

Injection Well Chemical Cleanouts at Zunil, Guatemala: A Low-Cost Caustic Treatment to Remove Silica Scale from Injection Wells R3 and R5

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ABSTRACT

The Ormat-operated Zunil geothermal power plant in Guatemala generates 20 MW of geothermal energy, utilizing combined brine and steam for power generation, with full reinjection through the use of binary technology. The field currently utilizes seven artesian production wells and up to four injection wells for a total flow of over 530 tons/hour (T/h) at a resource temperature of up to 275°C. As of 2018, the historic ZCQ-R3 and ZCQ-R5 multi-leg injection wells were taking 275-500 T/h brine each at average wellhead pressures (WHP) of 2-3 barg and injection temperatures between 80-90°C. Since that time, injection has declined to 60-150 T/h at 4.2-6.4 barg for the two wells and has been attributed to scaling within the wellbore and near wellbore formation. In an attempt to remediate scaling within these wells, an online chemical cleanout of the two wells was performed in June 2022 using the cycling of hot (80°C) injectate containing 2.5 wt.% sodium hydroxide (NaOH) and 0.25 wt. % ethylenediaminetetraacetic acid (EDTA) with the goal of 1) increasing silica solubility through increase of injectate above pH 12, and 2) mitigation of secondary calcite and metal silicate precipitation. Total cost for the project was less than \$70,000 USD and took place over a 48-hour period, and within 36 hours of treatment, the wells were showing a 65-75% improvement on injection volumes. Performance continued to improve over the next several months and had showed a 300-500% increase in injection capacity by the end of 2022. The program's success was such that the two wells are now capable of handling full plant capacity, allowing optimization of injection configuration strategies to other wells, reducing risks of long-term enthalpy declines, and providing additional capacity for production. Such programs highlight that simple, robust chemical cleanouts can remediate many injection-related scale issues without the need for complex pumping or chemical programs and can be done as part of regular reservoir maintenance.

1. Introduction

Silica oversaturation and precipitation has been a well-documented phenomena in the geothermal industry (Harvey, et al., 1976; Gunnarsson and Arnorsson, 2003; Brown, 2011; Brown, 2013) and, as a result, significant research has gone into understanding the mechanisms for scale formation (Marsh, et al., 1975; Weres, 1978; van den Heuvel, et al., 2018), its kinetics (Weres and Yee, 1978), and methods to reduce or mitigate those risks through operational design (Addison, et al., 2015) or chemical treatment options (Gallup, 2005; Gallup, 2011). Despite these efforts, proper silica management continues to be a challenge at a number of geothermal facilities, requiring alternative methods to adequately remove scale from surface equipment and injection wells through mechanical (McClatchie, Verity, 2000) or chemical methods (Lawson, et. al, 2018; Richardson, et al., 2018; Goh, et al., 2020), which can result in increased downtime and operational costs at those facilities. Chemical treatments have largely utilized a combination of hydrofluoric and hydrochloric acid (“mud acid”) to dissolve silica deposits in heat exchangers and injection wells, but the use of such acids is operationally challenging and poses risks to human health. Recent publications (Rose, et al., 2007; Portier, et al., 2009; Muller and Wilson, 2019; McLean, et al., 2021; Muller, et al., 2021) have highlighted alternative methods at laboratory and field levels, where the use of caustic and chelants are used to remove calcite and/or silica scaling in the near wellbore areas. Recent application at the field level has utilized the use of caustic and chelant at high pump rates and have shown to regain injection well capacity by up to several hundred percent, oftentimes exceeding the original injection capacity of the well for several months after treatment. These studies have not shown longer-term benefits of such treatments and may be partially masked by short-term thermal stimulation of the reservoirs but do suggest that alternative methods that utilize the increased solubility of silica at elevated pH and temperatures may be a more effective method for scale removal and recovering lost injectivity in wells affected by silica scale deposition.

The Zunil geothermal power plant is an Ormat-operated facility generating up to 20 MW of geothermal power through a combined binary system design with full-reinjection of brine and steam condensate into the reservoir. Recent loss of injectivity in two of the historic injection wells R3 and R5 was attributed to silica scaling within the wellbore and near-wellbore reservoir, resulting in a loss of generation of up to 4.5 MW due to lack of injection capacity for the excess production brine. As such, in June 2022, Ormat utilized a novel chemical cleanout option for these wells, applying a combination of caustic (NaOH) and chelant (ethylenediaminetetraacetic acid, EDTA) in an attempt to stimulate these wells and provide the necessary injection capacity without the need for additional drilling.

1.1 Resource Overview

The Zunil geothermal system (Figure 1) is situated within the Central American Volcanic Arc, a chain of dominantly calc-alkaline volcanoes stretching from southeastern Mexico to Central Panama that is a result of the subduction of the Cocos Plate. The oblique subduction of the Cocos Plate results in right-lateral intra-arc strain orientated along the NW-SE trend of the volcanic arc. Directly north of the volcanic arc in Guatemala, NW-SE to E-W extension dominates the deformation as a result of sinistral motion along the Polochic-Motagua Fault Zone. The Zunil Fault Zone is comprised of a series of NE-striking faults with perceived sinistral-normal kinematics, and which creates the steep-sided valleys that channel the Rio Samala.

As denoted by Foley et al. (1990), four key attributes may influence the location of geothermal activity at Zunil: (1) Enhanced permeability from caldera-margin faults of the 20 km-diameter Quetzaltenango Caldera; (2) enhanced permeability from the NE-striking Zunil Fault Zone; (3) a proximal young magmatic heat source (4 km to northeast of the center of the Santa Maria stratovolcano and 3 km from the Cerro Quernado domes/flows); and (4) the lower elevation of Zunil (approx. 2020-2175 mrs) relative to the surrounding topography (>2500 mrs).

Upflow occurs in the western region of the system, overlapping the NE slope of the Las Majadas Crater. The upflow reservoir fluid constitutes a 275-300°C, 0.2 wt.% TDS Na-Cl liquid reservoir with 0.1-0.4 wt% dissolved non-condensable gases and reservoir silica concentrations of 322 to 675 mg/kg; a typical range of resource chemistries at the field are shown in Table 1.

