values greater than 1 indicating a potential for scaling, while values less than 1 suggest that scaling is less likely. This index is particularly relevant for geothermal power plants where silica scaling can pose operational challenges. The calculation of SSI is an integral part of managing scale deposition in such systems [11].

Q(t1,m) is the solubility of quartz at reservoir temperature (t1) and salinity m, S(T,m) is the solubility of amorphous at flashing temperature and salinity m, x_2 is flashing vapor quality. The rate of scaling thickening in pipes can be calculated using the following equation:

$$S_t = \frac{[Q(T_1,m) - s(T_2,m)]}{1743 x \rho_{silica}} x365 \qquad t_{25\%} = \frac{D}{4 x s_t}$$

St is thickening rate of silica scaling (inch/year), ρ is silica silica density (43.442 g/in3), Q(t1,m) is solubility of quartz at reservoir temperature (t1) and salinity m, S(T,m) solubility of amorphous at flashing temperature and salinity m, D is pipe diameter (inch).

Calcium carbonate scaling, often in the form of calcite or aragonite crystals, is typically encountered within geothermal wells that operate at reservoir temperatures ranging from 140–240 °C. The formation of these scales primarily occurs at depths where water begins to boil within the well, a process which can precipitate these minerals from the geothermal fluids [12]. In addition to the well-known silica scaling, carbonate scaling is another significant issue in geothermal fields, often facilitated by an excess of bicarbonate (HCO_3^-) ions in the water. The likelihood of carbonate scaling can be assessed using the Larson Index (LI), which is a predictive equation taking into account various water chemistry parameters that influence carbonate mineral solubility and hence scaling potential [13]:

$$LI = \frac{[Cl] + [SO_4]}{ALK}$$

Cl   = chloride concentration (mg/l)
SO$_4$ = sulfate concentration (mg/l)
ALK   = bicarbonate concentration (HCO_3) (mg/l)

Carbonate scaling analysis can be seen using the Larson Index (LI) value, LI > 0.5 indicates that there is no scaling or corrosion, LI < 0.5 indicates the possibility of scaling.

Calcium carbonate scales can remain in well formation with high enthalpy and high drawdown as a result of fluid flow before reaching the wellbore.

Case Study

Flores Island, located in East Nusa Tenggara, possesses geothermal resource potential close to 1,000 megawatts, with reserves reaching 402.5 MW. PLN is currently developing the Ulumbu Geothermal Power Plant on the island to bolster the supply of clean and eco-friendly energy, as well as to address local electricity shortages. Ulumbu represents the inaugural geothermal drilling venture in East Nusa Tenggara (NTT) and covers an area of approximately 18,280 hectares.

The Ulumbu Geothermal Power Plant (PLTP Ulumbu) encompasses three geothermal wells: UL-01, UL-02, and UL-03. Presently, only the fluid from well UL-02 is utilized for electricity generation, while the output from wells UL-01 and UL-03 remains untapped. This document includes a cross-section of wells UL-01, UL-02, and UL-03. The Ulumbu PLTP features four generating units, labeled I, II, III, and IV, each with a 2.5 MW capacity. Unit IV commenced operations in December 2011, followed by unit III in June 2012. Units I and II started functioning in July 2014.

Each of the four generating units at the Ulumbu geothermal power plant is capable of producing 2.5 MW. Among these units, two are of the back pressure turbine type, while the remaining two are of the condensing type. This report includes further details such as the inlet pressure for each turbine and the steam consumption of each unit.

Fluid sampling conducted in 2018 revealed a calcium concentration of 53 ppm. During the fluid sampling process, with a wellhead pressure (WHP) ranging from 6.3 to 22.5 bar and a flow control valve (FCV) setting of 100 to 10%, well UL-03 exclusively produced steam, with no brine discharge. Samples of non-condensable gases (NCG) were collected using glass bottles, while condensate samples were gathered in plastic bottles. Total Dissolved Solids (TDS) measurements indicated a bicarbonate (HCO_3) concentration ranging from 64 to 461 mg/L. The analyses presented in this report cover geochemical and scaling assessments, as well as an evaluation of the scaling thickness within the UL-03 wellbore, taking into account scaling sample tests from the UL-02 well.