The reservoir is dominantly hosted in andesitic lavas and ash flow tuffs, and basement fractured granodiorite. Primary production for the field comes from this western part of the reservoir (e.g., ZD-1, ZD-2, ZD-3, ZD-4, ZD-6, ZCQ-3, and ZCQ-5RD2). A 15-25 bar pressure draw down has occurred in this part of the field since the pre-development state, resulting in the formation of a vapor-mobile two-phase zone in the upper ~600 m of the subsurface in the vicinity of well ZD-1; this zone supplies excess enthalpy to some of the production wells.

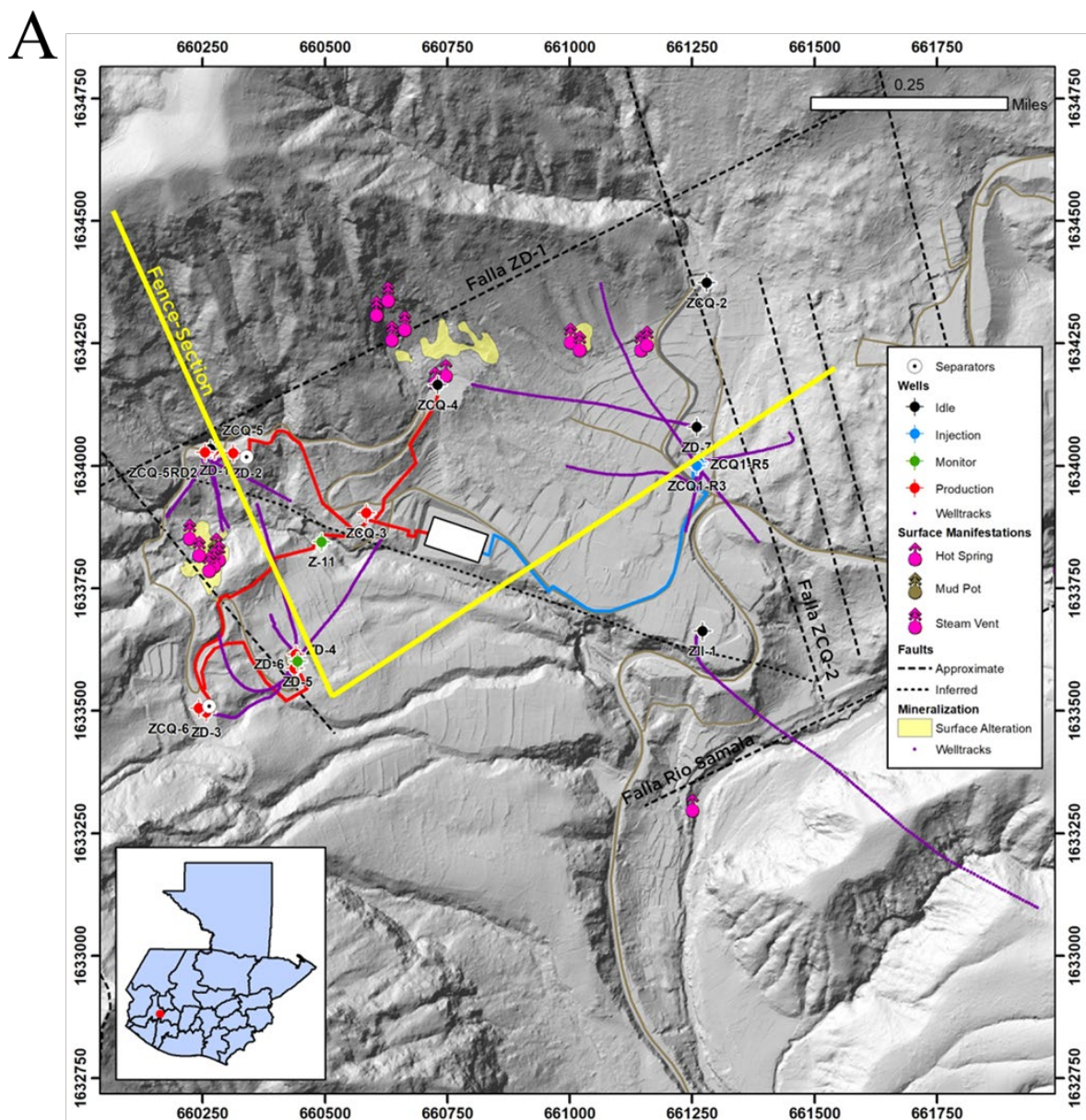
Field and LiDAR lineament mapping, the orientation of surface manifestations, feed zone alignment, and image log data from ZCQ-5RD2 support the notion that NE-striking faults, parallel to the Zunil Fault System (e.g., the ZD-1 and ZD-3 Faults) play an important role in supplying permeability to the system. A ~10,000 m² area of advanced argillic alteration, fumaroles, steaming ground, and vigorously boiling mud pools occurs above the main upflow region, seemingly controlled by the intersection of the NW-striking ZD-6 Fault with NE-striking fractures parallel to the Zunil Fault Zone.

Outflow is primarily directed to the northeast (i.e., towards the wells ZCQ-2 and ZCQ-1R3/R5), creating steam features proximal to the trace of the ZD-1 Fault and stretching east to the Las Cumbres Eco Hotel. Outflow also flows to the southeast, discharging as thermal bicarbonate, acid-sulfate, and Na-Cl springs and steam features along the banks of the Samala River (Adams et al., 1990). Injection into Zunil occurs in this eastern outflow region.

Table 1: 2022 Liquid Reservoir Characteristics for the Zunil Geothermal Field

Analyte	Range	Units
Enthalpy	873 to 1361	kJ/kg
Sodium	546.4 to 657.9	mg/kg
Potassium	63.2 to 145.7	mg/kg
Calcium	2.8 to 16.8	mg/kg
Magnesium	0.0 to 0.02	mg/kg
Lithium	3.7 to 6.2	mg/kg
Aluminum	0.13 to 0.45	mg/kg
Arsenic	4.7 to 6.3	mg/kg
Boron	21.9 to 28.0	mg/kg
Silica	321.6 to 674.6	mg/kg
Chloride	898 to 1023	mg/kg
Sulfate	21.0 to 111.4	mg/kg
Fluoride	2.4 to 4.8	mg/kg

Total Alkalinity	53.1 to 108.0	mg/kg as HCO ₃
pH	6.2 to 8.3	S.U.
Total Gas	0.03 to 0.34	Weight % in Total Flow



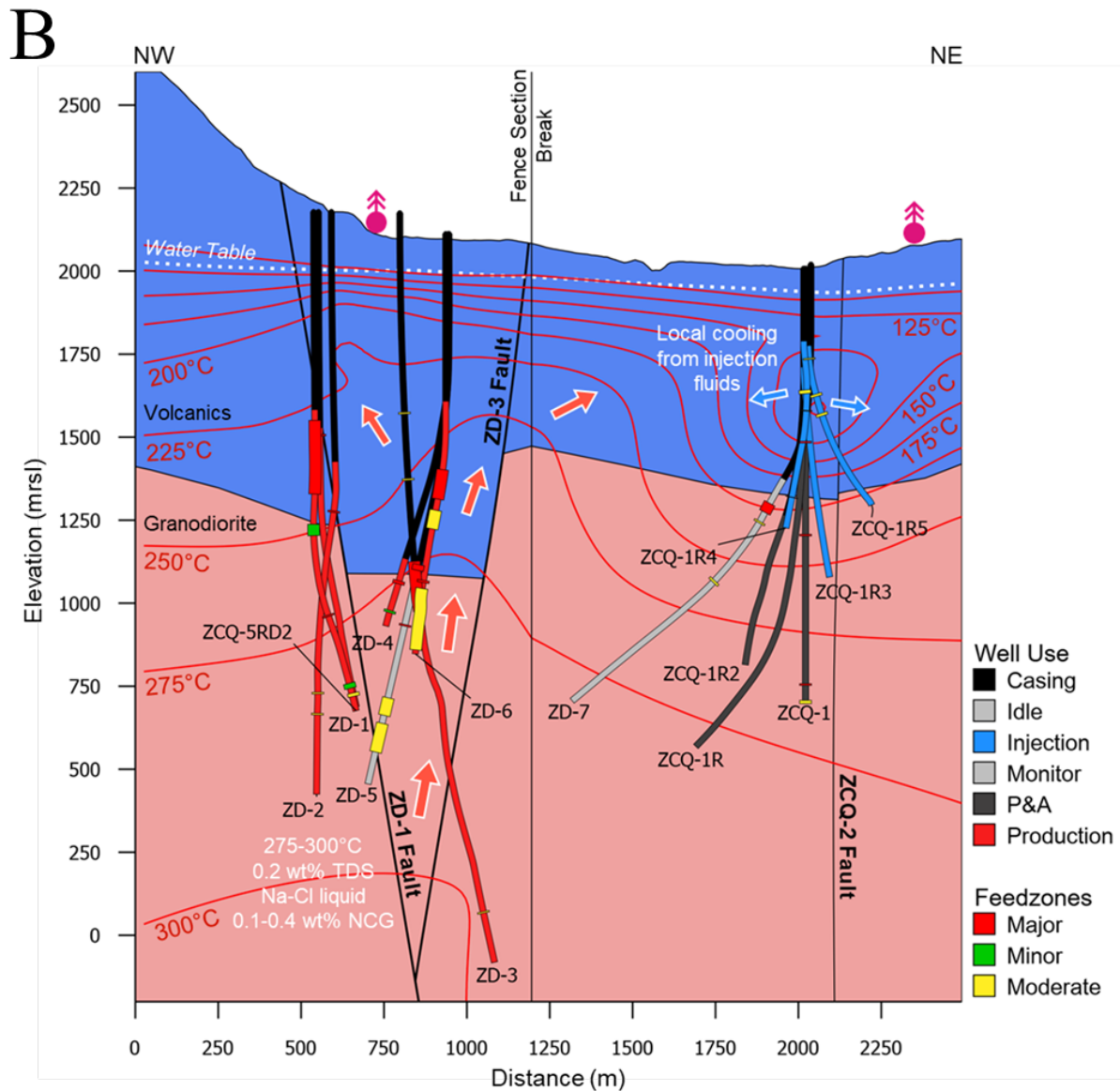


Figure 1B: Conceptual model fence section of the Zunil geothermal system shown by yellow line in Figure 1A

1.2 Plant and Injection Well Design and Operational History

Ormat operates the Zunil two-phase binary power plant with a design capacity of approximately 30 MW net (34 MW gross). The official start-up date for the plant was September 1999 when the plant capacity was 24 MW net. Since 2019, Ormat has done several upgrades at the plant and steam gathering system, and as of July 2023, the plant was generating at an average of about 17 MW net by using seven production wells, two active injection wells (R5 and R3) and one injection well which is under testing. Ormat has been operating the plant since the beginning of the project, but the well field was operated by the national electrical utility, Instituto Nacional de

Electrificación (INDE), until 2014 when Ormat started to operate the wellfield when geothermal fluid provided to the plant was only enough to generate approximately 8 MW net. Significant capital expenditures and time commitments have been made by Ormat in an attempt to reach design setpoints for the facility, including optimization and management of injection strategies for the field.

The historic ZCQ1-R3 and ZCQ1-R5 injection wells (R3 and R5; Figure 1) have been active since the start-up of the plant. All produced fluid had been injected into both wells until 2017 when ORMAT started to look into alternative injection strategies for the field. Well ZCQ1-R5 was planned to deviate the original ZCQ-1R, which had been drilled in 1992. Well R5 was drilled directionally from a kicking-off depth of 232 mTD, taking total losses at 274 mTD and completed to a final depth of 758 mTD (Figure 2A). Well ZCQ1-R3 is the first sidetrack of well ZCQ-1R2 and was deviated at 281 mTD with a total depth of 964 m. Another leg was drilled in ZCQ-1R2 and called ZCQ-2R4; the well encountered partial losses and it's considered that all injection into the well is going out of the R3 and R4 legs (Figure 2B).