2. DISCUSSION

a. Geochemical Analysis of the UL-03 Well

Based on total dissolved solids (TDS) measurements, the bicarbonate (HCO_3^-) content was found to be predominant in well UL-03, with sulphate (SO_4^{2-}) content following closely behind. Bicarbonate often indicates the dilution of chloride-rich water, either by groundwater or by water containing bicarbonates, and it typically manifests in low-temperature system springs. These are generally located in the peripheral zones (outflow areas), where the pH is near neutral. This neutrality is a result of reactions between the geothermal fluids, surrounding rock formations, and groundwater. Sulphate, on the other hand, is a product of the condensation of H_2S and other ion particles. These elements find their way into the near-surface groundwater fluid (steam-heated water), affecting its geochemical composition (Table 1).

Table 1. Geochemical test results of UL-03 well condensate samples

Summary			#4	#3	#2	#1
WHP		bar	22.5	16.3	11	6.3
FCV		%	10	11	24	100
Sodium	Na	mg/L	0.38	0.12	0.07	4.57
Chloride	Cl-	mq/L	0.09	0.02	0.39	2.19
Boron	B	mq/L	<0.02	<0.02	0.91	1.21
Silica	SiO2	mg/L	<0.02	<0.02	<0.02	0.1
Arsenic	As	mq/L	0	0	0	0.01
Mercury	Hq	ma/L	<0.0005	<0.0005	<0.0005	<0.0005
Iron	Fe	mq/L	0.04	<0.03	0.1	<0.03
pH			6.78	7.02	6.21	6.79
Bicarbonate	HC03-	mg/L	61	232	64	132
Sulphate	5042-	mg/L	4.1	4	3.1	1.4

The geochemical analysis of four geothermal fluid samples reveals insightful trends in wellhead pressure (WHP), flow control valve (FCV) settings, and various elemental concentrations, which collectively suggest a dynamic and complex geothermal reservoir environment. The decreasing WHP from sample #4 to sample #1, coupled with an inverse relationship with FCV settings, hints at a sequential sampling strategy that may range from deeper to shallower reservoir locations, necessitating greater flow control at lower pressures. Notably, sample #1 stands out with significantly higher sodium and chloride levels, implying a strong saline influence or intense water-rock interaction processes. Similarly, this sample exhibits the highest concentrations of boron and the only detectable levels of silica, pointing towards marine influences or specific geochemical conditions that favor silica solubility. Interestingly, arsenic is present only in sample #1, suggesting localized mineral dissolution or contamination, whereas mercury remains undetectable, indicating its efficient removal or naturally low levels.

Iron concentrations, though generally low, are observable in samples #4 and #2, likely due to the oxidation of iron-bearing minerals. The pH values, varying from slightly acidic to near neutral, with sample #3 being the most neutral, reflect the potential for mineral solubility and scaling within the system. Furthermore, bicarbonate levels peak in sample #3, possibly indicating CO_2 degassing processes or dilution by meteoric water, while sulphate concentrations decrease towards sample #1, likely due to dilution or specific reducing conditions. These findings underscore the intricate interactions within the geothermal system and the importance of detailed geochemical monitoring to understand and manage these resources effectively.

This bicarbonate element can also cause scaling (deposition), especially when there is a decrease in temperature and pressure, where the deposition of bicarbonate can be seen from the spring output which contains travertine deposits. This sediment can then become a scaling process in the wellbore and be used in production facilities if the UL-03 well is later produced.

b. Geochemical Analysis of the UL-02 Well

The geochemical test results for the UL-02 well fluid sample, conducted before the fluid entered the Demister, revealed a significantly high silica (SiO_2) content, marked as being greater than 0.02. This is in stark contrast to the findings from the UL-03 sample, which registered a minimal SiO_2 content, also noted as being greater than 0.02 but presumably lower than that of UL-02. The silica content in the UL-03 well fluid sample is pending further confirmation through scale sample tests at the UL-03 well production unit. This discrepancy in SiO_2 concentrations between the two wells could indicate differences in geothermal fluid composition or interactions within the geothermal reservoir, underscoring the variability of geochemical characteristics across different sections of the geothermal field.