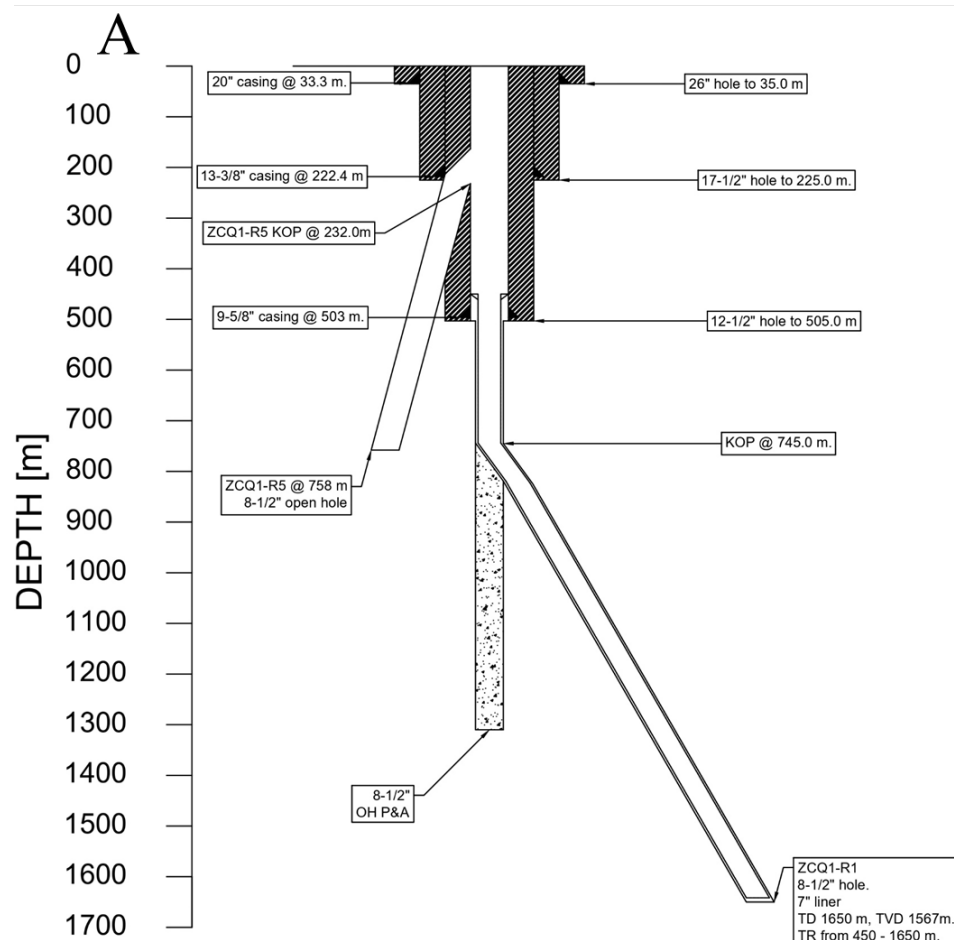


Figure 2A: Wellbore diagrams for ZCQ1-R5 showing the multi-leg nature of these injection wells.

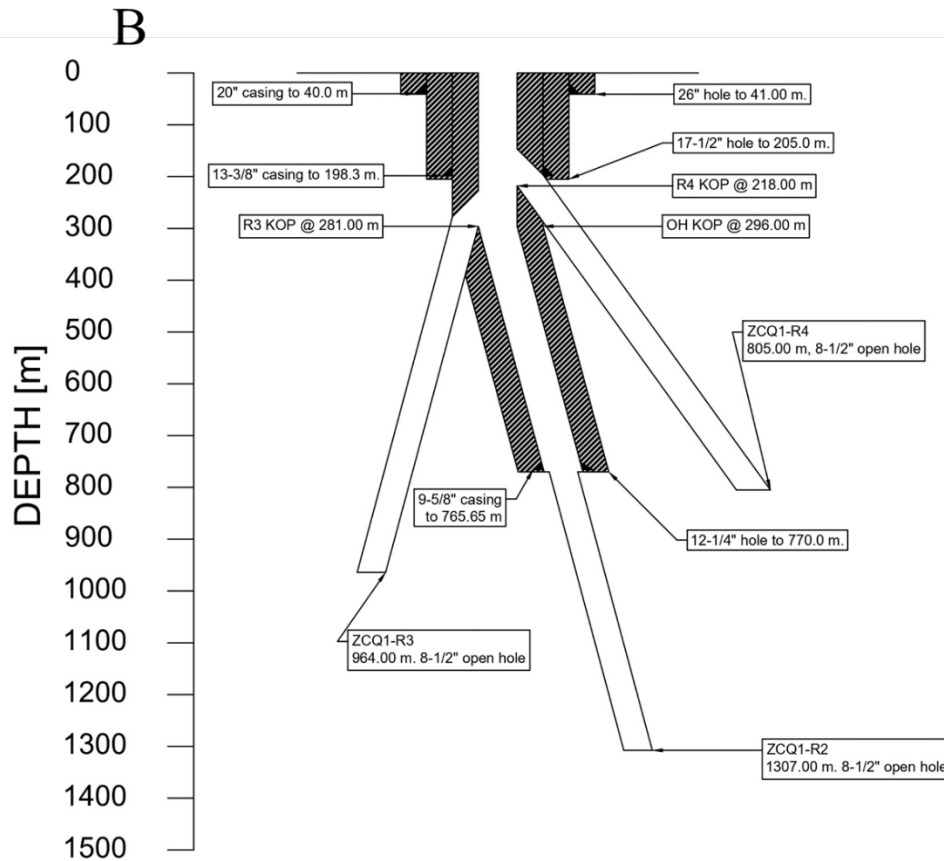


Figure 2B: Wellbore diagram for ZCQ1-R3 showing the multi-leg nature of these injection wells.

1.3 Production Challenges and Injection Scaling

Production scaling at the Zunil geothermal field includes downhole calcite scaling in production well ZCQ-3 (Rodriguez, 2021), as well as precipitation of aluminous and pure amorphous silica phases downstream of the primary separation stations. Silica scale occurs as a result of the reduced separator pressures that result in a silica saturation index (SSI) of 1.0-1.2 at the production well pads and causing scale deposition in brine accumulators and production piping (Figure 3). This resulted in significant loss of generation due to backpressure in production lines to the plant and the loss of brine at temporary surface discharges and lack of injection capacity, reducing generation by up to 4.5 MW. Silica scale had historically been treated using a chemical inhibitor with little to no effect and has been discontinued since 2022 in favor of regular cleanouts of surface piping using mechanical milling.