Table 2. Geochemical Water Analysis results of UL-02 well fluid before demister

Parameter	Unit	Result	Metode
pH (25° C) In tab	-	4.1	APHA 4500 H 8-2017
Dissolved Sodium (Na)	mg/L	0.1	APHA 31118-2017
Dissolved Potassium (K)	mg/L	0.2	APHA 31118-2017
Dissolved Calcium (Ca)	mg/L	<0.1	APHA 31110-2017
Dissolved Magnesium (Mg)	mg/L	0.01	APHA 31118-2017
Ammonia (NH)	mg/L	45	APHA 4500 NM,F-2017
Dissolved Lithium (Li)	mg/L	<0.01	APHA 31118-2017
Chloride (CI)	mg/L	0.08	IKL 5 Bab 6.72
Bicarbonate (HCO$_2$)	mg/L	<1	APHA 23208-2017
Sulfate (SO$_4$)	mg/L	16	DXL, 5 Bab 6.7
Fluoride (F)	mg/L	<<0.1	APHA 4500 FC-2017
Boron (B)	mg/L	2.6	JKL 5 Bab 6.9
Dissolved Silica (SiO$_2$)	mg/L	0.17	APHA 4500 SIO-D

The geochemical results of the UL-02 well fluid sample showed Ca values <0.1 mg/L and HCO_3 <1 mg/L, which are very low. These results indicate that the scale formed from the UL-02 well is not a bicarbonate product or not carbonate scaling.

From the results of the UL-02 geochemical well sample, it was obtained that the highest elements detected were sulfate (SO_4) and ammonia (NH_3). The high value of the sulfate element (SO_4) in the UL-02 well can be caused because the UL-02 well penetrates volcanic rock (Quaternary Volcanic Lower), allowing the presence of volcanic gas which then condenses the soil fluid near the surface. The presence of high levels of ammonia (NH_3) indicates that steam condensation has occurred near the surface and indicates that the basement (bedrock) is sedimentary rock (Figure 2).
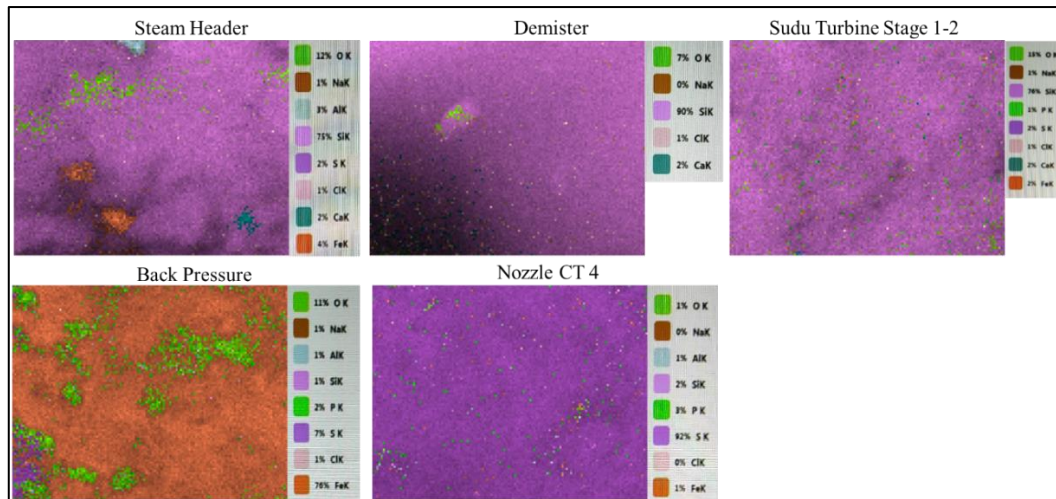
Figure 2. EDAX Map Test Results of scale samples from the UL-02 production well

This table shows (
Table **3**) the concentrations of chemical elements in various steam turbine components. These elements are essential to steam turbine function, and their concentrations must be monitored to ensure optimal turbine performance. In general, the concentrations of chemical elements in this image are within a reasonable range. However, there are several things you need to pay attention.

Table 3. EDAX Map table Test Results of scale samples from the UL-02 production well

Unsur	Steam Header (%)	Demister (%)	Stage 1-2 Pressure (%)	Sudu Turbine Back (%)	Nozle CT (%)
O	12	7	15	11	11
Na	1	0	1	1	0
Al	3	0	0	1	1
Si	75	90	76	1	2
S	2	0	2	1	92
Cl	1	0	1	1	0
Ca	2	2	2	0	0
Fe	4	0	2	76	1
P	0	0	0	2	3

provides a detailed look at the distribution of various elements across five distinct stages of a process, potentially indicative of a geothermal power plant's operational phases or similar industrial applications. Oxygen, represented in all stages with a moderate consistency, suggests its pervasive presence, likely tied to the steam or water vapor integral to the system's function. Notably, silicon (Si) dominates the early stages, particularly in the Steam Header and Demister, pointing towards its significant role or abundance in the initial process fluid, possibly due to the silica-rich nature of the geothermal fluid.

Sulfur (S) exhibits a dramatic shift, with minimal presence in initial stages but becoming the predominant element by the Nozzle CT stage, indicating processes that either concentrate sulfur or introduce it as a byproduct or contaminant at later stages. Iron (Fe) also shows an interesting distribution, with a substantial spike in the Sudu Turbine Back stage, suggesting processes of corrosion or the entrainment of iron-rich particles at high-temperature phases.

Other elements such as sodium (Na), chloride (Cl), calcium (Ca), and phosphorus (P) present in smaller amounts, fluctuate minimally across the stages, pointing to their lesser role or effective management within the system. The presence of aluminum (Al) is minimal and only notable at the beginning and towards the end, which could be indicative of specific interactions with the system's materials or particulate capture mechanisms in place.

Overall, the elemental distribution across the stages highlights the complex chemical dynamics within the system, illustrating how different components are introduced, removed, or concentrated throughout the process. This underscores the importance of monitoring and managing these elements to optimize performance, mitigate corrosion or scaling, and ensure environmental compliance.

Based on the EDAX test results for the UL-02 well, it was found that several elements were detected, where the highest element detected was Silicon (Si) content in the steam header, demister and turbine blade, indicating that product from scaling silica (SiO_2). The composition of Iron (Fe) is dominant in scale from Back Pressure, indicating the erosion of metal material in back pressure unit. Sulfur (S) dominates in scale at cooling tower nozzle and comes from sulfate (SO_4) which is condensed during the cooling tower unit and sulfate is very soluble in water. That's result equivalent with statement related Figure *1*.

Table 4. UL-02 XRF Test Results

Elemen	Konsentrasi	Satuan
Al	0.15%	%
S	9027%	%
Ca	0.12%	%
Mn	0.11%	%
Fe	699,148	%
Ni	361.7	ppm
Cu	491	ppm
Zn	56.8	ppm
Re	33.6	ppm

Note: ppm = parts per million

Based on the table above, it can be concluded that scale silica sample analyzed has highest iron (Fe) content, with 69.9148%. This iron content is much higher than other elements. The high iron content in scale silica samples is possibly caused by a corrosion process in the iron material. In samples at the back-pressure turbine location, indicating the erosion of metal material in the back pressure unit back pressure.

The content of other elements in scale silica samples is also quite high, like sulfur (S) at 9.027%, aluminum (Al) at 0.146%, calcium (Ca) at 0.122%, manganese (Mn) at 0.113%, nickel (Ni) at 361.7 ppm, copper (Cu) of 491 ppm, zinc (Zn) of 56.8 ppm, and rhenium (Re) of 33.6 ppm. The content of these elements may also be caused by corrosion processes in other materials, such as aluminum, manganese and nickel.

Analysis of the content of this scale silica sample can be used to determine the composition of the material contained in it. This information can be used for various purposes, such as to determine the quality of the material, to determine material processing methods, or to determine the potential utilization of the material.

c. Differences in Well scaling products UL-03 and UL-02

The test results of the fluid sample from the UL-03 well and the scale scale test results from the UL-02 sample show the dominant compositional differences in the test results. The element that dominates the scale scale test results of the UL-02 well is Silicon (Si) which is the forming

element of scaling silica SiO2 (shown in Figure 3), while the test results of the UL-03 well fluid sample show that bicarbonate is dominant which can form scaling carbonate.