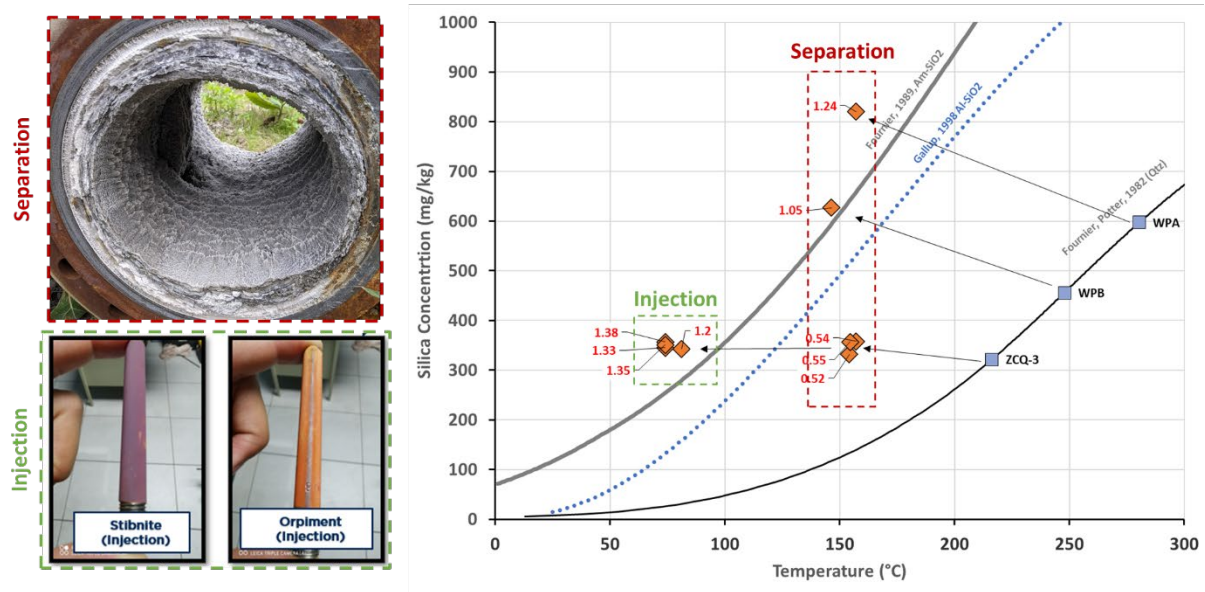


Figure 3: Production and injection scale risk for the Zunil geothermal plant for Q1 2022. Silica is oversaturated at Wellpad A and Wellpad B separation stations but undersaturated at the ZCQ-3 separator. Condensate dilution and heat extraction through the binary plant yields a final SSI of 1.2-1.4 at injection with antimony and arsenic sulfide deposition in the preheaters and injection lines. Historic injection (not shown) has reached SSI's as high as 1.8

Scaling within the heat exchangers and injection surface piping is limited to arsenic and antimony sulfides based on scale coupons and samples collected during outages, with no visual evidence for silica scaling during injection despite an SSI of > 1.3 (Figure 3). The lack of silica scale in the heat exchangers and injection piping is inferred to be the result of increasing polymerization induction times due to natural pH reduction of the injection fluids to pH ~ 5.6 - 6.0 with condensate reinjection. However, decreases in injection capacity at wells R3 and R5 raised concerns as to the possibility of silica scaling in the wellbore and near-wellbore region. Figure 4A and 4B shows wellhead pressure (WHP) and injection rate history for wells R3 and R5 from 2015 to 2023. Data in Figure 4A shows how well R3 was able to accept between 300 and 450 t/h with WHP below 3 barg as far back as 2016, but by 2020, injectivity had dropped to between 150 and 190 t/h at wellhead pressures between 3 and 6 barg. Similar trends are seen for well R5, with major losses in injectivity between 2018 and 2022 (Figure 4B). This coincides with reduction in injection temperatures from near 100°C to 75°C in early 2018 and suggests scaling as a root cause for injection loss (Figure 5).

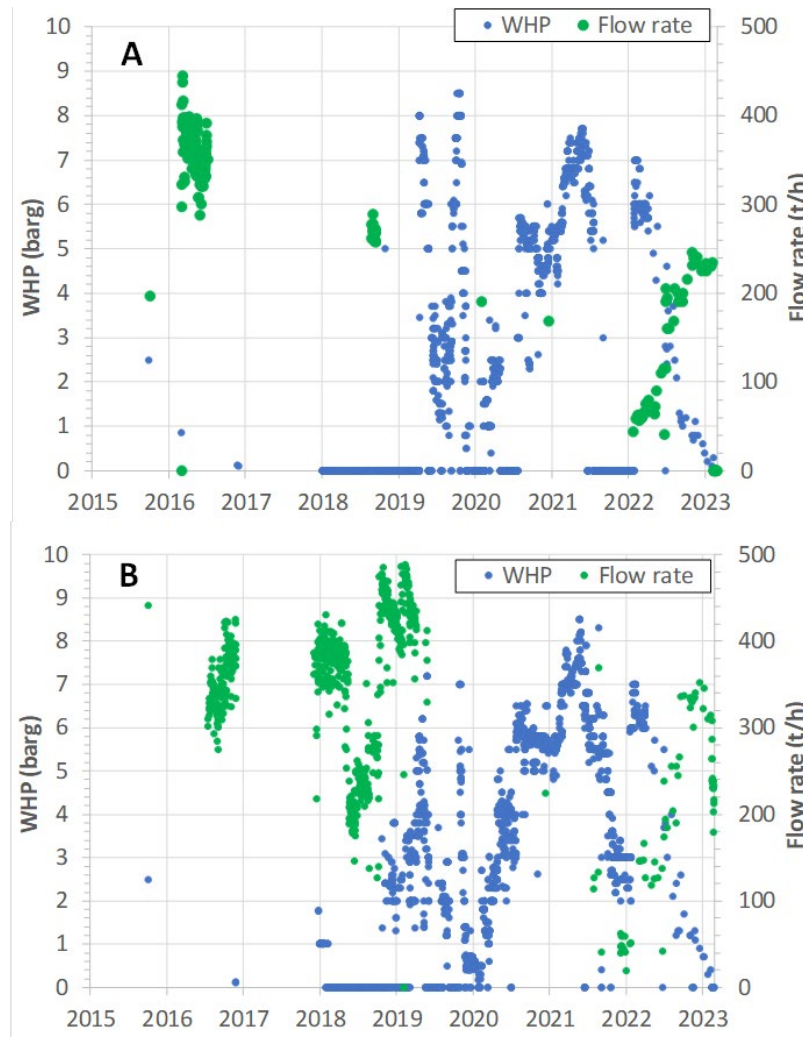


Figure 4: Injectivity plots showing measured wellhead pressures (WHP) in barg and injection rates in tons/per hour for injection wells A) R3 and B) R5 from 2015 through 2023. Initial high injection rates and low wellhead pressures through 2016 and 2017 gave way to decreasing flow while maintaining or increasing wellhead pressures in 2018, with the wells taking less than 100-190 t/h by 2020.