The difference in scaling products could be due to differences in rock types in the production zones of the UL-02 and UL-03 wells. Geothermal fluids in some sandstone reservoirs tend to form calcium carbonate scaling and do not form calcium sulfate and silicate crusts (Shuai Ma, 2023). The UL-03 well contains HCO_3 which is the dominant potential Carbonate Scaling compound. The production zone of the UL-03 well penetrates to the depth of the Mudstone-Limestone & Sandstone rocks (explained in Figure...). The UL-02 well only reaches volcanic rock, so the scaling product is dominated by silica scaling. The products from UL-03 and UL-02 scaling tend to be different.
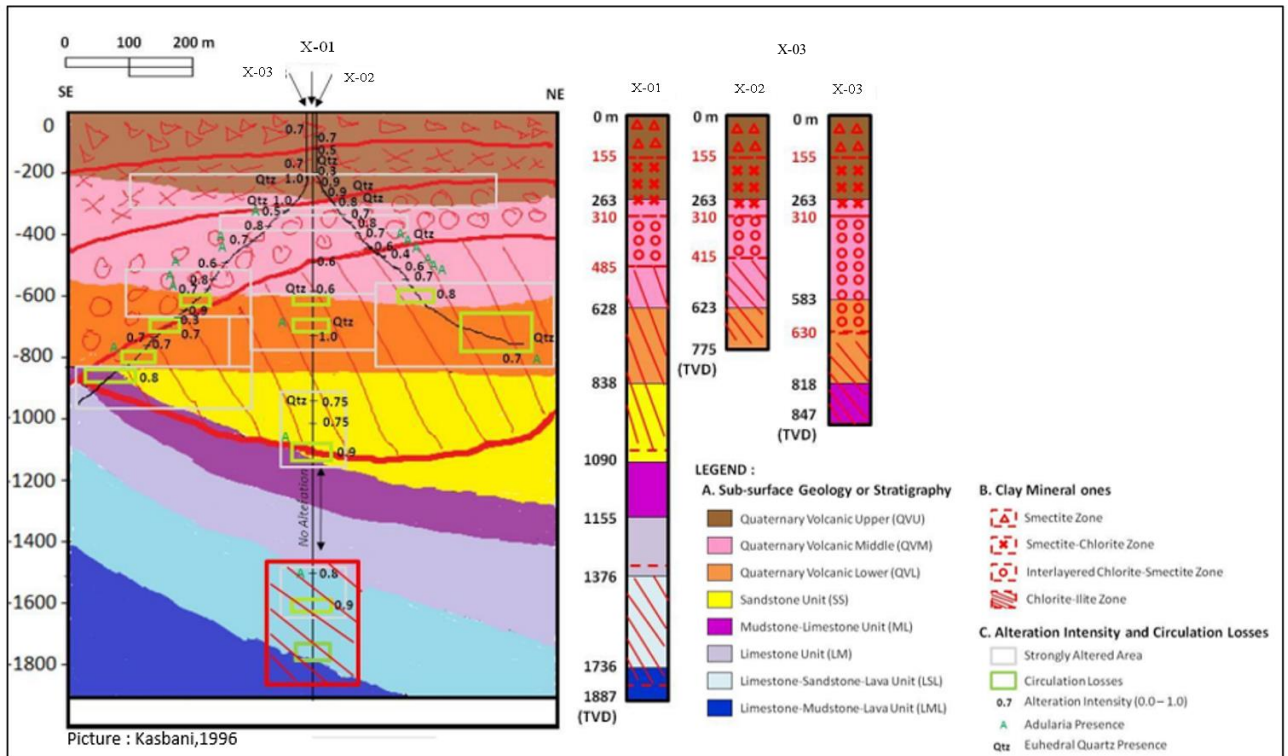

Figure 3. Well Profile UL-01, UL-02 and UL-03

Using the Template

d.   Silica Saturation Indeks

To estimate the occurrence of silica scaling in the UL-02 well, it is done by knowing the SSI value using data (**Table 2**) and the following formula:

$$SSI = \frac{Q(t_1,m)}{[s(T,m)(1-x_2)]}$$

$Q(t_1,m)$ is solubility of quartz at reservoir temperature (t_1) and salinity m. $S(T,m)$ is amorphous solubility at flashing temperature and salinity m. X_2 is flashing steam quality.