As part of the root cause analysis, surveys of nearby well ZD-7 (Figure 1) identified cooling of the shallow feeds in that well to near 80°C, suggesting that R3 and R5 injection had generated a low-temperature injection zone around the injection wells (Figure 6B). Historic reservoir tracer data was used to calculate a residence times for injection fluids within that zone, and based on that data, suggested that fluids may spend 10-44 hours migrating out of that region into higher temperature portions of the field (Figure 6A). Published silica polymerization curves (Gunnarsson and Arnorsson, 2005) suggest that, at the pH and temperature of the Zunil injectate, silica induction times may be retarded by the reduced pH by up to 17 hours (Figure 6C), although this sensitive to absolute silica concentrations and brine chemistries. However, this inhibition of silica polymerization is consistent with the lack of visual silica scaling in near-surface equipment and piping but may not be preventing scaling in the wellbore. To test this further, downhole cameras were used to inspect for scale in these wells and was able to identify the presence of significant amounts of amorphous silica scale on casing walls and downhole capillary tubing (Figure 7A) and was inferred to be the cause of the observed injection declines in those wells.

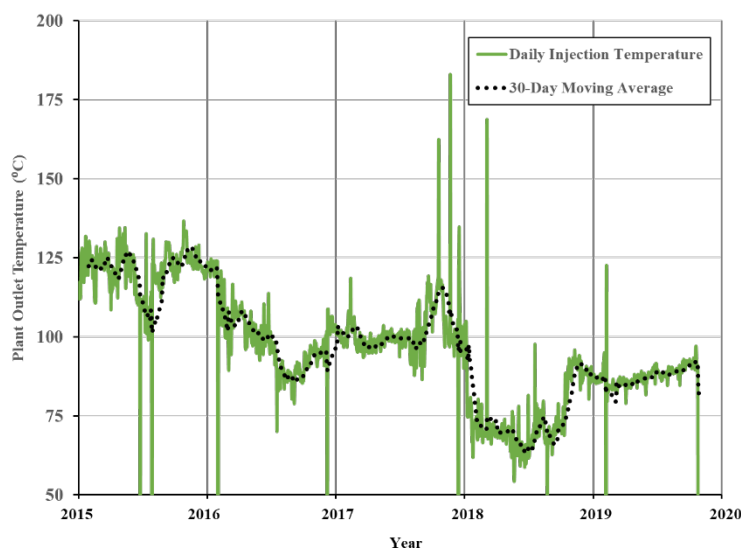


Figure 5: Reported plant outlet temperatures for the Zunil geothermal plant from January 2015 through October 2019. Outlet temperatures underwent a sharp decline from 2015 to 2016 (-25°C) and again between 2018 and 2019 (-25°C) to a final temperature of near 75°C as part of attempts to maximize generation from the facility.

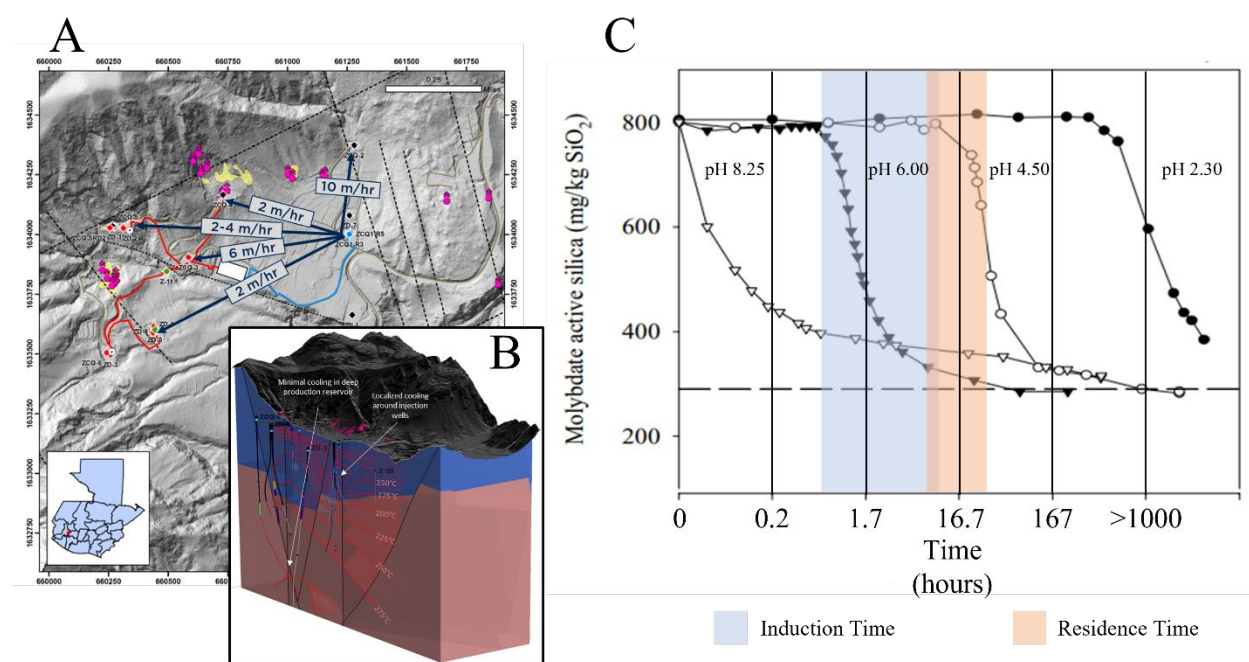


Figure 6: A) Inferred flow rates from injection wells R3 and R5 to nearby production wells based on several years of reservoir tracer studies at the Zunil geothermal field; flow rates were calculated based on first returns to a given production well and assumed a linear distance between the wells. Deviations of flow within subsurface structures were not considered. B) Surveys of adjacent well ZD-7 showed shallow cooling of this portion of the field and is inferred to be the result of long-term injection into R3 and R5. C) Polymerization curves as a function of pH at 80°C as determined by Gunnarsson and Arnorsson (2005) that suggest at the Zunil injection pH (5.6-6.0), induction times for silica polymerization may have been less than 17 hours, while residence times in the cooled injection zone may have been up to 44 hours.