Table 5. SSI UL-02 Calculation Results

Column	Value
Reservoir Temperature (C)	230
Reservoir Temperature (K)	503.15
Solubility of Quartz at Reservoir Temperature (mg/kg)	261.31
Demister Fluid Geochemical Test Results (mg/L)	0.17
Demister Fluid Geochemical Test Results (mg/kg)	170

SSI	1.54
St	0.44
t25%	4.61

Based on the results of the SSI calculation, it was found that the SSI value was 1.54. From the results of these calculations, it can be estimated that scaling could occur. Based on the provisions of SSI > 1 then silica scaling may occur, SSI < 1 then silica scaling will not occur.

i. Indeks Larson

The Larson index is used to predict the calcium carbonate scale. The Larson Index (LI) can be defined as [13]:

$$LI = \frac{[Cl] + [SO_4]}{ALK}$$

[CI] is the concentration of chloride or halide, equivalently $CaCO_3$ (mg/L); [SO4] is the sulfate concentration, equivalent $CaCO_3$ (mg/L); and ALK is total alkalinity, namely the concentration of HCO_3 bicarbonate, equivalent to $CaCO_3$ (mg/L). Zhang et al. (2016) stated that: LI > 0,5, indicates no scaling or corrosion, and LI <0.5, indicating the possibility of scaling [13].

Table 6. Calculation results of silica potential using the Larson UL-03 index

Summary	Sampel #2	Sampel #3	Sampel #4	Sampel #1
The Larson index (LI)	0.06869	0.01733	0.05453	0.0272
	< 0.5 indicating possible scaling			

The Larson Index (LI) calculation results [13] show that there is a possibility of bicarbonate scaling, indicated by LI < 0.5. Based on both calculations, it was found that for the UL-03 well it was possible for silica scaling to occur, while for the UL-03 well from the Larson Index calculations it was possible for calcium carbonate scaling to occur.

e. Estimated Rate of Scaling Thickening of the UL-02 Well

In this study, because the potential for scaling that will occur in the UL-03 well is carbonate scaling, the rate of scale thickening in the UL-03 well cannot be predicted. The rate of scale thickening in the wellbore is predicted in the UL-03 well, using data Table 5 and the following equation:

$$S_t = \frac{[Q(T_1,m) - s(T_2,m)]}{1743 x \rho_{silica}} x365 \qquad t_{25\%} = \frac{D}{4xs_t}$$

S_t : silica scaling thickening rate (inch/year), ρ_{silica} : silica density = 43,442 g/in^3, Q (t_1,m) : solubility of quartz at reservoir temperature (t_1) and salinity m, S(T,m) : amorphous solubility at flashing temperature and salinity m, D : Pipe diameter (inch)

On Table 5 it was found that the rate of silica scaling thickening in the UL-02 well was 0.44 inches/years, and it was predicted that the drilling hole diameter would decrease by 25% of its original size in the 4.61st year. Where the rate of thickening of silica scaling is very fast so it is necessary to prevent silica scaling in the UL-02 well.

3. CONCLUSION

The UL-03 well contains HCO3 which is the dominant potential Carbonate Scaling compound. The production zone of the UL-03 well penetrates to the depth of Mudstone-Limestone & Sandstone rocks. The UL-02 well only reaches volcanic rock, so the scaling product is dominated by silica scaling. The products from UL-03 and UL-02 scaling tend to be different. The possibility of sedimentation (scaling) in production facilities from the UL-02 and UL-03 wells can form, but the scaling that is formed is different for the UL-02 well, which is silica scaling, while UL-03 is bicarbonate scaling. The rate of silica scaling thickening in the UL-02 well is 0.44 inches/years, and it is predicted that the drilling hole diameter will decrease by 25% of its original size in the 4,61 year. The Calcium Carbonate scale prevention program can be carried out by injecting scale dispersion online continuously until it reaches the total depth of the well. The scale disperser is injected through the capillary tubing with a special pump using a method called downhole scale inhibition (DSI).

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