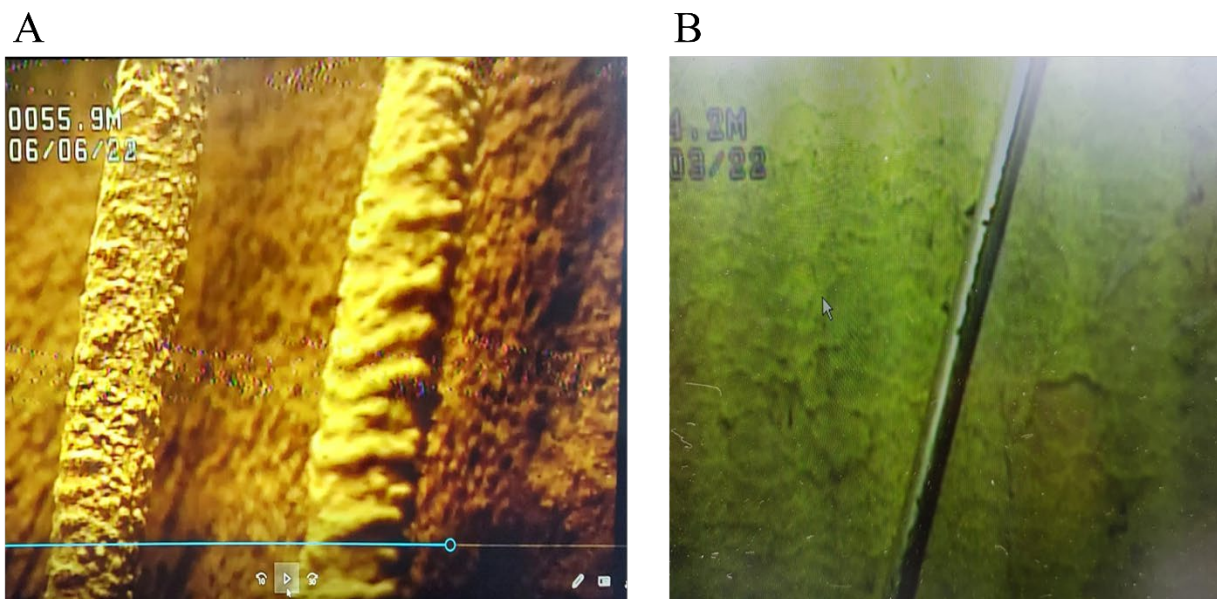


Figure 7: Downhole imaging from injection well R3 A) June 6, 2022, approximately 3 weeks prior to chemical cleanout, and B) August 3, 2022, approximately 5 weeks after chemical cleanout. Downhole capillary tubing left in place by INDE showed complete removal of silica scale, and wellbore walls showed significantly less to no silica buildup on those surfaces.

2. Methodology and Implementation

2.1 Proposed Treatment Program

In order to recover lost injectivity in injection wells R3 and R5, Ormat proposed the use of a combined caustic and chelant chemical program that was based on previous work by (K. Brown, pers. com). Caustic programs work to remove silica scale by increasing fluid pH to 10-12 and forcing silicic acid (H_4SiO_4) to dissociate to the highly soluble H_3SiO_4^- (Eikenberg, 1990; Brown, 2011; Lunevich, 2020). Scaling associated with the increased fluid pH is controlled through the use of a chelating agent (EDTA), which is supplied in above-stoichiometric dose rates to bind competing metals such as Ca, Mg, Fe, and Al that could lead to formation of carbonate or metal silicate species. The program would use pre-mixed solutions of 50% sodium hydroxide (NaOH) dosed at 2.5% by weight at injection temperatures (85°C) at an injection rate of 40 t/h (180 gpm). A 40% solution of ethylenediaminetetraacetic acid would be added at 0.25% by weight as a scale control additive and prevent secondary precipitation of calcite minerals or silicates. Chemical was to be dosed for 1 hour (R3) and 1.5 hour (R5) based on calculated wellbore volumes to major feed zones, then allowed to rest for 1 hour, then repeated for an additional two doses. After three total doses, the wells were to be shut in overnight prior to being returned to injection. Flow rates would be incrementally increased and WHP monitored for increases associated with blockages or secondary scale formation. Chemicals were to be purchased from in-country vendors and onsite mixing and pumping support was to be provided by a third-party contractor. Total estimated time for treating two wells was two days and wells were to be immediately returned to service after the program was complete.

2.2 Chemical Program

Table 2: Chemical Program

Well	Chemical	Flow Rate (gpm)	Dose Rate (gpm)	Stage Time (hr)	Gallons Chemical per Stage	Total Stages	Total Gallons Chemical
R3	50% NaOH	180	9.0	1.0	540	3	1620
	40% EDTA		0.9		54		162
R5	50% NaOH	180	9.0	1.5	810	3	2430
	40% EDTA		0.9		81		243

2.3 Operation Details and Cost

Table 3: Chemical Pumping Program

Stage	Well	Flow Rate (gpm)	NaOH Dose Rate (gpm)	EDTA Dose Rate (gpm)	Dose Time (hr)	Rest Time (hr)	Stage Time (hr)	Total Gallons per Stage
1	R3	180	9	0.9	1	1	2	10,800
2	R3	180	9	0.9	1	1	2	10,800
3	R3	180	9	0.9	1	1	2	10,800
1	R5	180	9	0.9	1.5	1	2.5	16,200
2	R5	180	9	0.9	1.5	1	2.5	16,200
3	R5	180	9	0.9	1.5	1	2.5	16,200

Table 4: Total Expected Budget for Wells R3 and R5

Line Item	Line-Item Description	Estimated Costs (USD)
1	Onsite Support (Chemical Mixing, Pumping)	40,560
2	(16) x 275 gal IBC 50% NaOH	18,252
3	650 kg EDTA Powder	6,812
4	Total Estimate	65,624

3. Results and Discussion

3.1 Visual Observations from Downhole Surveys

Subsequent visual surveys of R3 several weeks post-treatment showed marked visual differences as a result of the chemical cleanout. Previously scale-encapsulated capillary tubing (Figure 7A) was completely scale-free (Figure 7B) and previously heavy scaling on wellbore casing showed marked improvements in appearance.

3.2 Injectivity Trends: July 2022 through January 2023

Chemical cleaning was organized in Q2 2022 and performed in late June of that year, with results shown in Figures 8A and B. Wells showed improvement in injectivity near immediately and continued to improve over the next several months. By the end of 2022, R3 was accepting nearly 250 t/h at WHP of less than 1 barg (Figure 8A, inset), while R5 was accepting up to 310 t/h at similar wellhead pressures of less than 1 barg (Figure 8B, inset). Calculated injectivity indices, defined as the flow rate per unit wellhead pressure, showed a 300-500% increase for R3 and R5, respectively (Figure 8). This behavior of WHP and flow rate post-cleanout confirms that the wells were most likely losing injection capacity between 2018 and mid-2022 as a result of downhole silica scaling, and that injectivity improved as a result of the caustic chemical cleanout and removal of silica scale from the wellbore and formation. Continued improvement with time suggests no precipitation of secondary minerals or scale as a result of the cleanout and likely additional thermal stimulation of fracture networks as a result of scale removal and increased fluid flow into the formation.

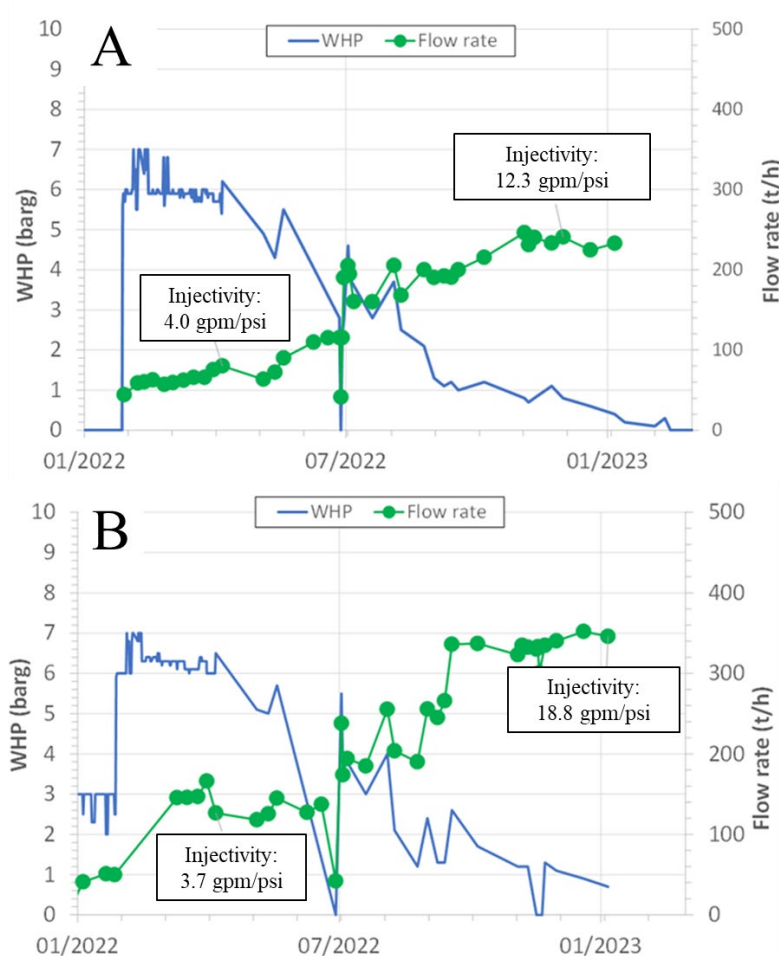


Figure 8: Injection and wellhead pressure trends for 2022 for the A) R3 and B) R5 injection wells and calculated injectivity indices based on multi-step injection tests. Injectivity for the two wells was near 3.5-4.0 gpm/psi for the first half of 2022 but increased by 300-500% after treatment in late June. Injection rates increased steadily from July 2022 through January 2023, with continuing drops in wellhead pressures to < 1 barg. Current injection rates for the wells are near 250 and 350 T/h for R3 and R5, respectively.

4. Conclusions

Silica scale and its appropriate management will continue to be a challenge to the geothermal industry, particularly as technology continues to improve our ability to develop resources of all temperatures and as energy demands continue to push the business to operate fields at lower and lower injection temperatures. While appropriate design and mitigation strategies are the best approach for controlling scale risks during production, appropriate remediation programs must also exist to recover critical assets such as injection wells.

The use of a simple, low-cost caustic treatment at the Zunil geothermal field was capable of recovering 300-500% of injectivity over pretreatment values, providing suitable injection capacity for the field and allowing flexibility in designing optimal injection strategies to reduce long-term cooling effects as a result of injection returns. The treatment utilized a 2.5 wt. % solution of NaOH and a 0.25 wt. % solution of EDTA and was capable of being done online, with less than 24 hours total downtime during the pumping and well shut-in process. After shut-in, the wells were returned to service immediately and there was a nearly immediate increase to injection capacity that continued to improve over the next several months. Total costs were less than \$70,000 USD for both wells and did not require complex pumping equipment or design process and did not include the use of hazardous or corrosive acids such as HF or HCl, reducing the need for specialized PPE and/or corrosion inhibitor chemical systems. Care must be taken to ensure that the metallurgy of the system is compatible with caustic treatments at injection temperatures, as elevated temperatures may lead to embrittlement and increased corrosion of some duplex steels.

Application of such caustic cleanout programs on high-enthalpy fields where silica scaling in injection wells is an issue can reduce the need for well-workover and new well drilling and could potentially be applied to online systems where silica scale affects heat exchanger efficiency. Additionally, the use of caustic also acts to remove antimony or arsenic sulfide species from surface piping and wellbore, providing removal of multiple injection-scale related species with a single, low-cost treatment (Brown, 2011). These sorts of programs can increase the lifetime of projects and reduce overall long-term capital expenditures, and such programs are being investigated at other Ormat fields and are likely to be included as part of the general reservoir maintenance strategy.

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